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Ph.D Thesis

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THE APPLICATION OF COMPUTATIONAL TECHNIQUES
TO THE DESIGN OF THERMAL ICE PROTECTION SYSTEMS

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Abstract

A bibliography citing 1350 references related to all aspects of aircraft icing is presented. An ice adhesion database has been compiled, and a survey of ice adhesion test rig designs is presented. An ice shear adhesion test rig is designed, manufactured and operated. The results are added to and compared with those in the database. The adhesion of ice accreted on metal and non-metallic composite aircraft propeller blades in flight is assessed. A one-dimensional thermodynamic study of ice accreted on a non-metallic composite propeller blade with 'built-in' electrothermal de-icing system is effected and compared with a solid metal blade. A two-dimensional aerofoil icing prediction program is modified and executed in series with additionally created software to predict icing on aircraft engine air intake duct lips in flight. Hence a new de-icing system design method is developed to replace and improve upon an existing one. Validation of the new design method is initiated and a programme for its completion is presented. Icing predictions produced using the new method correlate well with expected values derived by several methods. The new design method is incorporated in the sponsoring companies business with an appropriate computer hardware/software system and employed, in parallel with the 'old' approach (till validation completion), on commercial projects. Market response indicates a definite preference for the new design method.

The 'non-technical' and other related practical topics of implementing the new de-icing system design method, including specification and installation of computer hardware and software are discussed. Marketing, financial and other commercially oriented subjects are addressed in justifying the research and the implications of introducing the new design method into the commercial business of the sponsoring organisation are considered.

This research programme forms a part of a large, long term icing research commitment. Continued research subjects and investigative routes including the integration of ice adhesion mechanical characteristics into the de-icing system design method are discussed together with their relationship to this and the overall icing research plan.

Notation

	Units
	(Dimensionless = -)
a - Index ice density term (Figs.20 and 21)	- ⁻¹
a - Speed of sound	ms
A _c - Contact area of ice accretion to blade	m ²
A _i - Cross-sectional area of ice accretion	m ²
A _l - Cross-sectional area of blade leading edge beneath the ice accretion	m ²
c - Blade local chord, aerofoil/lip chord, or characteristic dimension	m
C _f - Centrifugal force acting on ice accretion	N
C _f - Skin friction coefficient	-
C _p - Specific heat at constant pressure	J.kg ⁻¹ K ⁻¹
d - Ice thickness forward of the blade leading edge	m
D - Droplet diameter	m
DD - Droplet diameter	μm
h - Absolute value of adhesion of the ice accretion to the blade	N
h _t (s) - Turbulent heat transfer coefficient	W.m ⁻² K ⁻¹
h _l (s) - Laminar convective heat transfer coefficient	W.m ⁻² K ⁻¹
H - Adhesion strength (per unit area) of the ice accretion to the blade	N.m ⁻²
k - Thermal conductivity	W.m ⁻¹ K ⁻¹
k - Constant to account for blade leading edge thickness in ice accretion profile simulation	-
K - Droplet inertia parameter	-
K _s - Surface equivalent sand grain roughness	m
K ₀ ^s - Modified droplet inertia parameter	-
l ₀ - Blade leading edge perimeter beneath the ice	m
LWC - Cloud liquid water content	kg.m ⁻³
m - Mass of ice accretion	kg
M - Mach number	-
Nu - Nusselt number	-
OAT - Outside air temperature (ambient)	°C or K
p - Effective blade leading edge perimeter beneath the effective area of contact of the ice to the blade	m
Pr - Prandtl number	-
P _∞ - Ambient static pressure (pressure altitude)	kPa
q _h - Heater electrical power	W.m ⁻²

q_{in}	- Heat flow into blade from de-icer	$W.m^{-2}$
q_o	- Heat flow out of blade leading edge from de-icer	$W.m^{-2}$
r	- Local blade radius or mean blade radius at which an ice accretion is located	m
r_i	- Blade radial location of the inboard limit of an ice accretion.	m
r_o	- Blade radial location of the outboard limit of an ice accretion.	m
R	- Gas constant	$J.kg^{-1}K^{-1}$
Re	- Reynolds number	-
R_q	- Ratio of heat flow out of blade to heater power	-
s	- Aircraft velocity	$m.s^{-1}$
S	- Distance aft of leading edge on curved surface	m
St	- Stanton number	-
St_k	- Roughness Stanton number	-
S/C	- S non-dimensionalised with respect to chord	-
t	- Local blade thickness, perpendicular to blade chord	m
t	- Static temperature	K or °C
time	- Time in icing	minutes
T	- Stagnation temperature	K or °C
T_∞	- Ambient freestream static temperature	°C
U_∞	- Local velocity	ms^{-1}
U_{in}	- Thermal resistance to heat flow into blade	$W.m^{-2}K^{-1}$
U_o	- Thermal resistance to heat flow out of blade	$W.m^{-2}K^{-1}$
U_T	- Surface shear velocity	ms^{-1}
v	- Velocity	ms^{-1}
V	- Freestream velocity	ms^{-1}
x	- Material thickness	m
X	- Abscissa of symmetrical generic ice accretion profile	m
y	- Ordinate of symmetrical generic ice accretion profile	m
Y_0	- Ordinate of origin of droplet 7 chords ahead of leading edge	m
α	- Incidence	°
β	- ice catch efficiency	-
γ	- Gas ratio	-
δ	- Boundary layer thickness	m
θ_t	- Turbulent boundary layer momentum thickness	$s.m^{-1}$
θ_l	- Laminar boundary layer momentum thickness	$s.m^{-1}$
λ_s	- Range of a particle launched in still air assuming Stokes law holds	m

λ	- Actual range of a particle	m
μ	- Viscosity (air)	$kgm^{-1}s^{-1}$
ν	- Air kinematic viscosity	m^2s^{-1}
ρ	- Mass density	$kg.m^{-3}$
ρ_A	- Density of air	kgm^{-3}
ρ_D	- Density of droplet (water)	kgm^{-3}
σ	- air thermal conductivity	$Wm^{-1}K^{-1}$
ω	- Blade angular velocity	$rad.s^{-1}$

Subfixes

a	Aluminium Alloy
A	Air
c	Carbon fibre impregnated with epoxy resin
D	Droplet
e	Edge of boundary layer
f	Polyurethane foam cuff
g	Glass fibre impregnated with epoxy resin
h	Heater
i	Ice
j	Polyurethane foam core
k	Parameter value at height K_s in boundary layer
l	Laminar
n	Neoprene
p	Polyurethane
t	Turbulent
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L1	Shear adhesion	- Stainless steel
L2		- Titanium
L3		- Brass
L4		- Aluminium
L5		- Steel
L6		- Teflon
L7		- Polystyrene
L8		- Polyacetal
L9		- Rubber
L10		- Polyethylene
L11		- Neoprene
L12		- Viton
L13		- Lubricated Aluminium
L14		- Lubricated Stainless steel
L15		- Lubricated Steel
L16		- Lubricated Brass
L17		- Lubricated Teflon
L18	Tensile adhesion	- Stainless steel
L19		- Steel
L20		- Aluminium
L21		- Brass
L22		- Polystyrene
L23	Tensile strength	- Polyethylene
L24		- Teflon
L25		- Lubricated Brass
L26		- Metal
L27		- Hard non-metal
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L30		- General (all substrates)
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Note on Referencing

To maintain correlation between sections of the text, references are made in three basic manners, corresponding to three material sources.

- (Ref.12) - reference 12 in the reference section of this text
- (Bib.302) - bibliography reference (302)
- (Bib.- 4.1.3) - bibliography section 4.1.3
- (Sub.Ref.2) - reference 2 of the report referred to e.g. (Bib.302), (Sub.Ref.2) refers to reference 2 cited in bibliography reference 302.
- (Sup.3 - 4.2.1) - supporting material report 3, section 4.2.1

Thus it is possible for the same number to be employed for different references, and care must be taken to note the type of referencing employed.

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1 INTRODUCTION

Ever since the earliest days of commercial and military flying the accretion of ice on the aircraft has been a hazard; even small amounts of ice could produce serious effects on performance and handling. In the period up to, and throughout World War II a considerable amount of research and development effort was expended on the methods of de-icing and anti-icing of aircraft. This was necessary because the aircraft of that time were operating at heights and speeds at which icing was most likely to occur.

Introduction of the turbojet engine into civil and military aircraft in the years following WWII enabled aircraft to fly higher and faster spending less time in the levels of the atmosphere in which icing is generally encountered and the established methods of icing clearance were generally adequate for that generation of aircraft. This led to a reduction of the significance of icing on aircraft and a consequent reduction in de-icing research. In the years between 1952 and 1975 few reports on this subject are recorded (Bibliography - Appendix C).

Two events in recent years have reversed this trend. Firstly, the oil embargo of 1973 raised the price of fuel and turned the emphasis from the turbojet towards the turbofan, propeller and unducted fan, all of which show better propulsive efficiency. Secondly, deregulation of the airlines in 1978 (Ref.1) allowed the operators of smaller aircraft to fly on scheduled routes. These two events meant that more propeller driven aircraft are now flying on airways routes which are likely to take them into icing conditions and the significance of icing on the propeller and engine air intakes has re-emerged.

Considerable development has taken place in both the propeller and engine design over the past few years. The solid metal propeller blade is being replaced by reinforced plastic blades which have quite different shapes, aerodynamic properties and thermal characteristics. The engines are often small turboshaft units which have relatively small air intakes and are sensitive to the flow changes caused by ice accretion. They are also easily damaged by ingestion of ice which may be shed from the intake lip and find its way into the compressor. It was these developments which led to the programme of research described in this thesis.

For many years the effect of ice accretion on the propeller was not a serious problem. The centrifugal forces acting on the ice kept the blade clear of significant accretion at the outer part of the blade. However in the inner section of the blade, where the centrifugal forces are smaller, some assistance was required to ensure that the ice accretion was shed. This was usually achieved by electrical heating applied to the leading edge of the blade which weakened the ice bond and allowed the ice to shed under the action of centrifugal force. The large, heavy propellers and engines of the transport aircraft could cope with significant ice accretion on the propeller since the vibration levels were acceptable due to the low rotational speeds and heavy engine-propeller installations. However in

the case of the smaller aircraft now operating with the modern, lightweight turboshaft engines the ice accretion can produce much more significant vibration levels which are unacceptable and potentially dangerous. It became necessary to consider more efficient forms of de-icing systems which would clear the propeller of ice more reliably. This consideration led to the initiation of this research programme.

Dowty Rotol Limited design and manufacture aircraft propellers fitted with de-icing systems. This includes the complete process from initial sizing for performance, through detailed design, manufacture, and testing. On a parallel course, the de-icing system is also designed, manufactured and fitted to the propeller. To satisfy current requirements for more efficient de-icing systems, of lower power consumption, it is now necessary to consider the propeller/de-icer combination as a whole from the initial design stage to produce an integrated de-icing system.

As in most engineering research programmes, it is first necessary to determine the extent of existing knowledge on the subject (and other, closely related, subjects). This programme began with a survey of all related literature. Due to the nature of this research, there are many related subjects, including; ice physics, ice accretion, de-icing systems, meteorology, heat transfer and computer flow simulation. Within each of these subjects there are many avenues of investigation which include a large number of sub-topics. Hence the literature survey developed into a bibliography of over 1350 references (Appendix C).

Some references date back to the 1850's and, in the main, are concerned with basic ice physics. This was followed by an interest in ice adhesion strength to various materials and surface finishes mainly for application to sea vessels. During wartime (WWII) a great many reports emerged concerned with ice accretion on and adhesion to the leading edges of aircraft wings, tail units, propeller blades and engine air intakes. There was a marked decrease in the level of interest in aircraft icing, reflected in the small number of related reports, during the turbojet years, due to the relatively plentiful supply of hot compressor bleed air for de-icing purposes. This was followed by a gradual renewed interest as the turboprop power unit re-emerged with a requirement for economic and efficient de-icing. The highly competitive aerospace industries of recent years now demand a modern approach to aircraft icing research. This is reflected in the increasing number of reports involving computer flow simulation and derivation of icing prediction techniques.

Relatively little data on ice shear adhesion was available and an initial aim of the programme became the compilation of an ice shear adhesion database ("Ice Adhesion Survey"), developed from the bibliography. However, little quantitative and not abundant qualitative data was found available with respect to the adhesion of ice to materials employed in modern composite propeller blades.

Ice shear adhesion testing was required to produce additional information, as a part of the research programme. The results are

eventually to be applied to the design process, in material allocation, surface finishes and possibly aerofoil section profiles. This involved the design and manufacture of a suitable test rig developed from consideration of previous designs in the literature. The rig was operated to produce ice shear adhesion data for materials employed on composite propeller blades. The adhesion data was analysed and compared with that of the literature. However, there being little data in the literature, a second database for ice shear adhesion was developed through the use of flight test photographic evidence.

As the overall intention was to improve the design techniques applied to the composite blade, including the de-icing system, the next step was to investigate the basic thermodynamics of ice adhered to the composite blade as compared with the solid metal blade as little thermodynamic analysis of the composite blade had taken place. In the long term, the intention was to modify a two-dimensional aerofoil icing prediction computer program for application to the propeller blade. Thus in the short term, the aim of the one-dimensional thermodynamic study was to acquire a better understanding of the thermodynamics of the system and a better appreciation for the thermal differences between the solid metal and non-metallic composite blades.

Toward completion of the second year of the research programme as ice adhesion testing was progressing and the one-dimensional thermodynamic investigation was nearing completion, several changes took place within the sponsoring company, including reductions in research funding; the propeller de-icing research programme was cancelled as a result of this. An offer was made by Lucas Aerospace, Luton to continue the work since they had interests in de-icing and anti-icing system design and manufacture. It was not, however, possible to continue with the propeller de-icing programme since Lucas had no requirement in that field and so the direction of the research was turned toward engine intake anti-icing. This was a major change in direction at a late stage in the programme. There were, however, sufficient common areas of interest to continue the research in the new direction.

Since the air intake lip does not experience the centrifugal acceleration, the major force attempting to remove the ice from the duct surface in areas downstream of the stagnation point is a shear force due to aerodynamic drag on the ice accretion. Thus although experiencing a much lower force level, shear adhesion of ice to modern composite aircraft structure is of interest to engine air intake lip icing research as well as propeller blade icing research. The one-dimensional thermodynamic investigation although not directly applicable to the engine intake lip, did serve to provide an insight into the basic theory involved in some of the ensuing two-dimensional software thermodynamic theory.

The research required the modification of a two-dimensional aerofoil icing prediction computer code for application to the engine air intake duct lip. The flow around the intake lip section differs from the flow around the aerofoil in a few fundamental ways. The inlet

serving its function to supply the gas turbine engine compressor with the correct air mass flow rate, produces a flow over the inner surface which differs from that experienced by a simple aerofoil section in a 'free-flow'. Hence a new code was compiled to act as a 'pre-processor' to a modified version of the existing code to predict icing on the intake lip for employment in the de-icing system design method.

The RAE software has been extensively validated against icing tunnel experimental tests and other computer codes employing different mathematical techniques. Hence for simple 2-D aerofoil icing prediction such as for helicopter rotor blades (the purpose for which the RAE software was written), the RAE software is already employable in its unmodified state.

For application to air intake duct lip icing prediction using the modified software, additional validation is necessary. Due to the financial implications of effecting the necessary icing tunnel tests, the solution 'common' to this type of engineering problem is employed. The validation is initiated and progressed as far as feasibly possible through previous test data and comparison with other similar methods. Experimental test data is costly to acquire, and thus the 'new' method is employed alongside the existing one in commercially supported work, until a database of validating material has been accumulated.

A limited amount of icing tunnel experimental test work was carried out within the research programme as a part of a current commercial project, and the new de-icer design method has been applied to commercial projects in parallel with the 'old' method. The results are encouraging and indicate a strong preference for the new method.

This research programme was carried out under the relatively new "Total Technology" scheme. In this scheme the research programme addresses several related topics involved in the implementation of the findings of the research within the commercial business of the sponsoring organisation. This included the commercial and technical justifications for the research to proceed, and the technical and commercial implications of implementing the results. These 'non-technical' sections concentrated mainly on the latter part of the research. "Continued Research and Development" is described in the proposed schedule of events to progress this research programme into the future. Research to improve the product is a continuous exercise and this PhD programme forms a section in a continuous research project.

The new computer program oriented design technique required computing facilities considerably in excess of those available in the engineering department of the second sponsor. Thus the provision of adequate 'in-house' computing facilities became an integral part of the research programme.

2 COMMERCIAL JUSTIFICATION

2.1 Product Description

Spraymat

Definition:- "'Spraymat' is a glass-fibre reinforced epoxy resin laminate incorporating a sprayed metal, electrically conducting heating element", (Ref.4). Spraymat is a type of anti-icer/de-icer mainly for aerospace application. It is well established and has been developed to a high level of performance in varied applications, making it a reliable, economic and efficient product.

Spraymat is produced by sandwiching a flame-sprayed metal element array between layers of epoxy resin impregnated glass-fibre matrix fabrics. It may be constructed on the substrate surface ('wet lay-up'), or manufactured separately as a pre-impregnated composite for application to the substrate surface at a later date ('pre-preg'). The manufacturing process is relatively complex, requiring considerable knowledge and experience, and a high degree of inspection. Thus, after a long time in the field, where a great deal of knowledge and experience has been accumulated, spraymat is a well developed product. However the application to specific de-icing cases requires a knowledge of the rate and area of ice accretion and the heat required to clear the ice. The purpose of this research is to improve that knowledge.

2.2 Product Demand

When investigating the demand for spraymat, it soon becomes apparent that it has fluctuated considerably over the history of spraymat sales. The reasons must be clearly understood if the demand for the product is going to be forecast with any reasonable confidence level. Therefore, it is necessary to explore the major types of external factors, beyond the control of the organisation, that influence the demand for spraymat, (and also the marketing effort of the organisation), and the important changes that have taken place in these factors during say, the last ten years. The major external influence on the spraymat market has been the price of aviation fuel, which itself is mainly influenced by the price of oil. As has already been discussed, the oil embargo of 1973 was, and still is, effective in demanding the best possible engine fuel efficiency for each application.

When spraymat was introduced in 1951, aviation fuel was relatively low priced compared with what was to happen in later years. Spraymat experienced a relatively stable market on aircraft such as the Vanguard, Argosy, Britannia and Belfast. It was fitted on the tailplane leading edges, engine air intake, spinner, bullet, etc.. Reasons why spraymat was not fitted on the mainplane leading edge and propeller blades are detailed later, but are summarised presently by simply saying that it was a matter of cost for large area coverage, and poor demonstration of its ability against the competition. These

turboprop aircraft did not have sufficient engine compressor bleed hot air to de-ice the areas where spraymat was fitted, and thus the manufacturers turned mainly to electro-thermal systems for de-icing. Of course, it is also impractical to de-ice the tailplane leading edge using engine compressor bleed air in cases where the engines are mounted on the mainplane. The coming of the bypass, then high-bypass turbofan to the large long haul aircraft, replacing some of the older turboprop types, released sufficient engine compressor bleed hot air for de-icing engine intakes, bullets, and sections of the wing leading edge. The use of hot engine compressor bleed air was the most economic choice of the day for these large, hollow, usually relatively empty, metal structures where heat transfer through the skin is favourable.

This caused a definite slump in spraymat demand and subsequent sales. During this period, spraymat was restricted to Concorde and Tornado engine air intakes, plus a few, small order, ancillary items such as antennas and underwing pods. Efforts to apply spraymat in non-aerospace applications such as domestic, heated food warming ovens etc., were unsuccessful, mainly because of the high standard, high cost background in the aerospace sector. The appropriately organised manufacturing layout, is uncompetitive in a high volume, mass production, relatively low price type of market.

Then came the 1973 fuel embargo, forcing higher turbofan bypass ratios and bringing back more turboprop aircraft, this time with a much more efficient engine and a high degree of emphasis all round on improving efficiency to a maximum. Thus once more, only this time based on engine efficiency rather than lack of power, there was little and often no engine compressor bleed hot air for de-icing purposes. This resulted in a marked improvement in demand for alternatives to hot air de-icing. The simplest, cleanest, reliable, most adaptable and most compact alternative systems are all electrothermal in operation. Hence spraymat received a large boost in demand. This oil price driven demand is unlikely to reverse, and much more likely to increase into the foreseeable future. Therefore, the move towards improved efficiency in civil applications, and to a lesser extent in military applications (where payload/range is sometimes more important than cost), will continue.

A second external influence, which came into effect about ten years ago and is detailed in the introduction, is the deregulation of the airlines. Increased demand for spraymat due to oil price increases was further accelerated by the increasing number of relatively low flying, weather penetrating, twin-engined turboprop commuter aircraft. Almost free competition amongst the airlines has seen the birth of new airlines and growth of existing ones into new areas. For best efficiency in the lower speed, lower altitude, short haul market, the propeller (turboprop) is superior to turbojet and turbofan power units. Fierce competition dictates a high level of operating efficiency required of an airline to remain competitive. Hence there was an increase in the number of twin turboprop, 30-60 passenger (or 3-7 tonnes freight), aircraft such as the F50, BAe ATP, S340, CN235, ATR42 and SD360. Initially, deregulation generated a lot of new orders for the existing aircraft types available at the time (e.g. BAe 748,

F27, etc.) and semi-suitable for the application, until the new, purpose designed aircraft arrived. These new designs are very operating-cost conscious, and thus fuel and therefore power economy conscious. The low altitude operating environment combined with the drive for economy led to a further increase in spraymat demand. Hence, the requirement for new de-icer design work was delayed somewhat, till the birth of these new aircraft designs. Although this market will eventually saturate, the need for continual replacement, modification, and further more efficient design, will ensure a strong demand for spraymat well into the next decade.

At the high speed (supersonic) end of the market, previously virtually untouched by de-icing systems, except for Concorde where de-icing is only required during climb and descent through the weather band, another major change took place. Introduction of high speed fighter and fighter-bomber aircraft such as Tornado, capable of terrain-following, electronically controlled flight at extremely low altitude (typically below 500 feet), in all weather conditions has exposed these aircraft to icing conditions, in areas of the flight envelope previously unaffected by icing. Thus, there emerged a whole new area in the market for de-icing systems on engine air intakes, wing and tailplane leading edges, antennae, various under-wing stores, flap system leading edges, etc.. The use of engine compressor bleed air is impractical in these relatively small military aircraft which demand the full performance of their engines, which in turn were not designed to deliver bleed air.

More recently, two new major spraymat markets were born. These are the all-weather helicopter (EH101), where spraymat is featured on the main and tail rotors and tailplane leading edge, and the V22 (Osprey) tilt rotor aircraft where spraymat is to be employed on the engine air intakes and spinners. Both aircraft are intended for relatively large volume production. V22 initial orders are: Marines - 552, US Air Force - 80, US Navy - 50 (Ref.5). The use of spraymat on the EH101 will introduce it as a de-icing system solution for the large market represented by future helicopter designs developed from the EH101, and all-weather helicopter designs from other manufacturers. Hence spraymat could benefit from another increase in demand, comparable in size to that driven by the fuel crisis. Although the number of civil helicopters requiring de-icing is relatively low (mainly off-shore oil rig applications), compared with the number of civil twin turboprop aircraft, the number of military helicopters which will require all-weather capability, is very large. The V22 market is numerically and financially large. The Osprey forms a new market, there being few tilt rotor aircraft designs around, and none that have all-weather capability. So this also may be a useful lead-in market for future tilt rotor aircraft designs, especially the civil version of the V22 competing in the operating area between the large helicopter and small twin turboprop aircraft. This latter market will probably develop once the V22 has successfully proved its worth in its various military roles.

A large market probably about to emerge for de-icing system demand will result from the employment of terrain following flight

strategy, by American and Canadian, previously non de-iced aircraft such as the F15, F16 and F18. Especially in Canada these aircraft, already beginning trials in this role, are beginning to suffer considerable icing problems and will almost certainly have to be fitted with de-icing equipment in the near future. Not new designs, and well down the road of development, they possess little space for bulky new equipment. In light of the reluctance to bleed engine compressor air from these high performance, engine demanding aircraft, the de-icing systems chosen for all areas to be de-iced will have to be electrothermal. These aircraft exist in large numbers, and a lot of aircraft will require this retrofit. This represents a considerable potential market for spraymat. It is convenient to point out at this stage that although spraymat is not an 'add-on' system, it may be fitted to new 'add-on' or replacement components such as leading edge skins, pods, antennas, engine intake lips and ducts, etc..

A fourth external factor is the nationality of the manufacturer of new aircraft designs, and also to a lesser extent, the manufacturer of the engines for the new aircraft. If the aircraft designer and manufacturer are American, then the choice of engine is likely to be in favour of an American unit. In this case the choice of de-icing system manufacturer for engine air intakes and to a lesser extent, all other de-iced areas of the aircraft, is also likely to be American. However, should the aircraft and engine be European, then the competition is much less nationally limited. Of course, some aircraft or engine manufacturers are traditional (rather than patriotic) in their choice of equipment manufacturers, staying with the same supplier almost irrespective of advances and improvements which may be available elsewhere. In these cases, where the sponsoring company has not been the traditional choice, it is up to the combined efforts of the Marketing, Engineering and Sales teams to become more effective in influencing that aircraft or engine manufacturer to break tradition. The immediate case that comes to mind is that of the European aircraft powered by American engines, ie. S340, having a Swedish (and part American - Fairchild) original aircraft manufacturer and American engines (General Electric). The choice of General Electric engines is not surprising considering the influence of Fairchild in the aircraft manufacturing organisation. Here a non-American de-icing system has to be good to be considered. SAAB-Fairchild chose an American system initially, but it failed to perform to sufficiently high standards. After this, SAAB chose spraymat, probably based upon previous experience and a knowledge of the product.

A fifth factor favouring electrothermal de-icing is the expanding use of non-metallic composite materials in areas where hot gas de-icing systems would be too destructive to the local structure by degrading material properties, causing delamination and subsequent structural failure. This is another factor which is predictably one-directional in its increasing effect upon the product market. It is unlikely that a reversal of preference to favour metals will occur in these areas already dominated by non-metallic composite laminates.

Finally, an often under-rated factor is the influence of the relationship between the de-icing system manufacturer and the aircraft

manufacturer on a long term historical basis. Although not entirely external to the influence of the de-icing system manufacturing organisation, this influence can typically last for several decades, as it were, until the retirement of at least one generation of management within the aircraft manufacturing organisation.

As can be appreciated, most external factors beyond the control of the organisation have been in favour of increasing the demand for electrothermal de-icing systems, and present a healthy product demand for spraymat well into the future. Hence it can be appreciated that the growing market for spraymat on an historical basis in addition to recent trends justifies research to maintain the competitive edge of the product.

2.2.1 Market Segmentation

The second important step to understanding the demand for spraymat is to learn more about the segmentation of the market. A market may be segmented with respect to various criteria. For instance, it may be broken down according to the nationality of the customers, the size of order for the product, separated according to the various products offered, or many other criteria. The criterion selected should be the one providing the best basis for exploiting the potential offered in the market. For spraymat, it would appear that for design and research purposes, the most useful segmentation is based on product application. The segmentation best suited to other areas of interest such as sales may well be different, the obvious contender being order value. It is possible and often the case that a market may be segmented in different ways in different areas of the organisation. Here, in the research project, we shall concentrate on segmenting the market in a manner most clearly beneficial to the work of the project.

Hence, the spraymat market has been segmented as follows:-

1. Engine air intakes.
2. Helicopter rotor blades and aircraft propellers.
3. Leading edges, e.g. mainplane, tailplane, fin, flaps, etc..
4. Spinners and bullets.
5. Empennages, e.g. antennas, pods, weapons, domes, etc..

1. Engine Air Intakes

Segment one may be further segmented into two definite areas.

- 1(a). Subsonic
- 1(b). Supersonic.

Segment 1(a). has accompanied the product since its introduction in 1951. For subsonic inlet ducts, in addition to the duct inner surface, it is necessary to de-ice a small but significant area on the outside edge of the intake lip. In certain circumstances where the air velocity in the duct is greater than the flight speed, the stagnation point is outside the lip highlight and ice shedding from the outside edge of the lip may be ingested by the engine. Many of these subsonic intakes will spend long time periods in icing conditions where the de-icing system could be in operation over the whole of the flight. For this type of application therefore, the de-icing system must be capable of dealing with rapid ice accretion rates, and widely varying conditions.

Segment 1(b) differs from 1(a) in that the air flow, being supersonic in the ruling intake design cases, requires a sharp intake lip. Thus even when flying subsonic, ice shedding from an area just aft of the lip highlight on the outside edge of the duct does not enter the duct in all but the ground static cases. Hence the de-icing system is only required over a short distance of the outside edge of the lip, on the lower 'blunter' lip, and not at all on the side and upper panels. Supersonic aircraft generally fly at altitudes outside the icing envelope and thus only require the use of de-icing systems during climb and descent through icing conditions. Also, for cases of supersonic flight within the icing envelope (e.g. in some military operations), the aircraft skin temperature is heated by air friction to values outside the icing region. Hence, for this application the de-icing system is small and only occasionally operated. However, the obvious exception to this generalisation is that mentioned earlier of the terrain following low level flying. Thus the de-icing systems must also be capable of dealing with the occasional relatively sustained subsonic (and transonic) flight well into the icing region, on aircraft flown in this role.

For both cases 1(a) and 1(b), the intake lip area of the de-icer in its most common location (between the wing root leading edge and the fuselage side, or underwing pod), must be capable of resisting damage from runway stone chip debris. In segment 1(a), there is also a hazard to the intake lip de-icer presented by ice shed from propellers. In segment one it is usual practice to employ anti-icing inside the duct on smaller engines where the largest allowable section of ice to be shed without damaging the engine compressor is small, (typically less than five grammes).

As mentioned earlier, the engine air intake de-icing system market is potentially large, presently growing, probably about to further accelerate in growth, and unlikely to decline within the long term future (ie. probably in excess of 25 years). This market segment also covers helicopter and tilt rotor engine air intakes as well as fixed wing cases. A prime case is that of the V22 project detailed earlier where the engine intake de-icing system is large and forms an integral part of the composite duct which is manufactured by the same company.

2. Helicopter Rotor Blades and Aircraft Propellers

This segment is also best subdivided into two areas, being, (a). helicopter main and tail rotor blades, (b). aircraft propellers (turboprop and piston/prop).

Segment 2(a) has only developed in latter years, in that the requirement for a true all-weather helicopter has only recently been appreciated both in military and civil guise. Although a military all-weather helicopter has long been desired, it is only the very latest helicopters that are being considered with de-icing in mind at the onset of the aircraft design process. The first new all-weather helicopter design, ie. the EH101, which also stems from a company now having a strong American content (Westland Helicopters Limited - Sikorsky), employs the spraymat de-icing system.

Segment 2(b) has traditionally been one of heavy, solid and hollow, metal propeller blades of large thermal capacity ("One-Dimensional Thermodynamics" section). In these cases the application of a relatively light weight (compared with the propeller), "add-on" de-icing electrical rubber boot on the surface of the blade has presented a simple obvious solution. In fact, before the full introduction of the rubber boot (Bib.-4.4.1), several cases existed where exhaust gas from the engine was employed in prototype propellers, passed through the cavity inside hollow steel blades to exhaust at the blade tips (Bib.-4.1.1). However, they were unsuccessful due to overall propulsive efficiency losses incurred. Although the presence of the hot gas exhausting at the periphery of the propeller disc flow caused a 0.5 % drop in propulsive efficiency, the rubbing seal required between the engine nacelle and the spinner produced approximately a six percent loss in efficiency. Even after the introduction of more efficient, light weight, non-metallic composite, propeller blades of low thermal capacity, there is still an historic attachment to the rubber boot type of de-icing system. There tends to be a traditional reluctance to consider alternative de-icing systems at the beginning of propeller blade design, enhanced by a well established relationship with the de-icing boot manufacturers. As spraymat is a new, relatively none "tried and tested", de-icing system, (in this application), and bearing in mind the prohibitively high costs and risks involved in certification, this market, although potentially a large expansion to spraymat, would be difficult to break into. Therefore it can be seen that segment 2(b) is not available to spraymat at present but is a large potential market segment for future plans.

3. Leading Edges, (e.g. Mainplane, Tailplane, Fin, Flaps, etc.).

De-icers fitted to helicopter rotor blades and aircraft propellers are leading edge devices. However, it is intended here that this segment should include all other leading edge devices where the substrate is non-rotating and effectively two-dimensional on a simplistic basis, ie. not including nose cones and alike.

For leading edge devices, the market is again dominated by traditional methods due to close relationships between companies, experience with various systems, after sales service, etc. and a reluctance to change for fear of re-certification costs. Mainplane leading edge devices are inherently large in area relative to most other de-icer applications, and thus cost becomes a relevant factor in addition to electrical power requirement and technical advantages achievable. Rubber boots are well established in a lot of cases, mainly the electrical type, where an electrical wire matrix heating element vulcanised between layers of neoprene is periodically energised to heat the surface, (Fig.1). A number of pneumatic boot systems, being hollow tubes in a rubber skin, periodically air inflated to ripple the outer surface, (Fig.2) are still in use, but decreasing in popularity (Bib.- 4.5). A few fluid de-icing systems employing a freezing point depressant liquid excreted through a porous surface to act like anti-freeze, (Fig.3), (Bib.-4.6) still exist, but these are also of decreasing popularity. On aircraft powered by turbofan units, hot engine compressor bleed air remains the most economic method in areas in close proximity to the engines (Fig.4), (Bib.- 4.1.3). Two new types of de-icing system presently under research and development, particularly for application on wing, tailplane and fin leading edges, are the electro-impulsive (Fig.5) and electro-expulsive (Fig.6) systems (Bib.- 4.8). "Electro-Impulsive" uses electrical coils to deliver a sharp shock movement to a metal skin (or skin doubler on a non-metallic structure) analogous to delivering an impact blow to the non-iced side of the substrate. "Electro-Expulsive" involves a metal strip inside a rubber "boot" which is electromagnetically repelled by an electrical coil within the structure in a manner similar to the metal skin or doubler of the electro-impulsive system. These two systems are obviously only applicable in hollow structures where there is sufficient space for the electrical coils, or where the outer skin/ice substrate may be moved slightly relative to the structure.

4. Spinners and Bullets.

This market segment like segment 1(a) originated at the birth of spraymat when the bullets (spinners, or nose cones on gas turbine engine compressors), of the various aircraft engine intakes to which spraymat de-icing was applied, were also de-iced by spraymat. Although these items were usually relatively small in size, it was a steady income and required little design work compared with the intake de-icer. However, it must be appreciated that ice shed from the bullet or spinner is a potential hazard for engine ingestion and thus there is an element of design with this in mind. As the turboprops were phased out for preference of turbojets and turbofans the bullets were hot engine bleed air de-iced. The return of the propeller with a non-spraymat de-icing system meant that in most cases, the spinners received the same type of de-icing system as the propeller blades. Thus spraymat de-icing systems now exist on few aircraft propeller spinners. For large engines, employed on large civil aircraft, there is still a demand for high subsonic speed making the high bypass turbofan a necessity, except for the potential introduction of the UDF (un-ducted fan) from GE and Propfan from Rolls Royce. For these

relatively large spinners, the obvious solution in the relatively short time spent in icing conditions is to use engine compressor bleed hot air. On the smaller gas turbine engines employed in turboprop power units, the bullet does not effectively exist, rather there is a drive shaft housing tube and this is de-iced using spraymat in the cases where the engine air intake duct is also spraymat de-iced. Hence it can be seen that this is a small segment and also one in which spraymat has a small share.

5. Empennages, (e.g. Antennas, Pods, Weapons, Domes, etc.).

This segment is unique in its diversity and also in its typical volume production. Many of the items produced in this segment are actually 'one-off' cases to satisfy a singular particular need such as an object used in a test or experiment. A large number of products are for low (relatively few in number) volume sales such as nose cones for underwing pods, aircraft fuel droptanks, or missile nose cones. However, some cases involve potentially large volume production of small items, e.g. antenna de-icing. There will always be a demand for electrothermally de-iced empennages as no other type of system is sufficiently autonomous. Thus this segment provides a steady small income with occasional large orders.

2.2.2 Market Share

In planning research programmes it is important to consider the competition to ensure that new product developments are timed to maximise advantages and minimise risks. The Company holds a major share of the market in three main areas. Spraymat provides engine air intake duct de-icing systems for the supersonic Tornado multi-role aircraft, and the S340 and CN235 twin turboprop commuters. The S340 employs a rather complicated duct shape incorporating an inlet protection device ("birdcatcher") or 'ice separator' due to the low particle ingestion tolerance of the engine. It has also produced the complete engine air inlet for the new V22 "Osprey" tiltrotor aircraft from Bell and Boeing (BHTI - Bell Helicopter Textron Incorporated) which has an abnormally complex shape involving many three-dimensional reflexed (re-entrant) curves. On this duct there is no real competitor to spraymat where Lucas Aerospace produce the complete article of composite duct inlet with built-in de-icing system. In the 'Spinner' category is the V22 spinner which is more complex than the average spinner, and of large dimensions. The third major area is in helicopter rotor blades where Lucas Aerospace produce and fit the spraymat de-icing system to the new EH101 helicopter main rotor. This blade has a 'BERP' (British Experimental Rotor Programme) tip and thus inherently complex shape to which to fit a de-icing system. Thus it can be seen that Lucas Aerospace is a major supplier of de-icing systems to the aerospace industries of the western world. It holds a major share in most of the market areas and smaller shares in others, (such as leading edges, pods and other empennages).

2.2.3 Competitors

Competitors may be subdivided in two ways; by market segment (as the previous section), or subdivided into existing and potential competitors. Potential competitor de-icing methods are mentioned in preference to actual competing organisations for reasons of commercial security.

Engine Air Intakes

Present Competitors

Regarding engine health, it is not practical to employ any type of system which will shed fluids or particles (other than small sections of ice and water) into the engine. Hence ice phobic pastes, most freezing point depressant fluid de-icing systems, electro-impulsive and electro-expulsive systems are out of the question. All serious competitors are in the electrothermal field.

Future Competitors

On large gas turbine engines possessing compressors capable of swallowing relatively large pieces of ice shed from the intake duct (typically 150 grammes), electro-impulse systems may be considered in the near future, but it is doubtful whether their economy would exceed that of the simple use of hot compressor bleed air. Spraymat is not, and is never likely to be a serious contender in this area of application. Potential future competitors in this segment will likely be those presently existing.

Helicopter Rotor Blades and Aircraft Propellers

The subject of helicopter de-icing is covered in detail in the AGARD manual (Bib.109), and (Bib.- 4.2.3, 4.13.3). Many different de-icing methods have been investigated and tested for application to helicopter rotor blades, (main and tail rotors), including Pneumatic boots, fluid systems, paste systems and even microwave based systems, in addition to electrothermal systems. The pneumatic system failed in that the effect of centrifugal force on the gas within the boots caused the boots to inflate to greater dimensions at the rotor tips than elsewhere along the leading edge. Fluid excretion type systems require relatively complex feeder pipe systems along the inside of the leading edge being highly impractical, and also suffer from blocked pores on aircraft flying in close proximity to the ground. Pastes are soon eroded off the leading edge and require constant replacement. The microwave system required an uneconomic supply of electrical power and suffered design difficulties in channelling the microwaves to the rotor blades. Helicopter rotor blades are highly stressed components rendering any form of mechanical shock such as that applied by an electro-impulse system, out of the question. However, an electro-expulsive system if developed to a very small electrical coil size, may present a future possibility.

Present Competitors

Thus all spraymat competitors in this segment are also electrothermal. Electric rubber boot de-icers have been tested on helicopter rotor blades but in general are too heavy, too vulnerable to damage, and cause an unacceptable drag increase on the short chord blades. This leaves only built-in metal foil and sprayed metal element type systems to compete with spraymat in this segment. In the case of "built-in" metal foils, it is the fatigue damage due to differential strain rate at the metal/composite interfaces which causes structural degradation and thus unsuitability to this application.

Future Competitors

As detailed in the previous section, all competitors in this segment are electrothermal, with the one potential exception of electro-expulsive.

Leading Edges, (e.g. mainplane, tailplane, flaps, etc.).

This segment is one where virtually all de-icer types have some application, but with reservations in some areas. For large high altitude turbofan aircraft, the hot compressor bleed air type of system remains unbeatable from operating economy and simplistic, reliable design considerations. For components located far from the engines, an electrical system is almost always the answer. A few smaller, lower level aircraft still make use of a freezing point depressant, fluid excretion type of system such as the T.K.S. system on the BAe 125. These systems are declining in their use, mainly due to the need for storage of fluid tanks, pumps, pipes, etc., problems resulting from blocked pores, and the relatively high maintenance levels caused by constant re-filling of the tanks. Pneumatic boots also remain in use on some aircraft wing and tail leading edges, but occurrences are decreasing in number. Thus all major spraymat competitors in this segment employ electrothermal or hot gas systems.

Present Competitors

As described above, spraymat cannot successfully compete against hot gas systems in the applications where hot gas systems are economically preferential, and thus the only competitors worth consideration are all electrothermal.

Future Competitors

A serious competitor for aircraft possessing hollow leading edges (mainplane, tailplane, fin, foreplane, winglet, etc.), with a good advantage of requiring low electrical power levels, compared with systems such as spraymat or rubber boots, is the electro-impulse type of system (Fig.5), (Bib.- 4.8). Although still at the development stage, and certainly not useable in highly stressed areas, this type of system is already under test on composite and metal hollow 'D' section leading edges of various static aircraft components (mainplane, tailplane, wing strut, etc.). It will be some time before

the well established traditional aircraft manufacturers are convinced that electro-impulse is a safe design choice on which to risk the companies reputation. However it is being used on radically new canard type aircraft (e.g. Starship I), probably because being at the "forefront of technology" is the overall selling theme of the aircraft. Electro-Expulsive systems however, could present a good alternative to electro-impulsive systems, but the covering of the icing area with a rubber boot will not be attractive to spraymat customers who are accustomed to seeing a "clean" aerodynamic surface with integral de-icer.

Spinners and Bullets

Present Competitors

Bullets to gas turbine engines are nearly all hot gas de-iced for best economy, as detailed earlier. Spinners to turboprop engines tend to either not be de-iced, or to employ electrothermal "over-shoe" type boots on the inside surface of a thin metal shell. Spraymat is built into the new V22 aircraft composite spinners which form a relatively large market and could be an opening to future spinner markets on other aircraft.

Future Competitors

Electro-impulse type systems could be a serious contender for use on spinners, but not on compressor bullets for the same reasons as mentioned earlier, except on large engines which can tolerate shed ice ingestion. Most spinners are electrothermally de-iced and thus present a potential market to spraymat.

Empennages, (e.g. antennae, pods, weapons, domes, etc.).

For the reasons described earlier (autonomy) when defining this segment, the only really effective competitors in this market must all be electrothermal (except for the use of mechanically vibrating leading edges on certain antennae).

2.2.4 Concluding Remarks

In order to maintain a competitive edge, the competition must be considered, in all applications, and their proximity to spraymat in technical ability, popular demand and all other relevant attributes, including traditional choice. The most obvious competitors to spraymat are all electrothermal in their operation, except potential future competition from electro-impulsive and electro-expulsive systems. The application of non-electrical systems is usually only considered in areas where it is unsuitable to use an electrical system. It is obvious, from the following list of advantages and disadvantages when compared with the competition, that spraymat, as a product, is well suited to its application. It has few weak areas, and those it has are also weak areas in the competitors products. Any competitor wishing to

break into this market would suffer a long period of non-profitability whilst accumulating expertise, experience and equipment to serve a low volume market already dedicated to Spraymat.

Product Technical and Marketing Advantages

1. The product is well established in the market place and well known to its customers.
2. The manufacturer has accumulated over 35 years of experience in de-icing with spraymat which was first introduced in 1951.
3. The heating intensity in spraymat is uniform over an area, rather than a discrete line as in a wire based system. This leads to more efficient use of power and more uniform temperatures, in addition to reduced 'burn-out' risk. This also means that the overall system maximum temperatures are kept to a minimum, thus avoiding over-heating some ice accretion areas to the extent of producing meltwater runback ice.
4. The ratio of heated area to unheated area for a spraymat system is high, thus avoiding cold spots and reducing overall system size. In a wire based system the unheated area is greater than the heated area whereas this ratio is typically 5-10 percent for spraymat.
5. The heating elements are continuous, avoiding welded or soldered joints as are often employed in electrical rubber boot systems which, as well as producing temperature variation, are undesirable in fatigue situations.
6. The heat output may be graded in the element without fluctuation of element width, and without joints. Wire based boot systems use a wire of constant cross-section and rely on woven density for variation of heat output as is usually the case in embedded foil systems. For fluid freezing point depression systems, this variation is achieved by varying the density of the pores or the individual pore size (diameter). On electro-impulsive and electro-expulsive systems, a simple graded coil power will suffice to produce the desired effect.
7. The elements may be built into the structure to reduce weight, avoid unnecessary, unwanted, additional, thermal insulation and ensure good structural integrity in the system. Compared with spraymat, rubber boot and fluid systems tend to be rather heavy and bulky. Electro-impulse is probably of comparable weight but requires considerably more storage space inside the structure and the provision of a gap to allow surface movement (usually a hollow 'D' section leading edge).

8. As the system may be applied directly onto the substrate (or even built-in), shape conformity is maintained, even on complex surface shapes. Other 'add-on' systems tend to experience difficulty in conforming to complex shapes such as curvature in two planes or sharp radii, thus often protruding and increasing the drag of the surface to which it is applied. A problem area is at the extreme edges of boots where it is difficult to blend into the substrate surface as a minimum thickness of rubber is necessary at the edge to prevent fraying. It is not possible to achieve an effective rebate into the surface as the rubber is not completely dimensionally stable with ageing, or ultraviolet exposure.
9. The product is inspectable at all stages in manufacture, enabling fault rectification, reducing wastage, and minimising overall production costs. Some systems employ manufacturing processes involving vacuums or non-human-survivable atmospheres where the resulting product does not reveal the successfulness of the process in externally visible signs until testing after several other costly processing operations. Thus the scrap rate associated with these other systems can become higher than that of spraymat which is considerably power distribution adjustable at many stages during manufacture.
10. The dimensions of the product are stable with respect to time, ie. they do not change with ageing, wetting or exposure to ultraviolet rays. As mentioned above, this is not the case for some other systems.
11. The system does not require a regular supply of liquids, gases or pastes as for fluid and hot gas systems.
12. The system is autonomous except for the requirement of electrical power. Fluid de-icing systems require complex networks of fluid supply pipes, breathers, 'back-ups', pumps, fillers, etc.. Hot gas systems require relatively large ducting pipes and vents with associated seals, heat insulation and thermal protection. Electro-impulse systems require arrays of coils and backing plates. Pneumatic boots require compressors and associated piping.
13. The system has proved reliable, "already accumulated many millions of flying hours on all types of civil and military aircraft in severe conditions", (Ref.4). Rubber boots are also well established, but electro-impulse does not benefit in this manner.
14. It is damage resistant both in service and during installation. Systems embedded in rubber tend not to be so well protected.
15. It has low aerodynamic drag due to being thin and shape conformal with no protruberances. As mentioned earlier, some other systems are not so conformal and thus present higher drag penalties.

16. There is a capability for "on-aircraft" repairability as with most other systems except electrical rubber boots.
17. Spraymat has good erosion resistance properties, unlike ice-phobic pastes or fluids.
18. Spraymat incorporates an earth fault detection system. Fault detection is not so simple with pneumatic or fluid based systems.
19. It may be applied to substrates of many different materials. Hot gas systems require the intervening skin between the gas and ice to be of good thermal conductivity as is not the case with modern non-metallic laminates.
20. There is practically no system size limitation, apart from the magnitude of the available electrical power supply. Pneumatic and fluid systems have to consider the size of the fluid storage tank and air compressor respectively.
21. It incorporates wide elements using metals of high specific electrical resistance to reduce inter-element gaps and therefore element path length. Rubber boots tend to employ thin elements and large gaps with relatively long path lengths.
22. It possesses inter-laminar strengths of a similar standard to composite substrates to maintain structural integrity. Rubber boots employ materials of different physical properties to the substrate material, thus introducing possible fatigue sensitive areas. This is also the case for embedded metal foils, as opposed to spraymat where the metal element is held in material of a similar rigidity modulus.
23. Spraymat may be used on anti-icing, de-icing and combined anti-icing/de-icing systems. Other systems are not so flexible and tend to be either anti-icing or de-icing, often also with a fixed cycle frequency.
24. Its modulus of elasticity is no greater than that of the surrounding insulating layers, thus reducing interlaminar stresses during bending. Thermal expansivity is also similar therefore minimising thermal stresses, leading to a long fatigue life. The rubber in some systems tends to be hardened by thermal cycling.
25. It can be supplied as a "pre-preg" (pre-impregnated), prefabricated mat for application at the customers premises. This is possible with some boot systems, but generally not advisable.
26. By using an electrical system there is a high degree of control flexibility in cycle timing and power output level. The power level and cycle frequency in some versions may be varied according to conditions, which is not so easy with fluid, pneumatic and hot gas systems.

27. Lucas Aerospace manufacture complete systems with ancillary equipment including thermal controllers, cyclic power switches, icing detection instruments and system health monitoring instrumentation. Many other system manufacturers rely on 'bought-out' ancillary equipment not specifically designed to be compatible with their de-icing equipment.
28. The manufacturer provides an advisory design service and take the product from concept to production. Few other manufacturers offer a complete service.
29. Lucas Aerospace are able to test their designs using their own icing wing tunnel (Ref.3). They also possess various other test facilities for electrical, mechanical and fatigue testing at the Luton factory site. Thus certification trials may be effected as an integral part of a design project.
30. The system is tailored to aerospace use and manufactured to aerospace standards, using materials compatible with modern aircraft composite structures. Some other systems require a considerable degree of adaptation or interface materials and equipment.
31. High temperature mats are available for use in supersonic applications such as on Concorde where the de-icing system has to undergo long periods of high surface temperature without fatigue damage.

Disadvantages

1. Large spraymat systems do require a substantial electrical power supply. However, any similar electrothermal systems require electrical power in similar or greater quantities. Electro-impulse systems are not so encumbered, requiring considerably less electrical power.
2. Spraymat cannot easily be replaced in the field or supplied as an "add-on" kit (except "pre-preg" systems), the substrate component should be returned to the factory for spraymat removal and refitting. However, apart from small ancillary component replacement, this is the case for most competing systems.
3. The heat energy dissipated from the surface of an engine air intake duct internal panel is ingested by the engine causing a reduction in engine power output, in addition to the engine power required to produce the electrical power to run the de-icing system in the first place. An electro-impulse system does not emit significant quantities of heat, gas, liquid or solid (except the shedding ice).

Electro-Impulsive and electro-expulsive systems present a potential future competitor to spraymat in some applications, but due to the nature of these systems, they are totally unsuitable in some areas where spraymat excels. Thus, although maintaining

performance in other areas, it would probably be good practice to concentrate on, and expand the areas which are likely to remain free from competitors. Thus it is imperative to maintain the popularity of spraymat amongst all competition, and to ensure its continual development to maintain its present competitive edge. To achieve this requires continual research and development to improve the product and reduce all associated design and production costs. Hence this research programme has been established to improve spraymat design methods in their technical ability and efficiency of application.

The potential marketing advantages of introducing the proposed improvements to the spraymat design method ("Technical Justification") are listed below in justifying the research programme.

Marketing-Advantages of the New Design Method

1. The ability to run a whole range of test cases to explore the complete flight envelope.
2. Improved accuracy of calculations, (catch limit, catch efficiency and power requirement), and cycle timing estimations.
3. Reduced design labour time, or better use of the same time.
4. Improved consistency between cases.
5. Improved consistency between projects.
6. Better ability to use results from previous projects to reduce design work on present projects, ie. better format compatibility.
7. Reduced learning time for new engineers to the design method.
8. Reduced icing wind tunnel testing time.
9. Better use of the icing wind tunnel testing time.
10. More precise and consistent logging of the input and output data.
11. More confidence in the results due to the use of actual substrate surface contours rather than those of a 'similar' aerofoil.
12. The ability to re-run cases in exactly the same manner with identical results, ie. without personal interpretation during the calculation phase.
13. The ability to accurately study temperature transient distribution at several depths under the surface of a multi-layered material with incorporated spraymat elements.
14. Faster response time in producing the proposal, to answer a customer specification.

15. The ability to react to changes in the customers specification as the customer develops and refines his needs.
16. The ability to produce more impressive output data for presentation to the customer, such as two-dimensional presentations of the flow representation, droplet trajectories, ice accretion and catch efficiency distribution (Figs.P103-P202).
17. Documentation more easily understood by recently trained engineers (SI units, etc.).
18. A method that has not been developed to such an extent that the original theory is no longer visible to an engineer beginning to use the method.
19. Better continuity of the design method as it develops, ie. not as likely to be extrapolated beyond its limits of applicability (and accuracy).
20. The authenticity of the results is more easily assessed as the approach is more clearly presented at every stage from input to output with ample supportive reporting of a non-ambiguous nature.

3 TECHNICAL JUSTIFICATION

Ice has never ceased to interest many scientists, being unique in some of its physical properties, rather unpredictable in nature, and possessing the ability to adhere to substrates by a bond mechanism not yet specifically determined. Various theories have been postulated. One theory involves a "keying" of the ice into the relief of the substrate surface, ie. producing a mechanical bond. This resulted in investigation using finely polished surfaces employing very specific manufacturing techniques, detailed in some cases down to the type of protective gloves worn whilst cleaning the sample in solvents. Another theory looks at the presence of a thin "liquid-like" layer between the ice and substrate, even at the lowest achievable temperatures, the adhesion force being the pressure required to replace this sealing layer with air, or some other atmosphere.

In the industrial and commercial world, ice itself is of little interest except as a cooling agent, of greater concern are its effects on the substrates to which it adheres, where it is almost invariably unwanted. Ice formation on static structures is of interest to manufacturers and operators of buildings, bridges, aeriels, hanging power transmission cables, etc.. It is of greater concern when accreted on moving vehicles, mainly due to its weight, aerodynamic performance degradation, electromagnetic insulation, and mechanical obstruction. On water vehicles (surface and submersible), the additional weight of an ice accretion is of primary importance, which may amount to several hundreds of tons over a relatively short period (hours-days) on a large vessel. For ground based surface vehicles the obstruction of vents and jamming of hatches and other moving mechanical equipment tends in most cases to be of more detrimental effect than the weight of the ice. Ice adhered to the surface on which the vehicle travels is also of interest in both positive, and negative contributions to vehicle movement. However, aircraft are affected in all four aspects (weight, aerodynamic performance degradation, electromagnetic insulation and obstruction). The combination of weight and deteriorated aerodynamics of a thin (say 2 mm) film of ice over significant areas (leading edges of the wing, tailplane and fin, plus most forward facing surfaces of the fuselage), of a fixed-wing airframe may amount to a critical value. The aircraft may be unable to maintain level flight, even with full power applied, in not many minutes. Electromagnetic insulation is of concern to transmission and reception antennae, and obstruction, to engine air intakes, and other equipment requiring ventilation holes in the outer skin of the aircraft, plus canopies and scanners.

On rotating substrates such as helicopter rotor blades, the centrifugal force on the ice accretion aids its removal from de-iced and anti-iced surfaces, and forms virtually the entire removal force in the case of self-shedding on non-de-iced surfaces. Other forces are the aerodynamic lift of the ice accretion, and gyroscopic forces produced during changes of bank angle or pitch of the plane of the rotor. However, the sum of these forces, plus a centrifugal force tendency to reduce pitch (angle of attack) of ice whose centre of gravity does not lie in the plane of rotation of the pitch change axis

of the blade, is negligible in comparison to the radial component of centrifugal force. It is such that the radial centrifugal force only is normally used for de-icing system design and testing. Also because this force is directly proportional to the ice rotational velocity and weight, and remains unaffected by pitch angle or flow velocity changes. Thus it can be appreciated why helicopter rotor blade icing is of serious concern (Bib.- 3.3). Rotorcraft (especially military vehicles) will soon need to be operational in all weather conditions (described earlier). Hence a great deal of research into helicopter rotor icing is presently taking place (Bib.- 2.6). On this substrate, ice accretion weight can become critical in severe conditions in less than one minute if no action is taken to remove it. The aerodynamic performance degradation (reduced lift and increased drag) is of similar importance, the oscillating angle of attack causing large accretions due to the changing stagnation point location on the aerofoil, (Fig.8). But, another phenomenon, often of more detrimental effect both in magnitude and rate of degradation, is that caused by the out-of-balance forces due to the unpredictable asymmetric shedding of ice from the rotor blades. Consider an ice accretion with a thickness of 20 mm and an area of 100 cm² on combined pitch and camber faces of a helicopter rotor blade, situated with its centre of gravity at a spanwise radius of 5.5 m (70% span - Chinook), rotating at 225 rpm. The accretion has a mass of typically 0.36 kg (depending on ice air content and water purity) and experiences an acceleration due to rotation of 311 g. Thus, should this ice shed without simultaneous shedding of its counterpart on an opposing blade, an out-of-balance force of approximately 1 kN is set up. The vibration caused by this size of out-of-balance force could rapidly destroy the aircraft if allowed to continue, assuming no further beneficial shedding is initiated by the vibration.

Considering a typical aircraft propeller blade, e.g. S340. A 0.36 kg ice accretion at 70% span (1.173 m) and 1300 rpm (cruise) experiences 2216 g acceleration due to rotation, producing a 7.8 kN out-of-balance force. With similar operating requirements to those of the helicopter, but with greater emphasis in the civilian sector and in increased numbers, it can now be appreciated why propeller icing and de-icing is also of growing and serious interest, (Bib.-2.4, 3.1, 4.1.4). Thus it can be appreciated why the subjects of ice accretion on, and methods for its removal from, the leading edges of fixed wing aircraft mainplanes, tailplanes and fins, helicopter rotor blades and aircraft propellers are either relatively well covered, or presently being researched. Considering ice accreted to the engine air intake, little recent research has progressed to the extent that qualitative and quantitative information in the context required for spraymat design purposes, is available. This is mainly due to the previous relatively plentiful supply of compressor bleed air as described earlier.

The functions of an aircraft air intake duct are to supply the engine compressor with the correct air mass flow rate for all engine performance levels in all flight conditions, and to change the velocity of the incoming air flow to one which is acceptable to the compressor. Obviously this is not always absolutely possible and the

result is a compromise design focused on producing peak efficiency in the aircraft cruise condition. The cross-sectional shape of the intake duct leading edge lip is designed also on a compromise basis. It has to entrain the airflow as smoothly as possible into the intake for all values of aircraft incidence, sideslip, airspeed, and climb and descent rate within the flight envelope. It must also simultaneously observe the previously mentioned criterion of providing the correct air mass flow rate. Thus the effect of ice accretion on the intake lip is two fold. The shape and surface smoothness of the lip are degraded, resulting in changes to the boundary layers and a translation of the transition point. Secondly, the intake duct internal area is reduced thus affecting the direct air mass flow capacity. Both these factors combine to reduce the overall performance of the duct, which change can become quite considerable if an appreciable ice accretion size is allowed to accumulate.

As can be appreciated from the material in the commercial justification, each new spraymat application requires design work to determine the size, shape and element network pattern of the spraymat system to be applied to the object in question, be it an intake lip, tailplane leading edge, antenna body, or other. This design work, although somewhat unique in each case, exhibits a few areas general to all applications. It is necessary to calculate the area of ice catch, ie. the surface area of the object over which supercooled water droplets will impinge in various icing conditions. This is basically in the form of catch limits as it is the downstream limiting range of icing that is of interest. The ice forms from the stagnation point aft to the catch limit. Secondly, it is necessary to know the rate of ice accumulation in anti-icing cases in order to predict the heat output rate from the spraymat necessary to melt the ice, and in some cases, go on to evaporate the meltwater. In de-icing cases it is necessary to know the heat output required to raise the bond interface temperature to the extent that adhesion is destroyed. Thus for de-icing, the icing rate is extrapolated to determine the accretion size accumulated between de-icing ice removal cycles. The ice accretion is never uniform in thickness, and thus what is actually required is the heat output distribution. This is usually a non-uniformly tapered output level from a maximum around stagnation, to a minimum near the catch limit (Fig.9).

Detailed research into a somewhat unpredictable and not fully understood subject should always return to the last fully understood set of principles. For ice accretion on intake lips, this means obtaining a knowledge of how ice adheres to a surface. However, this has been the aim of many experimental and theoretical investigations (Bib.- 1.4) with no precise conclusive results, and thus is not a feasible task to attempt during this research. Until recently, the physical and mechanical properties of ice in its adhesion to specific substrates, and ice accretion on modern intake lips have only been studied separately, and by different experimenters. Hence, this research programme studied ice properties and adhesion using current substrates, followed by research on methods to carry out the previously described spraymat design work.

As mentioned earlier, the research programme should begin with a study of the material already available. This was effected by compilation of a bibliography (Appendix C) covering all relevant areas of interest. The ice adhesion study (Ice Adhesion Database) is therefore an extension of the knowledge located in the bibliography with respect to this subject, and the ice adhesion work effected in the research programme is discussed in detail in the next chapter. From a knowledge of the characteristics of ice adhesion related to the intake lip, it is intended in future research projects to further improve the new lip de-icer design method resulting from this research by incorporating ice physical adhesion characteristics into the design software (described later). In order to appreciate the changes brought about by the research to the methods applied to de-icer design-for-application, and the need for those changes, it is therefore first necessary to have some knowledge of present methods and an understanding of the reasoning behind their evolution.

3.1 Existing De-Icer Design Method

The process is initiated when a customer presents a specification to Lucas Aerospace for the initial (preliminary) design of a spraymat de-icing/anti-icing system to fit their requirements. This specification should include drawings of the component about the area to be de-iced, and some form of flight conditions envelope in which it will serve. Also useful in de-icing cases is the tolerable ice accretion size allowed to accrete before it must be removed. This tends to vary considerably from case to case. An engine intake lip may be required to be constantly free of ice (anti-iced), This may be the case for a particularly small intake which will tolerate no blockage, and leads to a relatively small, high speed compressor (such as for a cruise missile), which is not able to cope with the ingestion of even a very small piece of ice shed from the duct. In comparison, the leading edge of a pylon carrying a pod or engine may not be sufficiently influenced by the presence of large ice accretions to warrant the fitting of de-icing equipment. In this case, the limiting allowable ice accretion size may be determined by the effect a shed accretion might have upon impact with structure downstream of the pylon, such as the tailplane, a flap system, or a rear-fuselage mounted engine.

Once these criteria are determined, the area of coverage of the heater mat, its power level distribution, and for cyclic units, the cycle timing, are calculated (Section 6.8).

3.2 Areas for Improvement

Observing the existing design method (Section 6.8), it is predictable that the system could benefit from some modernisation. One specific area of interest is in the initial part where, at present, the actual aerofoil is simulated by an equivalent aerofoil taken from the following rather limited selection.

Equivalent Aerofoil Sections

NACA 0006 - 64
65A004
65₁208

65₁212

65₂015

JOUKOWSKI 15 % t/c, cambered and uncambered

ELIPSOID, finess ratio 5:1 (application to spinners
10:1 and nose cones)

Modern aerofoils tend to exhibit a less circular leading edge than older versions. Comparing the 'old' aerofoils of (Figs.10(a)-10(e)) with the modern ARA-D (approximately) sections of (Figs.10(f)-10(h)), (Sup.6), and using rather highly cambered versions, it can be seen that the ARA-D aerofoils aim to reach maximum thickness much nearer the leading edge and maintain thickness for approximately one third to one half of a chord length. This is to better distribute the loading, both for improved structural loading and to de-sensitise the centre of lift positioning to allow more centre of gravity movement. Thus it would clearly be advantageous to employ a modern equivalent aerofoil, or preferably the actual aerofoil as there is not a great deal of catch data available for modern aerofoils, and certainly not sufficient to compile a full set of charts to replace the existing ones.

The current calculation sheet approach (Appendix B, Section 18.1.1) could benefit from computerisation, enabling more design cases to be analysed during the same time span, and more detail to be applied to each case. By analysing more cases, the probability of catering for the worst case is made more certain, and the ability to tailor the system more closely to fit current conditions during operation is a definite possibility. Thus if many more cases than the three or four presently attempted are analysed (say 30-50), then a good envelope of de-icing requirements variation with parameters relating to icing conditions may be constructed. From this evidence, it may be possible to design a system where the element power level and cycle timing are varied continuously, dependent on icing conditions parameters to a finer extent than currently exists, where in most cases, they are fixed. It may also become possible as the design system is developed, to design the heater mat element network in such a manner as to be able to vary the heated area coverage according to ice catch limit, which is in turn dependent upon icing conditions. A further advantage which would be introduced by computerisation is the reduction of calculation errors. These errors are two-fold. Firstly there is the obvious mathematical error introduced at random by the engineer responsible. Second, there is a cumulative error introduced by rounding off intermediate results in

the calculations, for re-introduction at a later stage. Both of these errors would be eliminated if all of the calculations were carried out in a single computer program execution, (assuming that the input values are entered correctly and accurately).

Probably the second largest area for improvement (after employment of the actual aerofoil profile is effected) offered by computerisation, is the ability to include most of the smaller secondary effects to be considered in calculation of the three main subsets, (catch limit, rate of ice accretion, and heat requirement). Some lesser variables have been estimated or ignored in the existing calculation method, where fixed values of parameters which only vary slightly with such other parameters as temperature and altitude, are assumed and combined into one constant to reduce the formulae and reduce the number of calculations necessary.

3.3 Engine Air Intake Duct Leading Edge Lip

More specifically, for engine air intake lips, the existing design method takes no account of the variation in flow characteristics between the internal flow inside the duct, and the external flow outside. An aerofoil representing the intake lip presents one face to the internal flow and the other to the external flow. The airflow velocities experienced in the internal flow are a function of the air mass flow rate required by the engine, which itself is a function of the engine performance characteristics, determined by the thrust required at the time. The internal and external flow systems are separated by the streamline impinging at stagnation. Thus, for an intake lip simulated by an aerofoil in a freestream flow, using the existing design method, the ice catch limit calculated on the aerofoil face representing the intake duct internal surface may be in error. Although it may be argued that at the intake lip (aerofoil leading edge), the internal flow effects will not be of sufficient magnitude to affect ice catch, the intake lip highlight is not necessarily the stagnation point. Particularly in subsonic flow, this highlight may be considerably upstream or downstream of stagnation. In cruise condition the effective incidence of the aerofoil representing the intake lip will be very small and thus stagnation will occur close to the lip highlight. For cruise speeds common to aircraft such as previously mentioned, stagnation will actually be slightly inboard of the highlight as a function of the intake in cruise is to slow down the flow to a velocity acceptable to the engine, (Fig.11(a)). In climb configuration (Fig.11(b)), the airflow velocity required inside the duct to supply the compressor with the required mass flow rate at an acceptable velocity is greater than the flight speed, and thus stagnation occurs outboard of the lip highlight. For an equivalent aerofoil, this is analogous to a negative value of incidence. Finally, in take-off configuration, the airflow velocity inside the duct is considerably greater than ambient (aircraft speed, which may be zero), thereby pushing stagnation outboard (Fig.11(c)). Hence it will be appreciated that it is difficult to define the dividing point between aerofoil faces experiencing the internal and external flow characteristics at first

appearance, should a design method similar to the existing one but involving the use of two sets of calculations with two different equivalent aerofoils be envisaged. It is difficult to imagine an equivalent aerofoil at 0° and 4° incidence which in free flow could achieve stagnation points realistic to the engine intake lip in this configuration. It will also be appreciated that each intake lip would require a different pair of equivalent aerofoils for each radial station around the lip and for several values of incidence. Those aerofoils would not be similar to any for which catch data is presently available.

Therefore it is obvious that any improvement to the design method applied to engine intake lips must abandon the existing catch data and use the actual aerofoil in some form of CFD (computational fluid dynamic) approach to generate unique catch data. The field of CFD is still new to most industries, Lucas Aerospace (Luton) being no exception, and the development of a completely new code from initial flow chart to implementation is beyond the scope of this research programme. However, there are several CFD codes already in existence, one or more of which may be available to Lucas Aerospace. In addition to computing the flow characteristics around the intake lip aerofoil, the program must continue to calculate ice catch limits and the ice accretion rate. Therefore a considerable amount of thermodynamic work is also required within the coding regarding freezing, melting, evaporation, convective cooling, sublimation, etc.. Such a program is already in existence for icing analysis of helicopter rotor blades (Ref.6). The coding of this program is available to Lucas Aerospace at zero cost.

Thus a major part of this research programme involves modifying this program for use in intake lip icing prediction. The approach is limited to subsonic, two-dimensional, inviscid, potential flow (with boundary layer). Although NASA and Boeing possess a full three-dimensional, viscous flow program for intake icing prediction, that program is very difficult and costly to operate, and runs on a Cray super-computer. One major problem with three-dimensional panel methods applied to surfaces of double curvature in CFD is that gaps exist in the overall network, through which the theoretical flow tends to escape. Apart from being commercially unavailable, it would not be possible to use the NASA/Boeing three-dimensional program on the computing facilities at Lucas Aerospace.

A relatively simple approach is required, which is easy to employ by a design engineer of no CFD and little general aerodynamic knowledge, which does not require uneconomic amounts of time and computing power, but is capable of yielding results sufficiently accurate for engineering applications. The RAE program thus represents an good opportunity to modernise the spraymat design method, and offers many possibilities for improvement.

3.4 Concluding Remarks

It remains to summarise this technical justification by stating the research which it is considered technically justified to carry out. It has therefore been decided to effect a survey of the available literature on all related icing subjects, for compilation of a bibliography which will not only be of use to the author during the research programme, but to the sponsoring organisation continuously, by regular updating. Thence an ice adhesion database should be compiled. This is to be followed by the design and manufacture of a test rig to investigate ice adhesion properties ("Ice Adhesion Study" chapter) with respect to modern substrate materials and surfaces applicable to propeller blades, (as originally intended before the change of emphasis to investigate computer ice prediction on aircraft engine air intake ducts at the end of the second year). The results of this adhesion testing should prove useful in subsequent research programmes when considering the intake de-icing design method, by incorporating various ice physics considerations into the software. Some of the adhesion data available in the literature ("Ice Adhesion Survey" - 'database') will be correlated with the findings using the ice adhesion test rig.

Following this, is a preliminary one-dimensional look at the thermodynamics of ice adhered to a heated composite propeller blade in flight, in preparation for two-dimensional computational ice accretion. This will prove useful in gaining experience and knowledge of the parameters involved and their interrelationship. At this stage the change in emphasis from propellers to engine air intakes, detailed in the introduction, took place. Finally is the modification of the RAE icing prediction computer program for application to engine air intakes. The use of this particular program is further justified by the fact that in its present state it is already useful to the sponsoring company in aiding helicopter rotor blade de-icing system design. It requires an engineer to gain knowledge of its contents, uses and limitations. This knowledge would be gained whilst modifying a copy of the coding in the previously mentioned manner. Thus risk of not being able to effect a suitable modification for use on air intakes is offset by the gains in helicopter de-icer design utilisation. The program is not restricted to helicopter rotor blades, but is capable in its present state of modelling virtually any 'free-flying', two-dimensional, subsonic aerofoil. The software development work within the programme is restricted to subsonic, two-dimensional, potential flow around relatively simple intake lips to fit within the time and computing resources available. Modifications and additions to include three-dimensional, viscous, supersonic flow about a three-dimensional lip and thence flow further downstream inside the duct are all subjects for investigation after completion of this research programme, as is also the inclusion of two other RAE programs to calculate heating power intensity distribution and element chordwise pattern format ("Continued Research").

4 ICE ADHESION STUDY

As briefly introduced in the technical justification, the ice adhesion study consists of four major parts;

Ice adhesion test rig design
Preliminary ice freezing tests
Ice adhesion tests
Ice adhesion survey

This list is in approximate chronological order. The preliminary ice freezing tests were carried out during manufacture of the test rig, upon completion of which the ice adhesion tests were conducted. The ice adhesion survey was a continuous activity throughout the adhesion study but searched material, in hard copy form, only became available in reasonable quantities when well into the adhesion testing. The experimental work was reaching termination (defined by the end of availability of the cold chamber for the tests), as the one-dimensional thermodynamic analysis was initiated.

4.1 Test Rig Design

Introduction (Sup.1 - 3)

As briefly described in the main introduction, the research programme includes investigation into ice adhesion on modern aerospace substrates. The ice shedding force exerted upon ice accreted on a rotating propeller blade is mainly a shear force. All other components, as described in the "Technical Justification", are negligible in comparison. Consider the ice accreted on the air intake duct surface around the lip. It will be appreciated that around stagnation there is a positive pressure exerted by the airflow on the ice in a direction so as to aid adhesion to the duct. At the stagnation point, this is equivalent to the stagnation pressure, and then decreases as a component away from the stagnation point. As the pressure 'head-on' component decreases, the tangential component increases such that most of the ice accreted on the surface will experience some degree of air pressure exerting a shear force on the adhesion bond to the substrate. In fact, in most cases, the resultant force will be almost completely shear. However, away from stagnation, the airflow over the ice accretion will cause a drop in pressure resulting in a 'lift' force acting so as to oppose the adhesion force. This force will be small compared with the shear force. Thus, adhesion in shear should dominate the experimental study, together with some tensile work.

In the main introduction, the need for a prior search into the available literature was detailed. For each research oriented subsection there is a similar need which involves extracting the relevant parts from the bibliography and investigating them to a more detailed extent. In the case of the test rig design study all reports detailing experimental work on ice adhesion are required, particularly those including some description of the test rig employed and its

associated equipment and instrumentation. Equally important to the actual rig description are the experimental notes and conclusions detailing advantages and disadvantages experienced using the test rig. Also important are the testing techniques adopted, reasons behind the test rig design choices, rig development, suggested improvements and authors conclusions regarding success rate.

Some previous experimenters included a diagram of the test rig, which forms a useful aid to this project. Sixteen reports with rig diagrams were located in the bibliography plus many other reports describing the test equipment to some level. However, from the reports including a description but no diagram, and from those carrying a sufficiently detailed text, it soon became apparent that the rigs were either actual ones from, or very similar to, the rigs for which a diagram had already been retrieved. Those possessing less detail did not go beyond the conceptual description which in all cases was already catered for by the designs in the acquired diagrams.

The designs were scrutinised and lists compiled of their various qualities with respect to assessed design requirements. To these lists, information from the bibliography reports from experimenter's notes as mentioned earlier, was added to give an overall analysis. The approach adopted was to study all the available information and compile lists of mandatory and desirable requirements (lists 1 and 2, Appendix A), for a new design specific to this research programme. All sixteen test rig designs taken from the bibliography were then assessed from observation of the respective diagrams (Figs.R1-R13(c)) and descriptions in relation to these two lists, with regard to their suitability for manufacture and employment in this programme.

By taking this approach to design optimisation, it could be assumed that most of the available support offered from the bibliography was used to its best advantage and little material relevant in this context was omitted. Brief descriptions of the test rig designs considered, (Figs.R1-R13(c)) appear in (list 3), and their assessment with respect to the design requirements (list 1), is situated in (list 4). The assessment phase was concluded with design criteria (list 5) for consultation in addition to (list 1) at the onset of design of the specific rig for the research programme. This latter list is terminated with a description of the development of the design finally derived.

4.1.1 Description of Adopted Design (Sup.1 - 8)

The test piece takes the form of a cylinder or bullet 38 mm in diameter and 25 mm in length (Fig.30). The test substrate may be in the form of such a cylinder machined from the particular test material, or a coating or plating applied to a cylinder curved surface, or a sheet or strip fastened to the surface. Through the centre of the cylinder exists a threaded hole to take a bolt for use during setting up of the apparatus which may be replaced by a heater element for testing. At the lower flat surface of the cylinder the hole is opened out to 25 mm diameter for location on a guide piece

tool for accurately aligning the cylinder within the test rig (Fig.R17). The cylinder is fitted accurately in position, using this guide tool, on the horizontal flat surface of the breech just covering the central 36 mm diameter hole through the breech so that there is a minimal contact area between the bottom of the cylinder and the upper flat surface of the breech.

A barrel with a heavy gauge screw thread is screwed onto the breech so that the upper flat surface of the barrel is level with the upper flat surface of the substrate. The barrel may be locked in this position by means of a set screw through its side wall onto the breech. By use of several breech-barrel sets, the barrel diameter and therefore ice thickness may be varied.

The breech has a heavy flange to locate and fasten it to the breech block which contains a small settling chamber under the hole through the breech, and is sealed to the breech. High-pressure gas (nitrogen) is supplied to the settling chamber via a hole in the breech block, and the gas temperature and pressure in the breech block monitored by means of a thermocouple and pressure transducer through holes in the breech block.

The assembled apparatus is secured to a base of one inch thick ply using three angle brackets and mounted on height adjustable legs in a chest type freezer. Should the cylinder move upward during testing in a manner not easily detectable ie. creep before total release, this will be detected by the potentiometer device fitted to the breech. This device is designed to rotate clear of ejecting bullets.

Envisaged Test Procedure (Sup.1 - 9)

Assuming the ice specimen is to be formed by bulk freezing of water, then the bullet, breech and barrel are assembled using the guide tool and applying a silicone sealing compound to the lower surface of the cylinder to prevent water ingestion into the breech. Silicone grease is also applied to all surfaces of the guide tool and associated bolt and washer to aid removal after freezing.

The water, which may be distilled or otherwise treated, is applied to the gap between the bullet and the barrel at the required temperature and allowed to freeze. If some method has been used to form a certain thickness of ice on the surface of the bullet of a nature more realistic to the air intake application, then the remaining gap between the outer curved surface of this ice cylinder and the inner curved surface of the barrel is filled with bulk frozen water as before to lock the ice to the barrel thread.

After freezing, the guide tool is removed by holding the bullet steady using an allen key in the screw in the top of the bullet to prevent any rotational force from being transmitted to the bond test surface, and the guide bolt and guide are removed.

Several bullet-ice-breech specimens may be formed and stored in the freezer before testing with gas pressure. It should be remembered at this stage that ice is known to "age" (Bib.- 1.1, 1.2), and the associated phenomena (sublimation and re-crystallisation) should be borne in mind when periodically observing stored ice specimens.

One of the breech-bullet-ice specimens is fitted to the breech block in the freezer using the six nuts, (the gas pressure supply and necessary instrumentation having been fitted and remaining in place), and the movement detector fitted.

Once the correct temperature is achieved, the gas pressure is increased until debonding is achieved (Fig.R18). This occurrence is easily noted by its characteristic associated sound, audible from outside the cold chamber. Alternatively a required gas pressure is set and then the interface temperature raised using a heater element replacing the bullet screw, until debonding is achieved. Some safety protection shielding is required to restrain excessive travel of the bullet after leaving the ice barrel.

If the interface bond is broken entirely adhesionaly (Fig.12), then the bond strength is derived from the required gas pressure. If some form of totally cohesional debonding takes place (Fig.13), then the cohesional strength may be derived from a knowledge of the debond surface area and orientation. Should the most likely case occur when a combination of debonding in adhesion and cohesion takes place (Fig.14) then from a knowledge of the cohesional strength (acquired in cases of total cohesional debonding), the proportional areas of adhesive and cohesive bonding, and the release pressure in the mixed condition, the bond strength of the adhesional area may be derived (Appendix A).

The bond interface temperature is measured using thermocouples, through holes in the bullet, or set in the ice, or both.

4.1.2 Test Rig Stress Analysis

The detailed stress report for the test rig appears in (Sup.2). A factor of safety of five has been applied to the ultimate stresses for the material in tension, shear and bending to give the allowable stresses. Thus any reserve factor calculated represents an increase in stress available whilst maintaining the above safety factor.

The nitrogen pressure of 69 bar is greater than the maximum required for testing and has been applied to the critical cases for stressing purposes.

The major components (breech block, breech and barrel) are manufactured from aluminium alloy for corrosion and machining purposes whilst maintaining an adequate heat sink. The bullet will be available in several materials and aluminium alloy which has the lowest strength (amongst all foreseeable metal bullets), is the example used for the stress analysis.

The stress analysis shows the rig to be of adequate strength for testing with a safety factor of five. Fatigue stress analysis is shown to be unnecessary due to the low number of loading cycles involved in the tests.

4.1.3 Ice Freezing Tests (Sup.3)

Objectives

The overall main objectives of these tests were to gain experience of the techniques required to produce particular types of ice samples, and to locate any flaws and indicate possible design improvements to the test rig before its completed manufacture and assembly. By defining the techniques and refining the design, the actual test time required in the cold chamber facility is minimised. This is reflected in reduced costs and availability of the facility for higher quality testing, making more use of its capabilities. The effectiveness of the adhesion tests is dependent to a considerable extent on the level of preparation applied, from which descriptions of the techniques necessary to effect particular types of ice sample are compiled.

Apparatus

Two test rigs were considered. The rig of main interest (Rig 1) was that specifically designed for use in this research programme (described in a previous section) where the ice mould is a permanent part of the rig. The active part of another rig (Rig 2, Fig.R1), also featured in these tests by request of its manufacturer. This was used for comparative purposes and to acquire design improvement data. The tests were carried out using a chest type domestic freezer. Various cleaning fluids and degreasing agents were used to prepare the equipment, and distilled water for ice forming.

Water Preparation

The relative air content of the water used was assessed from the relative air bubble content of the ice formed. It was found that boiling the water reduces the air content of the subsequently formed ice, and likewise allowing the water to settle in the vessel from whence it is poured into the test rig, or even, in the test rig itself in cases where single operation filling was adopted (explained later). However, commercial distilled water was found to contain less air than the boiled water, and allowing this water to settle in its new vessel further reduced ice air content. A settling time of one week was no more effective than one day. Thus it was decided to use distilled water in the adhesion tests which had been allowed at least one day to settle.

Adhesion surface preparation

For the programme rig (Rig 1), this includes the bullet outer curved surface, the barrel screw thread, the breech screw thread and the breech upper, flat, horizontal surface. For the other rig (Rig 2), only the two flat substrate surfaces require this attention. The first metal substrate test employed no cleaning preparation and resulted in zero ice adhesion magnifying the requirement for some degree of surface preparation. A propeller blade or engine air intake lip in flight through a cloud of supercooled, and therefore pure, water droplets is effectively being vapour blasted, and thus will be very clean. Hence, to best simulate this condition using available resources, and also effect a state of cleanliness of a standard level for test repeatability, the adhesion test surfaces should be cleaned to the highest degree possible. For Rig 1, as the ice is required to adhere to the rig at least as well as to the substrate, to avoid debonding in the former area, then all relevant ice adhesion surfaces should be cleaned to the same level.

Various sample approaches to the surface cleaning were made. Simple rinsing with distilled water is totally ineffective against any oil based impurity. Washing with water and commercial domestic detergent, followed by rinsing with distilled water, improves this situation, but some form of oil solvent is required. Methylated spirit alone proved unsuccessful. Degreasing in trichloroethylene, followed by washing in boiling water and detergent, then rinsing with distilled water was the approach found most effective.

The quality of the cleaning was judged by the ability with which drops of distilled water, dropped onto the surface, wet that surface. If the drops remained in tight globules of small area and highly convexed meniscus, as in (Fig.35), then the wetting was poor and an oil based contaminant was probably still present to some degree. If the drops spread out to a large area thin layer with a flat meniscus only convexed at the extreme perimeter, then the wetting was good.

Test Rig Assembly and Freezing Phenomena

Rig 1

Silicon grease was used to seal and lubricate the barrel/breech thread, taking care to apply grease to the breech only, such that the area of thread in the barrel required for ice adhesion remained clean. The set screw thread was similarly lubricated and sealed. It was discovered that by assembling the bullet in place on the breech, using the guide tool before fitting the barrel to the breech, enabled clear observation of the bullet/breech seal. This latter seal was also effected using a small amount of silicon grease applied to the lower flat surface of the bullet. Care was taken to ensure this seal formed edges perpendicular to the bullet and breech flat surfaces (Fig.15) to avoid sharp, stress raising, cracks at the edges of the ice (Fig.15). The same grease was applied to all surfaces on the guide tool to contact the breech, to enable its removal after freezing.

Freezing

Before detailing the observations related to the production of the ice sample from the water, it is beneficial at this stage to define a few terms frequently used later in this and other sections.

Freezing Front

The act of phase change from liquid to solid for water is mainly dependent on ambient temperature, pressure and water purity. Assuming the latter two are fixed in this situation, then temperature is the only controlling variable. Consider the assembled rig, full of water in the gap between the bullet and the barrel, it will be appreciated that in cases where the rig temperature is significantly lower than that of the water at a time just after the water is poured into the rig (say -20 and 0°C. respectively), the water temperature will fall to that of the rig (and cold chamber). The temperature of the rig will rise slightly for a short time due to the presence of the water, but this rise will be negligible for the temperatures considered. The ability of the rig to lower the temperature, and the rate at which the temperature falls, of the water, is dependent on the thermal conductivity of the system to transport that heat energy away from the water. Hence it can be seen that the water in contact with the rig will be first to freeze as its temperature falls through 0°C. This will be followed by adjacent layers of water, and so on. The advancing 'front' of liquid turning to solid is known as the 'freezing front'.

Bubble free zone (BFZ)

As explained earlier, the water contains a certain amount of air diffused within the liquid. As the temperature falls and the phase changes to solid, this air conglomerates into bubbles. The size of the bubbles is dependent mainly on the amount of trapped air (assuming ambient pressure to be fixed), and the freezing rate (speed of advance of the freezing front). A slowly advancing freezing front will push the bubbles forward as it travels, some of which will combine to form larger bubbles. Thus, in the initial stages, as the freezing front begins its journey from the substrate surface, it will leave a certain thickness of ice (dependent on freezing rate) which is bubble free, ie. the 'bubble free zone' (BFZ).

Bubble/specimen aspect ratio

This is a ratio developed for use in this study formed from the median bubble diameter present in an ice specimen, divided by a characteristic dimension of the ice specimen, e.g. for Rig 1 the bullet height, for Rig 2 the cube side length.

Free surface

This is another term developed for use in this study and refers to the surface of the water or ice which is in contact with the atmosphere, ie. not in contact with any part of the rig, except at its perimeter.

Air Bubble Formations

No two ice samples will ever have identical internal structural patterns, either in bubble or crystallographic formations. However, the general type of bubble formation may be controlled somewhat by variation of temperature and heat conductivity. If the rig is filled with water in one stage, the bubbles may travel throughout the whole ice specimen, driven by relative density and the advancing freezing front. In this case, long thin horizontal bubbles from the BFZ's at the bullet and barrel, and vertical at the breech surfaces, mark the locus of the freezing fronts and conglomerate at the central area where they meet (Fig.16). The free surface tends to freeze in a fine layer due to small ice crystals in the freezing front, but not yet attached to the bulk solid ice, rising due to their relative density with respect to the surrounding liquid water, to form an ice 'skin' at the free surface. This 'skin' tends to trap the bubbles within the ice and is forced upwards into a dome as the bubbles conglomerate into larger bubbles of much greater buoyancy and increasing volume, attempting to escape to atmosphere (Fig.17). Thus, for a slow freezing rate, these phenomena are less pronounced as time is allowed for a large portion of the air to escape (Fig.18), and vice versa (Fig.19).

The location at which the freezing fronts meet is thus dependent on the relative thermal conductivity of the bullet, barrel and breech. For a metal bullet, this meeting point, and therefore free surface anomaly, is roughly centrally placed as the thermal conductivities are well matched around the three surfaces of the water (Figs.16,18 and 20). For a non-metallic bullet, or bullet with a heat insulating coating, the freezing front is relatively slow to advance and thus the freezing front meeting area is located closer to the bullet surface (Fig.21). Thus for cases using bullets of low thermal conductivity and relatively fast freezing rates (due to temperature differential), the free surface anomaly and associated internal bubble clustering may locate themselves close to the substrate surface. The free surface anomaly in this case would significantly affect the adhesion area on the substrate and the bubble cluster will form a structurally weak area close to, and parallel to, the bond interface to be broken. Hence for the adhesion tests, it would appear beneficial to employ a slow freezing rate. However this approach has disadvantageous repercussions with regard to the crystallographic internal structure of the system, explained in the next subsection.

One method of controlling the bubble formations to some extent, is to fill the rig with water in stages of a few millimetres depth, allowing freezing to take place at each stage before the next stage is entered (Fig.22). This fixes the bubble pattern in each layer, not

allowing bubbles to travel large distances and thus preventing their conglomeration into large bubbles. It also has the advantage of flattening the free surface anomalies as the magnitude of the anomaly is dependent on the depth of water frozen (Fig.23). The main disadvantages are that the freezing rate is faster due to the smaller water heat sink at each stage, and that the overall operation takes typically 20-30 times as long as single stage filling, (e.g. several hours).

Crystal Formations

As explained earlier, some of the ice crystals forming within the water manage to float to the free surface before being entrapped in ice by the advancing freezing front. These crystals floating at the surface stimulate local freezing and grow in length. Crystal lengths of up to 5 cm were observed using this rig (Fig.24). If a stepped filling method is employed, then the resulting final specimen will contain several layers of these large crystals. As the overall specimen dimensions are of the same order as these large crystals, the specimen can no longer be considered isotropic for stressing purposes considering the forces involved during bullet release.

Sample Authenticity

Considering the intake lip in flight. Glaze ice is of the greatest adhesion and therefore the main consideration for testing. In glaze cases the supercooled water droplets lose their air content upon impact when they are spread out before freezing. As the ice is accumulated effectively in a great number of thin small areas, the crystal dimensions in the formed ice are very small. Thus it can be seen that to represent this type of ice requires a small crystal size and virtually no air bubbles. From the previous description of sample freezing in the rig, it is apparent that there is a conflict, it being possible to produce large crystals with few air bubbles, or small crystals (fast freezing rate) with many bubbles. A compromise situation should be adopted in the adhesion tests employing a reasonable freezing rate (driven by temperature) to minimise bubble content and maintain relatively small crystals. This authenticity study also emphasises the need for minimum air content in the water employed.

Ice Structure Observation

During freezing, the phenomena mentioned may be observed through the water, but not conveniently within a cold room. Thus a method was established to form suitable records. This involved removal of the ice annulus from the rig by raising the rig temperature until the ice may be lifted clear. This was effected by placing the breech in warm water to a level just over the flange. It should be possible after adhesion tests where the bullet is no longer attached to the ice, to maintain the bond interface ice surface in tact by very careful application of

heat to the other rig components whilst in the cold chamber, (perhaps using a hot air blower). Once removed, the ice annulus may be sectioned by cracking or hot wire cutting (or wire regelation), and photographed using polarised light shone through the specimen with a matt black background (Bib.125).

Rig 2

There are two ice moulds associated with this rig. Each mould is in the form of a cubic metal 'cup' with an inner nylon liner of the same shape and smaller dimensions (Fig.25). These cups must remain clamped to the substrate until the water inside is frozen, no longer requiring a mould. A slight modification was made to these moulds after discovering that excessive clamping forces were required to form a seal with the substrate, which resulted in damage to the substrate surface. This situation was remedied by machining the metal cups till the liners stood proud (Fig.26) whereupon this problem was rectified and lower clamping forces were required. This modification becomes more significant in conjunction with hard substrates such as metals. As in the case of the bullet guide tool of rig 1, the moulds require some form of release agent on all faces in contact with the ice and substrate. In addition to the difficulties encountered sealing the moulds to the substrate, the other problems predicted in the test rig survey of the previous section regarding this rig were experienced in respect of ice forming and setting up the moulds. Most of the ice bubble and crystal formation phenomena described in conjunction with rig 1, are also relevant to rig 2, with the associated remedies where applicable. It was concluded, when considering the number and magnitude of problems predicted and experienced using this test rig, that it was not suitable for use in this research programme, and subsequent adhesion tests employed only rig 1.

4.1.4 Concluding Remarks

The objectives of these freezing tests are met in that useful information has been acquired to aid adhesion testing. The tests were also useful in highlighting the effectiveness of employing two barrel/breech/bullet sets such that both may be ice filled simultaneously to reduce adhesion testing set-up time. It was not found necessary to make any design changes to the adhesion rig (Rig.1).

4.2 Ice Adhesion Tests

4.2.1 Introduction (Sup.4 - 3)

Once manufactured, the ice shear adhesion test rig (Sup.1 - 8), (Fig.R17), was equipped with the necessary instrumentation (Fig.27), and operated in an available refrigeration unit. The tests were carried out using bulk frozen ice (formed by simple freezing of a mass of water) in the main, apart from two which employed ice accreted on the substrate from a fine spray of liquid water as detailed in the supporting material (Fig.28). This approach was adopted as the forming of rime, glaze and rime/glaze type ice samples of a nature more closely related to the impact ice formed on an aircraft in flight through icing conditions, is much more time consuming than the simple bulk freezing of a mass of water. The major purposes of the first tests were to gain experience using the equipment, accumulate knowledge about the situation, develop testing technique, and to highlight some of the associated problems in the early stages. Thus it was not necessary at that stage to employ particularly realistic ice samples with respect to the flight case. A bullet catch mechanism was developed (Fig.29), to improve operator safety and to reduce damage to the test specimens and equipment. The substrates used for the tests were standard test bullets (Fig.30), of various materials, some incorporating particular coatings on their outside curved surface (Table 1).

Tests were carried out using various different techniques and procedures to investigate the importance of the parameters involved, and to check the repeatability with regard to the tolerance limitations on the process. Following these tests, adhesion determination tests were effected on various substrate materials. The results of the tests were processed to yield adhesional strengths for the different substrates (Fig.40), which have been incorporated in the results of the literature survey (described in the next section), (Table 2). A typical adhesional shear strength for an aluminium alloy substrate was 60 psi (0.4 MPa). A detailed description of some typical sample tests is contained in (Sup.4).

4.2.2 Trial Tests (Sup.4 - 4)

These tests were effected to gain experience using the ice shear adhesion test rig, and to test the associated instrumentation. The barrel/breech assembly was cold soaked in the cold chamber which contained the breech block and instrumentation, to a temperature of -32°C. The water was cooled to 0°C. (when ice crystals are first observed on the free surface - (Sup.4), poured into the test rig and left to freeze. The rig was assembled and temperature observed to be -32°C. measured by the thermocouple in the settling chamber in the breech block. In a typical test, the nitrogen pressure was raised to 100 psi (0.69 MPa) in one smooth movement taking approximately two or three seconds. During this time the bullet was heard to eject from the rig into the catch device. Ejection occurred at 65 psi (0.45 MPa) recorded by a pressure transducer and UV recorder. On removing the shielding and catch equipment, it was clear that a simple clean

debonding of the bullet from the ice did not occur. No ice remained in the test rig, and none remained adhered to the bullet. The ice shattered into many small pieces around the test area, no piece larger than 5 mm in any dimension. From the set of typical UV recorder traces produced by some of the tests (Figs.31(a)-31(i)), it was observed that the pressure fall upon bullet release was virtually instantaneous indicating almost instantaneous displacement of the bullet. It may be considered that the ice shattered before debonding took place at the bullet/ice interface. The fact that there was no trace of ice remaining in the rig after the test, even in the crevices of the barrel thread, could indicate that upon pressurisation, the bullet lifted slightly, bending the ice sample, allowing the pressurised nitrogen under the flat lower surface of the ice. This would greatly increase the force on the ice which would be reacted at the barrel threads/ice interface. If this was the case, then it is not unreasonable to assume that the ice fractured in a shear failure across the screw threads formed of ice moulded in the barrel threads. This threaded interface forms a series of sharp grooves and therefore stress raisers, to be opened up by the force on the ice, leading to many internal cracks in the ice and a complete breakdown of structural integrity.

Surface contamination of the bullet, barrel and breech was thought to play a major role in reducing ice adhesion to these components in these tests and thus it was decided that the next tests should employ cleaner equipment. It was thought that this would increase the adhesion strength to a more realistic level and also retain the ice within the rig upon departure of the bullet. A metal bullet was ultrasonically degreased in hot trichloroethylene, followed by washing in hot water and detergent, and rinsing in distilled water, with no apparent improvement upon wetting test as before. The next test involved 'sweating' the bullet by cyclic heating to around 100°C. and cleaning at each intermediate stage in acetone, followed by washing and rinsing as before with still no improvements.

4.2.3 Adhesion Tests

It was originally decided to maintain the testing technique established during the freezing tests. In subsequent tests, efforts were made to increase the ice adhesion strength to a more realistic value than the 20 psi (0.14 MPa) (calculated over the actual bond area) experienced in the earlier tests. One test was effected where the prepared water was cooled to 0°C. and sprayed into the rig using a standard commercially available atomising, insecticide, hand held, spray gun to increase adhesion by reducing the crystal size. A 2 mm ice layer was accumulated, but this operation took several hours. The remaining gap was filled with water at 0°C. which unfortunately caused the sprayed ice layer to melt before freezing of the bulk added water took place. A stepped filling method using very small steps (as described earlier), would probably have been more successful, but also would have taken several hours to effect. It was observed that in some tests, immediately after pouring water at 0°C. into the rig, which was at a temperature of say -20 to -30°C., the image of the substrate as seen through the water, became opaque. This would not be the case for

a BFZ but, more likely that the ice layer in contact with the substrate became detached from the substrate in that a fine air gap existed between the ice and the substrate. This could be caused by the relatively rapid expansion of this layer of ice once in the solid state, breaking adhesion with the substrate. A second reason for attempting to spray the water onto the substrate was to avoid this situation. It would appear that the problem may be rectified by allowing the rig and water to cool together, eliminating the damaging temperature difference at the interface. However, as mentioned earlier, this would result in a slow freezing rate and large ice crystals. For the propeller blade and engine intake lip in flight, this problem does not occur as the water and substrate come together at the same low temperature.

Thus it was decided to return to the techniques developed in the freezing tests, but adhesion of the ice to the breech upper flat surface was improved to a level where the ice remained in the rig during the test by grit blasting this surface. The grit blasted surface was thoroughly cleaned in the manner established in the early tests. The improved adhesion could have been a result of increased mechanical bond to the rougher surface, or removal of surface impurities with removal of surface material during blasting. The overall effect was to prevent the ice bending as previously thought to have occurred where the ice at the barrel thread remained whilst that at the bullet surface moved with the bullet.

By carefully following the established code for cleaning and operating the test rig, a stage was attained where, using aluminium alloy bullets, an ice shear adhesion of 60 psi (0.41 MPa) was reached. This was effected several times till a sufficient confidence level of repeatability was achieved. Some slight improvement in surface preparation was achieved using methylethaketon and trichloroethylene vapour. By this stage of development of the testing technique, a satisfactory level had been attained where all the ice remained in the rig throughout the test on an almost regular basis. Occasional internal cracking took place in the ice (Fig.32), which could be caused by shock waves reacted during rapid loading of the ice, by bending upon loading, or perhaps by tumbling of the bullet during its travel. Tumbling, where the bullet rotates about an axis in the horizontal plane, ie. lateral translation of its base and/or upper flat surface, would be caused by variation in adhesion strength over the bond area. This latter case could be the cause of the cracking as it is highly unlikely that the adhesion strength would be homogeneous over the whole bond area. In most test cases, some internal cracks were produced during freezing, which provided an initiation point for further cracking during loading.

The presence of these cracks, though small, brought about by freezing, raised concern over the stressing of the bullet/ice system once the ice was formed. It was postulated that, as the ice expanded on freezing, it produced a large radial compressive force on the substrate, thereby significantly increasing apparent adhesion. When the freezing formation is considered (Fig.18), where ice forms along the barrel, bullet and breech faces, advancing towards the centre of

the water volume but with a liquid path to the free surface, it can be appreciated that most of the expansion will be dissipated through liquid movement. If this were the case, we would expect to see a raised portion of the ice around the central area at the free surface. Thus the theory is justified by practice, and it can be assumed that the forces exerted by freezing are small compared to those applied by the pressurised nitrogen. A further test to confirm and quantify those forces could be effected, should the facility be available at some later date, by the approach detailed in (Appendix A - "Ice Freezing Stresses", Section 16.5) using a split, thin walled, hollow cylinder in place of the bullet for a freezing only test.

The results of the adhesion tests employing the established preparation method and grit blasted rig appear in (Fig.40) and Table 1(b), (Appendix A).

4.2.4 Adhesion Results Analysis

Observing (Figs.40(a)-(f)), the solid lines indicate the best single straight line slope from the origin (0°C , 0 MPa) through the data, whilst the chain-dot line represents a more suitable single straight line of the data without passing through the origin. In (Fig.40(g)) of all the substrates, the dashed line passes through the origin and represents a practical maximum outside which only the two most extreme values occur (Table 8, Appendix A).

4.3 Ice Adhesion Survey

4.3.1 Summary

This section summarises (Sup.5). It contains data extracted from reports referenced in the adhesion test rig literature survey carried out prior to test rig design, taken from the material in the bibliography, results of tests carried out by the author (previous section), and data derived from flight test photographic records (Figs.F1-F53).

In the literature, ice shear adhesion strength to various substrate materials and surface finishes is studied in depth, with some attention given to tensile adhesion and ice tensile strength, (Figs.L1-L31). The bulk of these tests were carried out under laboratory conditions, which varied considerably from test to test. A survey of the test techniques and test apparatus employed is featured in "Test Rig Design", (Section 4.1) and in more detail in (Sup.1). Several ice shear adhesion tests to various substrates were carried out in the research programme (Sup.4) in a purpose designed test rig (Sup.1) as described "Description of Adopted Design" (Section 4.1.1). These yielded adhesive strengths generally of a lower value than the upper areas of the distribution of results from the Literature Survey (Fig.L31), (up to 0.45 MPa (65 psi) compared with up to 1.6 MPa (230 psi)) respectively. The applicability of the results of the Literature Survey and the research programme tests to aircraft components such as the propeller blade and engine air intake, in flight in icing conditions was in question, and there was an obvious requirement for some third party evidence of adhesion strength in the situation under study.

As there is little evidence available of adhesion testing on impact accreted ice formed in flight, and considering the prohibitive costs associated with effecting flight tests, the shear adhesion of sections of ice adhered to aircraft propellers in flight was deduced from photographic recordings of various test flights, (Figs.F1-F53). Using aircraft propellers, it is possible to deduce ice adhesion strength from photographs by considering the centrifugal force acting on an area where shedding is just beginning to occur (Sup.5 - 5.2). Due to the small scale of the photographs, making measurements difficult and rendering definition of ice accretion cross-section profile difficult, an empirical mathematical procedure for predicting generic profiles from the available data enhanced by experience accrued during the project was developed "Empirical Adhesion Derivation" (Section 16.9), and (Sup.5 - 5.2.3).

A survey of ice physical properties, forming a summary of some of the material in the first few sections of the bibliography appears in (Appendix A) of (Sup.5). The overall final ice shear adhesion strength results appear in (Fig.33).

4.3.2 Introduction

A bibliography of the available literature was compiled (Appendix C) which provided much useful data both of previous test results regarding ice shear adhesion and in aiding the design of a test rig ("Test Rig Design" - Section 4.1).

The lack of sufficient evidence closely related to the actual case of the propeller blade or engine intake in flight, left these results somewhat unjustified in their application and provided the requirement for more data to corroborate and/or criticise the laboratory test results of the literature. This was effected by the assessment of apparent ice adhesion from photographic recordings taken in previous flight tests.

The literature material in the bibliography concerned with those physical properties of ice which might be associated with such phenomena as the shedding characteristics of ice accretions from an aircraft propeller blade or engine intake lip in flight, is introduced and summarised in (Appendix A) of (Sup.5). This provides a background to some of the physical attributes of the ice structure for consideration in all aspects of ice testing, such as shear adhesion strength.

4.3.3 Data analysis

Data from the Literature Survey

Introduction

The literature survey employed to produce the adhesion database is taken from the research programme bibliography (Appendix C) in the sections dealing with test rig design. The test results from reports written by many authors are tabulated (Table 2) and graphically presented (Figs.L1-L31). In some cases the results portrayed in a particular report are taken from a previous report and summarised into one smooth curve. On inspecting the original data where available, it became evident that in many cases, results having a relatively large degree of scatter had been presented in a subsequent report by a single curve (usually a straight line). In several cases the report containing the test results used as originals by a subsequent report was not available and thus only a record of the gradient and intercept of these straight-line graphs exists in this record. The data is taken only from actual reported test results ie. no interpolation, extrapolation, smoothing or averaging has occurred in (Figs.L1-L31). When comparing data from the literature, it must be noted that although the data is collected into a few presentations, the individual results differ in their methods of achievement in many ways, being extracted from a wide variation of tests, the intricacies of which are often unique in their influences on the test results. Thus before drawing any conclusions to explain relative differences in the results, the test conditions, technique and environment of all of the tests concerned, and the associated physical properties of the ice specimens under test (Sup.5) should be carefully considered. (Table

3), (Appendix A) was constructed in order to simplify this approach and to provide a list of considerations to allow for.

For ease of classification the information in (Table 2) has been categorised by test parameter, then substrate material. Each block of data is identified by a four or six character code for cross reference with (Figs.L1-L31). This code system is explained at the beginning of (Table 2). All test results have been standardised into SI units, but are occasionally accompanied by imperial equivalents within the text. As they will eventually become a part of the literature, some of the results taken from the adhesion tests carried out by the author using the specifically designed test rig (Figs.L1,L4,L8,L11,L31) are included in this section (denoted 'ResPgm' for "Research Programme").

Analysis (Sup.5 - 5.1.2)

Observing the plot of shear adhesion for all substrates (Fig.L31), by fitting the curve indicating the trend of the "softer" non-metallic substrate results (Fig.L29), it can be seen that the area above and left of the lines of 0.8 MPa (116 psi) and -20°C . respectively, contains only two results for non-metallic substrates. This implies that, at temperatures above -20°C ., adhesion values above 0.8 MPa are only effectively achievable using metallic substrates. This implication assumes a reasonably smooth substrate surface as very high values of adhesion are attainable on most materials of very rough surface where mechanical bonding (interlocking) is possible on a macro as well as micro scale. Also assumed is that there is sufficient data regarding non-metallic substrates tested to a similar standard as the metallic substrates in this region of (Fig.L31). Conversely and perhaps of more importance when studying de-icing, (Fig.L31) tends to indicate that the propeller blade or engine air intake surface in question must be non-metallic, assuming that an unlubricated surface is employed. The use of an ice-phobic or freezing point depressant liquid or relatively fast eroding solid surface coating on the propeller blade or intake lip to reduce ice adhesion should only be observed as an extra measure for use in rare and extreme circumstances in addition to more reliable and permanent systems, and not to achieve the requirements for normal icing conditions operations. However, there still remain advantages of employing a hard metallic surface, as will be explained later.

Observing (Fig.L27), (shear adhesion to metals), there is no reliably clear distinction between the different metals, apart from one set of results showing that high values of adhesion are possible at low temperatures (below -20°C .) using a stainless steel substrate. This set of results was obtained in (Bib.288), (Fig.L1) by H. H. G. Jellinek. (Figs.L2-L5) indicate no other results from (Bib.288), implying that the other metals were not tested in that report and thus, had they been so tested, might well have achieved results similar to or greater than (greater adhesion) those for stainless steel. Thus it cannot be concluded from this information that ice adheres to a much greater strength to stainless steel than to other metals such as those mentioned in (Fig.L27). Stainless steel is a

popular test substrate because of its corrosion resistant properties, availability, relatively low cost and ease of use.

A direct application of (Fig.L27) then brings the use of stainless steel and electroless nickel leading edge erosion shields, on some de-icing equipment systems, into question with regard to ice adhesion. However, any replacement material, besides exhibiting lower ice adhesive strength, must be of considerable corrosion, erosion and fatigue resistance. Thus a compromise replacement erosion shield might involve the use of a metal base with a corrosion and erosion resistant permanent non-metallic or hybrid metal/non-metal coating. An example of such a material is a product known as "NYFLOR" (produced by A. T. Poeton Limited of Gloucester) which consists of electroless nickel impregnated with PTFE (particle dia. 4 microns), having the "non-stick" properties of PTFE and hardness properties of nickel. This material may be applied as a coating to pure electroless nickel and maintains its hardness and "non-stick" properties throughout the time required to erode all of the thickness of the coating. A test specimen bullet (bullet 12) of aluminium alloy with a "Nyflor" coating has been obtained for future adhesion tests.

Although Jellinek achieved some high values of adhesion for stainless steel, a close observation of (Bib.288) relates that the meticulous preparation of the test substrates, ice samples and water used in the construction of the ice samples, was rather extensive. The substrate was polished using lapping compound. This process, although leaving a smoother surface thereby reducing adhesion, also has the effect of removing the contaminated surface layer. The water, besides being distilled, was passed through exchange resin and boiled out continuously. It can be seen from (Figs.L1-L5) that the more normal trend of results is toward lower values of adhesion at temperatures above -20°C than those of Jellinek's stainless steel. This is followed by an adhesional increase as the temperature falls towards -20°C and below, with one or two exceptions achieved at constant temperature (-6°C and -7.8°C) by experimenters who also went to great depth in the level of test preparation.

The question arises: Which test substrate surface contamination level and ice preparation method is closest applicable to the in-flight propeller blade and engine air intake lip. First thoughts would tend to imagine the engine air intake duct surface being relatively dirty and contaminated with runway dirt, atmospheric dust, smoke, insect carcasses and various aircraft system oils and greases. However, as explained earlier, a propeller blade or intake lip surface travelling at a speed of say Mach 0.4 in a cloud of supercooled (and therefore "super-pure"), water droplets is effectively continuously vapour blasted, and thus possibly a very clean and contamination free substrate. A more detailed look at the comparisons between ice samples formed by various different experimental techniques, and a comparison between these samples and ice accreted on a propeller blade or engine air intake duct in flight, has been effected in previous sections. The state of the substrate surface regarding its purity or contamination level would seem to be of importance as illustrated in many reports (Bib.- 1.4). This is an area for further investigation to establish

the actual substrate surface condition in flight in the appropriate environment.

There is considerable evidence (Sup.2) and (Ref.7), (Figs.L1-L31) to suggest a correlation between the water contact angle to the substrate surface (or surface wettability), and ice adhesion strength to that surface. A surface of low water contact angle (Fig.34) e.g. smooth stainless steel, fully degreased, surface blasted and contamination free, tends to exhibit high values of ice adhesion (in all loading modes), (e.g. (Bib.288), (Figs.L1-L6)), whereas a surface of high water contact angle (Fig.35), e.g. oil or silicone based lubricant, nylon, PTFE, polyacetal, etc. (Figs.L7 and L8) tends toward low (sometimes negligible) values of ice adhesion. This correlation between water contact angle and ice adhesion strength was disputed in (Bib.319) by Bascom, Cottingham and Singleterry. However, in this latter case, the tests concentrated on deliberately lubricated surfaces, ie. a high level of "oily" contamination on the pure metal surface, compared with small unwanted "oily" deposits which have not been effectively removed when attempting to produce a clean surface.

The degree of ability exhibited by a surface to attract water, (ie. its wettability), is dependent upon the surface energy level (surface tension) of that surface, (Refs.7 and 8), in that a high energy surface is more easily wetted than a low energy surface due to the greater number of molecules at the surface attracting the hydrogen bond of the water molecule. The surface energy of a homogeneous material is a measure of its strength, and thus a strong material such as stainless steel has a high surface energy due to the relatively large number of intermolecular bonds, compared with a weaker material such as PTFE having a relatively low surface energy and much fewer intermolecular bonds. Hence PTFE is hydrophobic. However, this general rule may be disrupted when considering a hybrid material such as that mentioned above, where the surface may be of a relatively strong nature with a fine dispersed low energy coating, or small pockets or particles of such material.

The performance of a material in rain erosion is closely related to its surface strength, in that a hard material such as stainless steel is a good resistor to rain erosion whereas PTFE is not. Therefore it is difficult to satisfy the requirements for rain erosion and ice adhesion in one material. The previously mentioned PTFE impregnated nickel would appear to present a possible solution but could fail to satisfy a further criteria combining the effects of rain and ice. High energy impacting rain particles are capable of penetrating microscopic surface irregularities in the substrate which after freezing increases mechanical bonding of the ice to the substrate. Any sintered material will usually display a relatively rough surface on a microscopic scale, and the PTFE to be impregnated into the nickel is primarily a sintered material. Thus, although a laboratory test may reveal promising results for the "Nyflor" material regarding low ice adhesion and good rain erosion resistance, an impact ice accretion test is required to confirm its suitability for use on aircraft propellers and engine air intakes.

The results attained in the research programme ice adhesion tests have been added to (Figs.L1,L4,L8 and L11). The tendency of these results to lie in the lower adhesion areas of the scatter bands from previous experimenters' results, is probably an indication of the level of test preparation and test equipment sophistication available. Additionally effective is the level of substrate contamination which was clearly present in the programme tests to the extent that a good water contact angle was never effectively achieved without grit blasting, which would destroy the surface to be tested in some cases.

A look at the non-metallic substrates (Figs.L6-L12, L28 and L29) shows a similarity to the metallic substrates for the harder non-metallic materials (Fig.L28), although in general, metallic substrates appear to adhere ice better than non-metallic substrates. Some previous authors (e.g. H. H. G. Jellinek (Bib.288), etc.) have partly attributed this phenomena to the electrical properties of metals compared with non-metals giving an attraction to the water with its strong electric dipole thus reducing the water contact angle and increasing ice adhesion strength. Some authors (e.g. P. V. Hobbs (Bib.125)) suggest that the bond between ice and virtually any substrate, in addition to mechanical "keying" into surface deformities, may on the atomic scale be entirely due to ionic bonding. P. V. Hobbs devotes a great deal of attention to a detailed investigation of this subject, but never proves it to be the case (as is common to all authors investigating the actual method by which ice bonds to a substrate), rather he presents another possibility. This and several other theories are discussed in (Sup.1), including Jellinek's "Liquid-Like Layer" theory where he indicates the possible attribution of ice adhesion to the pressure required to break continuity of a thin liquid water film at the ice/substrate interface (at all sub-zero temperatures).

A better adhesional strength for non-metallic substrates is obtained in exceptional cases employing meticulous techniques (as for the metallic substrates), where the more normal case is of lower values rising gently as the temperature falls toward -20°C . The softer materials (Fig.L29) exhibit greater adhesion of more predictable variation with temperature and over a much wider area of scatter, but with the same increase towards -20°C (or -25°C in (Fig.L29)).

The neoprene and similar material (e.g. rubber and viton) results (Figs.L9, L11, L12) are of importance with respect to neoprene de-icing boots currently employed on some aircraft components. Apart from one set of results with a rubber substrate, the general trend is a gradual increase from zero adhesion around 0°C to approximately 0.05 MPa (7 psi) at -10°C and a subsequent increase in gradient to approximately 0.55 MPa (80 psi) at -20°C . There is a large scatter band and perhaps more useful figures are the maximum experienced values of 0.1 MPa (15 psi) at -10°C and 0.8 MPa (116 psi) at -20°C . There is also some implication that adhesion may be effectively zero (0.01 MPa (1 psi)) at a non-zero temperature of say -5°C . It is difficult to test ice adhesion at temperatures around 0°C , ie. to verify the almost zero adhesion between zero and -5°C , in the test facility available, as it is not possible to maintain a constant

temperature close to 0°C. The temperature fluctuates to, and occasionally above 0°C causing melting, or at least, re-crystallisation (Bib.125) of the test ice sample. The increase in adhesive strength of these materials (e.g. neoprene) with falling temperature may in addition to increasing ice strength, partly be attributable to a stiffening of the neoprene surface more toward the hardness of a metal than a rubber material, as explained later.

Ice is a relatively hard crystalline material exhibiting little flexibility. Assume ice is adhered to a hard inflexible substrate and peeling of the ice from the substrate by the action of a force perpendicular to the ice/substrate interface is introduced via a crack at the interface. Then, due to the hard fracture toughness of both materials, there will be virtually no plastic deformation of either and the crack tip will be sharp causing stress concentration and rapid crack propagation whilst employing only a relatively weak peeling force, (Fig.36). If a relatively flexible substrate is used such as rubber or neoprene, the ice when subjected to peeling is capable of maintaining its adhesion to the rubber by deforming the rubber locally at the interface in a manner so as to increase the crack tip radius and thus diffuse the stress (Fig.37). This probably explains the relatively high values of adhesion experienced during tests with neoprene (Figs.L9 and L11).

Flexure of a hard surface on a large scale ie. bending with a large radius requires little absolute deformation to cause interface cracking from the adhered ice due to the lack of ice deformation and local substrate deformation, (viz. the relatively small forces involved when removing ice cubes from a good commercial ice cube mould by slight bending of the mould. From this knowledge, it therefore appears that a good surface construction for introducing and propagating sharp interface cracks is a flexible layer (e.g. rubber or neoprene) underlying an outer hard but fatigue resistant layer (e.g. stainless steel or nickel), (Fig.38). This surface would then allow small deviations of large radius bending of the metal outer layer to introduce the interface cracks, whilst preventing any local substrate deformation, maintaining crack tip stress concentration. However, tests employing such a surface on helicopter rotor blades in rain erosion (Ref.8) have shown that although performing well in ice adhesion, the high energy impact rain drops induce a shock which travels through the outer metal layer and is reflected within the rubber (Fig.39). This results in relatively rapid degradation of the rubber toward breakdown when the metal shield departs from the blade under the action of centrifugal force.

The maximum volume of ice occurs at a temperature of -4°C and thus at a temperature of -5°C, the ice is beginning to contract after expansion. This could indicate where adhesional bonds attained in test apparatus have been degraded due to relative movement between the ice and the substrate at the interface. If this is the case, then repair of this degradation must occur as the temperature falls further to establish the results obtained (ie. a reasonably good adhesion strength). This is not the case for supercooled water impacted in

small separate droplets, ie. the case of a propeller blade or engine air intake lip flying through icing cloud.

The question now arises: Are the plots (e.g. (Fig.L29)) a display of the post -4°C . rebonding of the ice to the substrate, being completely different to the flight case? Or, is relative movement at the interface restricted such as to be insufficient to cause significant degradation to the ice bond? If the former is true, then a large increase in adhesion over that tested in the laboratory could be expected using impact ice (Bib.91), (Figs.L1,L3,L4,L6 and L12). The impact ice adhesion is of a reasonable value in some cases, but comparable with the lower values attained by laboratory test in most cases, showing no tendency towards high laboratory test values. Thus it may be assumed that the small movement which occurs at temperatures around -4°C is not sufficient to destroy the ice adhesion, and in most cases is insignificant in its effect which is not visible in test results except to a minute extent, and in very few cases. Obviously, this relative movement at the interface will have negligible effect on the bond to flexible substrates where a greater level of deformation is possible.

There is a definite lack of data on the adhesive strength of ice accreted on propeller blades and engine air intake lips in flight through icing cloud conditions (sometimes referred to as "aeroice"), in the literature. Therefore, the level of confidence with which the adhesion envelope created by the collection of results may be applied to aeroice situations is relatively low. To increase the confidence level or show otherwise requires an addition of a reasonable quantity of relevant data. However, it is the nature of the problem of acquiring such data which has led to the lack of its existence within the literature. The substrate in a typical case is travelling at a speed of 100-300 kts on the wing of an aircraft flying at several thousand feet altitude in a sub zero temperature. This is a difficult substrate on which to effect tests. The ice is accreted from a cloud of droplets, typically 5-150 μm in diameter in the liquid state at a sub-zero temperature and suspended in the atmosphere by air currents and the Brownian movement. These droplets collide with the substrate and depending on the conditions, either freeze entirely, or partly freeze and partly run back along the surface to freeze further aft. With the additional effects of a rather complex and variable flow field, the situation is not reproducible to a realistic extent at ground level without the use of large, complex and inherently costly test facilities.

It was therefore decided that aeroice adhesion data for addition to that from the Literature Survey, to adapt for use in the production of an adhesion envelope for propeller blade and engine air intake lip de-icing system design, would be assessed from the apparent adhesion present in photographic evidence of iced propeller blades recorded during previous flight tests. Propeller blades were used as the apparent ice adhesion may be derived from the centrifugal force present, as detailed later (Section 16.9).

Concluding Remarks (Sup.5 - 5.1.3)

1. A need has been established to investigate the adhesion strength of ice accreted on the intake lip in flight, for comparison with the results from the Literature Survey (next section).
2. In general, metals appear to exhibit better ice adhesion strengths than non-metals.
3. A correlation between ice adhesion and water contact angle exists, in that a low water contact angle corresponds to a high value of ice adhesion strength.
4. Substrate surface contamination level plays an important part in ice adhesion, in that, in general a cleaner surface exhibits stronger adhesion.
5. It may be possible to achieve zero ice adhesion at sub-zero temperatures with a permanent, relatively hard, erosion resistant material.
6. When peeling may be introduced at the ice/substrate interface, it is advantageous to employ a hard substrate material to maintain a high stress concentration at the crack tip, causing rapid crack propagation.
7. There may be some new hybrid materials which satisfy the requirements for rain erosion and impact ice adhesion, which are more compatible with and suitable for application to the leading edge of the propeller blade and intake duct than the materials presently employed.
8. Vibration of the substrate surface probably has a small effect in reducing ice adhesion, or introducing cracking at the interface.
9. It would be useful in subsequent ice shear adhesion laboratory tests to have a knowledge of the substrate surface condition (regarding impurities and contamination level) of the propeller blade or intake duct leading edge in flight in icing cloud.
10. Neoprene does not appear to exhibit properties favourable to achieving low values of ice adhesion strength, and its use in some "rubber boot" de-icing systems is mainly attributable to its rain erosion, foreign object impact tolerance, availability, cost, electrical insulation and ease of use characteristics.

Data from Flight Test Photographs

Introduction

There is a requirement for the estimation of ice accretion adhesion to actual propeller blades and air intake lip surfaces in a representative environment. Due to the nature of the substrate and environment the only practical solution is to use photographic evidence recorded during flight tests. These tests were not dedicated to this research programme but took place under the conditions of interest to this study and thus provide evidence employable in this research programme. The photographs used in this analysis appear in (Figs.F1-F54). A considerable amount of approximation had to be employed and using photographic enlargements yielded little increase in resolution for a large forecast cost outlay.

Analysis

The method of deriving the apparent adhesion of the ice from the photographs is described in (Appendix A, Section 16.9). The results of this analysis are featured in (Fig.40), and compared with those from the literature and tests carried out within the research programme (Fig.33). Although, the accuracy of individual results derived in this manner is not high, the direction of the inaccuracies is completely random in their effect on the absolute resulting values. Therefore, provided that a sufficient number of cases are examined, the accuracy of the overall statistical trend will be of a standard sufficient for its intended use. Some of the figures (Figs.F20-F24, F33-F36, F42-F44 and F54) have been included to aid explanation of associated phenomena.

Concluding Remarks (Sup.5 - 5.2.5)

1. Although there are areas for inaccuracy in the adopted procedure for analysis of the flight test photographs (Section 16.9), a statistical view of the overall trend (Fig.40) indicates a correlation within the data, having a relatively low scatter considering the scale of the evidence.
2. There are two exceptionally high values (Fig.40) compared with the bulk of the data, which could be a multiplication of errors. It is possible that these results are correct, especially when recalling experience with data from the literature (Fig.L31), with specific regard to the results for stainless steel compared with the rest of the material substrates. It could be a combination of more preferable circumstances creating more ideal adhesional criteria in those two particular cases, indicating an approximation of the frequency with which abnormally high values occur (ie, 2% of occurrences). It is interesting to note that both of these photographic cases are concerned with ice adhesion to the stainless steel (or nickel) leading edge erosion shield, lending credence to the two high values in the adhesion database survey.

3. It can be seen that the adhesion strength sometimes decreases to almost zero, yet at the same temperature and under comparable conditions, can reach values of 0.45 MPa (65 psi). This is an indication that there are important factors other than temperature and substrate material. These remain undefined but may include vibration which can only be measured in special tests.
4. The substrate material variation (ie, from neoprene, through polyurethane to stainless steel (or nickel) depending on the construction of the leading edge of the composite propeller blade for these sample cases, appears to have a reasonably strong effect on the resulting ice adhesional strength. This is borne out by the higher values of the flight test data and the bulk of the literature survey data.
5. (Fig.42) may be used in many ways, not only to derive ice adhesion strength from ice mass density, accretion profile aspect ratio, blade radius and blade rotational speed. It may be used to aid de-icing system design for propeller blades. If the maximum accretion size and weight are determined from a performance and safety point of view, from which the ice density and accretion aspect ratio relationship are determined, then from a knowledge of a typical ice adhesion strength to the substrate material in question, (Fig.42) may be used, given the propeller rotational speed, to determine the outboard limit to which the de-icing system is required (Fig.43). Conversely, perhaps on an existing de-iced propeller blade, a knowledge of the rotational speed, ice adhesional strength to the concerned material, and ice density for a given ambient temperature, droplet diameter and liquid water content of the environment, the accretion size aspect ratio with respect to the blade radius is definable.
6. There is a large quantity of such flight data available for use in further substantiating the trends of adhesion results gathered in this manner. It may be worthwhile effecting a more accurate similar assessment using large photographic enlargements of original recordings to assess accretion dimensions, mass density and cross-sectional profile more accurately in flight tests specifically dedicated to this purpose. In such an analysis, a finer categorisation of ice accretion mass density may be possible, or measurable should it be possible to recover accretion samples.
7. Considering propeller blade de-icing system design, from the figures, it is obvious that the spanwise limit of the "rubber boot" de-icing system does not represent the radial limit to which ice remains adhered to the blade. It is apparent that ice is capable of remaining adhered to the blade almost as far outboard as the blade tip. The radial area covered by the de-icing system represents an area where the blade is relatively thick, which leads to ice accretions which are also relatively thick (measured perpendicular to their chord) and hence of considerable mass. The effect of asymmetrically shedding ice

accretions of large mass on opposite blades of a propeller can produce high levels of vibration if allowed to continue for some time, and thus these accretions must be shed within a short time interval of one another. The inboard thick area of blade leads to blunter ice accretion leading edges (as in the figures) increasing kinetic heating at the leading edge causing an even blunter profile which can lead to "double horn" type profiles (Figs.F41 and F42). The apparent "double horn" observed in these figures appears to be just that, but could be the remaining part of a large accretion whose leading edge portion has fractured from the part seen and subsequently shed. This is a relatively infrequent event where such a large remaining part of the accretion is left behind as it requires either, the adhesion of the ice to the blade to be greater than the cohesion in the ice, or a relatively large radial flaw formed in an accretion which is formed from integration of many small droplets.

For aerodynamic performance reasons, it is desirable to remove these large inboard accretions. Outboard, on the relatively thin blade, although accretions can be seen to accrete to a large chordwise thickness (Figs.F1-F9, and F11), it is relatively thin (perpendicular to chord) and of much less aerodynamic drag than its inboard equivalent. The early stages of ice accretion outboard can improve the aerodynamic performance of the blade by effectively increasing blade area for negligible mass and drag increase. The effective mass of glaze ice accretions outboard under centrifugal acceleration in conditions where asymmetric shedding takes place must be considered when determining the outboard radial limit of the de-icing system. The figures indicate that glaze ice does not tend to adhere outboard in large quantities (to a great depth), due to the combined effect of vibration and centrifugal force in breaking its bond.

4.3.4 Results

The results of the Literature Survey regarding ice shear and tensile adhesion to various specific substrate materials appear in tabular form in the relevant sections of Table 2, and in graphical form against temperature in (Figs.L1-L26). Collective graphical displays of overall shear adhesion results for comparison between different materials of a similar nature, are grouped into metals, soft non-metals, hard non-metals and lubricants in (Figs.L27-L29 and L30) respectively. A composite graph of the whole of the shear adhesion results taken from the Literature Survey together with those determined in tests within the research programme appears in (Fig.L31). The shear adhesion results deduced from the flight test photographs (Figs.F1-F53) are tabulated in Table 7(c) and presented graphically in (Fig.40). A combination graph of the flight test photograph, Literature Survey and research programme results for ice shear adhesion appears in (Fig.33) and is tabulated in Table 8.

The results of the flight test photographs display a tighter grouping of the data than those of the Literature Survey, with much less variance. The area of main interest of the flight data

corresponds with the conglomeration of literature survey results in the lower adhesion area of (Fig.L31). This lends credence to that data. At the same time it reinforces previous conclusions that it is the ideal laboratory adhesional conditions and environmental considerations which have led to such high values of shear adhesion as have been attained in that manner. This phenomenon supports the assumption that the ideal situations accomplished in the laboratory tests of the high adhesion values are not realistic or typical to the propeller blade or engine air intake lip operating conditions and environment. Thus the higher values of (Fig.L31) serve to indicate a shear adhesion ceiling, which may theoretically be attained in flight on rare occasions, when the conditions and environment are ideal to a degree comparable with the laboratory circumstances under which the reference results were obtained, (e.g. Bib.288). In (Fig.40) a maximum value approaching 1 MPa was attained and indicates that although the values of 1.6 MPa of (Fig.L31) are greater, it remains feasible that adhesion strengths in the region of 1 MPa on propeller blades and intake lips in flight will not be infrequent (ie. perhaps 1% of the cases). It is interesting to note that these maximum values of adhesion experienced in the test flight data occurred on the stainless steel (or nickel) leading edge erosion shield which correlates reasonably directly with the results of the Literature Survey in the relative adhesion strengths of different material substrates.

An average value of adhesion strength for ice adhered to the intake lip appears to be approximately 0.45 MPa (65 psi). This is in agreement with the results calculated and used by a propeller manufacturer where apparent ice adhesion was deduced by reference to the 1500 g centrifugal acceleration radial station beyond which it was assumed ice could not adhere to any significant mass. This supports the results of this report.

Runback ice is a definite phenomenon associated with all types of aircraft leading edge de-icing (see also following subsection on runback ice, and (Figs.F20-F24, F42-F44)). Any de-icing system, no matter how well influenced by, and tailored to, local and current conditions, must employ some degree of "overkill" in heating the ice/substrate interface to attain a sufficient level of confidence for removing the ice. Thus there will always be occurrences where meltwater is produced, resulting in runback ice where there are non-de-iced areas aft. Therefore runback ice accretion is an important consideration when designing de-icing systems. Although for a propeller blade, the forming of runback ice aft of the de-icer is serious, for an engine air intake, the duct is usually de-iced (or anti-iced) as far aft as the engine compressor.

(Figs.F34-F36) of ice accretions on the leading edge of an aircraft mainplane have been included because of their increased scale over the figures of ice on propeller blades, allowing closer observation of the nature of the ice accretion regarding its surface finish, local irregularities, appearance with respect to mass density estimation, and somewhat unpredictable shedding characteristics (Fig.F34). Similarly (Fig.F54) is included to provide a closer view of a typical pure glaze ice accretion around an oil cooler air intake

lip. Although the influence of centrifugal acceleration is not present in these cases, similarity in the criteria for observation exists.

4.3.5 Concluding Remarks

1. The ice shear adhesion data of the literature, where achieved under exceptional laboratory conditions is not directly applicable to aircraft propeller blades and engine air intake lips in flight in icing cloud. Although the nature of the ice bond may be similar, the presence of other interface bond fracturing influences such as vibration reduces the effective shear adhesion on the surface to a level similar to that experienced in tests carried out in the research programme. As vibration was not applied in the laboratory tests in the research programme, the correlation with the results of the flight data is brought about by the fact that the adhesion degrading influence of surface contamination of the substrate, experienced during the laboratory tests, was approximately equal in magnitude to the adhesion degrading influence of vibration in the flight tests.
2. The shear adhesion of impact accreted ice on a propeller blade in flight through icing cloud appears to be of the order of 0.45 MPa (65 psi) on average with reasonably frequent exceptional cases reaching 1 MPa (150 psi). Although of a slower impact velocity, it may be assumed that ice adhesion to the engine air intake lip is of a similar value.
3. In general, the material properties of a propeller blade leading edge shield to resist rain erosion have been fundamentally opposite to those required to resist ice adhesion, and the need to resist rain erosion is paramount over that to resist ice adhesion. Some relatively recent discoveries in hybrid materials may provide a satisfactory compromise solution of rain erosion resistance equal to or better than presently employed, with improved ice phobic qualities.
4. The variation in shear adhesion results with variation in testing technique, conditions and environment is an indication that the only way to acquire accurate reliable test data applicable to the propeller blade and air intake lip in flight through icing cloud, is by flight test in a real environment, or by employing a sophisticated full scale ground based test rig allowing actual flight speeds. Scaling of droplets and centrifugal effects is not easy or reliable. In the rig, a realistic atmosphere must be produced and continually monitored by observation of the relevant parameters (liquid water content, droplet size, pressure and temperature), and a constant observation of the type of accretion produced with respect to that observed in the flight case.

5 ONE-DIMENSIONAL THERMODYNAMIC ANALYSIS

Introduction

During the first two years of the research programme, it was decided to initialise a preliminary study of the thermodynamics of a composite propeller blade under icing conditions, compared with a typical metal blade. A classical approach to a one-dimensional steady state thermodynamic analysis perpendicular to the composite blade material layers, is followed by a brief two-dimensional investigation. This allowed heat energy to flow within the material layers along curved paths in preference to crossing interfaces at material boundaries of decreasing thermal conductivity compared with that within the layer. Specific heat capacity variation with varying material layer thicknesses is also considered in addition to simple relative thermal conductivity, especially in the leading edge area between pitch and camber face areas of the de-icer. This initial one-dimensional study was carried out as a preliminary study to the originally intended two-dimensional computational ice prediction software development for propeller blade application. The propeller blade was employed as the substrate as it was the intention to combine the findings of the ice adhesion data from the propeller icing flight test photographs in some manner with the results of the thermodynamic work in an effort to improve ice adhesion knowledge with regard to its variation with temperature and substrate thermal properties. The change in emphasis in the final year of the research programme to engine air intakes had not taken place at this time. It also gave the advantage of a simpler aerofoil section, less variation in section, and a closer approximation to two-dimensionality at each radial station.

Some interesting results were derived from this work, (see "Concluding Remarks" - following). De-icing system heating element temperatures achieved on composite blades were compared with those associated with the metal blade. The metal blade presents a large heat sink to the de-icing system as opposed to the good thermal insulating qualities of the composite material (typically 300 fold a better thermal insulator than the aluminium alloy). The de-icing system heater power density requirement of the composite blade is therefore less than that of its metal counterpart to achieve efficient, effective and reliable de-icing without over-heating the ice, producing unnecessary meltwater and subsequent undesirable runback ice formations.

In order to simplify the analysis assumptions must be made to limit the number of variables present and form some appreciation for the magnitude of the effect of less significant factors. These assumptions are described within this section. A typical blade design and de-icing system design was chosen for the composite blade analysis both to reduce the number of variables and design time of setting up some theoretical new design as an example, and to render the results more applicable to actual experience. A similar metal blade was chosen as it is only required at this stage for comparison between the metal blade thermodynamic performance and that of the composite blade. The

greater emphasis on the composite blade rather than the metal blade is made for two reasons. Firstly, because the composite blade is becoming increasingly more popular, replacing its metal counterpart due to its technological and other advantages (mentioned earlier), and secondly with a view to investigating the cause and alleviation of the problem of "Run back" ice.

5.1 Assumptions

1. The heater element, the surface paint applied over the whole blade, redux layers within the composite blade, and the adhesive used to bond the neoprene to the aluminium alloy or polyurethane are of negligible thicknesses.
2. The ice forms an evenly distributed layer of uniform thickness over the whole of the de-icing boot area, and does not exist over all other areas of the blade.
3. All components of the system, including the ice accretion are in perfect thermal contact with adjacent components.
4. The thermal conductivity for any of the materials in the system is considered to be constant irrespective of variations in temperature.
5. The effect of temperature on the ice adhesional bond strength is negligible, and the ice remains adhered until an interface temperature of 0°C . is achieved. Therefore the layer of ice at the interface which is liquidised is assumed to be infinitely thin, such that the specific latent heat of fusion may be ignored.
6. The effect of centrifugal force on the ice adhesion is insufficient to break the adhesional bond and thus no "self shedding" occurs.
7. There are no local inhomogenities in temperature distribution around discrete wire elements within the de-icer electrical heater matrix.
8. Kinetic heating of un-iced areas of the blade due to friction, is assumed to be of negligible magnitude and effect.
9. The airflow is assumed to be dry, ie. there are no suspended water droplets. This would yield a reasonable representation of an iced body leaving cloud into a clear dry atmosphere.
10. The de-icer cycle frequency is low enough that, by the time an interface temperature of 0°C . is reached, the assumption that a steady state condition applies, is valid within the limits of the requirements of the estimation.

11. The heat flow may be considered one-dimensional in that a streamline of heat flowing through material is of constant cross section. A certain degree of two-dimensionality is introduced in that to improve the relevance of the estimations, the heat is allowed to flow in a chordwise direction. However, dissipation perpendicular to the line of flow to cover an area, (or volume), remains outside the limitations of these calculations, and thus the system is still essentially one-dimensional. This approach was adopted in order to allow heat flowing into the blade to curve round toward the free surface of the blade aft of the de-icing boot, as is assumed the case in reality. Another effect is to allow heat flowing within the composite blade to flow along the fibres in certain thermodynamically preferable cases as opposed to transverse flow across the fibres.
12. No liquid water exists on the blade, ie. the ice, (and melt-water interface film), shed immediately the infinitely thin interface film melts. Thus there is no heat loss to evaporation.
13. Heat loss from the blade conducted into runback melt-water flowing over the blade surface aft of the de-icer is not considered.
14. As a steady true stagnation point is not actually achieved in flight on the propeller blade leading edge, for the purpose of heat transfer estimation the heat transfer coefficient was calculated 1 mm aft of the leading edge.
15. The stagnation point is assumed to be on the geometric leading edge of the blade, ie. no incidence (pitch) is considered.

5.2 Discussion

The temperature at the leading edge ice/air interface cannot be considered to be equal to the OAT due to the stagnation temperature rise at the leading edge. Thus, in order to assess a typical case, this temperature rise must be accounted for when working at the leading edge. To reduce the number of test cases, all cases employ an aircraft cruise speed of 272 kt (typical cruise - S340) and a propeller angular velocity of 1331 rpm (typical cruise rpm - S340).

5.2.1 Metal Propeller Blade

It is assumed that heat flowing from the inner surface of the de-icing element into the blade, exits the blade at a point aft of the de-icer. This surface is assumed to be ice free and parallel to the local airflow. No adjustment is made for pressure variation above ambient on the pitch face or below ambient on the camber face except for the effects of the presence of the boundary layer.

The de-icing heater matrix is wrapped around the leading edge of the blade thus effectively covering three sides of a 'rectangle', leaving only the route aft toward the trailing edge uncovered. The

neoprene protection layer over the outer surface of the heater matrix is almost twice the thickness of the electrothermally insulating layer between the electrical element and the metal blade. Hence it will be appreciated that the 'cold' metal blade interior presents an attractive heat sink to heat energy transmitted from the inner surface of the heater. This configuration encourages heat energy to escape aft toward the trailing edge. As heat flows into the blade metal, the metal temperature rises thus increasing the magnitude of the negative temperature gradient across the blade/air interface aft of the de-icer. Therefore heat energy released from the inner surface of the de-icer element will flow through the blade metal and emerge to the outside air through the blade surface aft of the de-icing system.

Consider a more realistic case of a relatively large temperature drop across the boundary as is the case during a "power-on" part of the de-icing cycle not far aft of the de-iced area of the blade. Heat within the blade metal aft of, and close to, the de-iced area of the blade will be encouraged both by incoming heat energy from the de-icer element, and the temperature drop in a direction out of the blade to change direction from heading into the blade perpendicularly from the de-icing element, to head toward the blade surface in a direction eventually becoming perpendicular to the blade surface, assuming sufficient time and distance for this change in direction.

This reasoning forms the justification for assuming that heat energy emitted from the electric de-icing matrix and transmitted into the blade, will actually re-appear crossing the blade surface boundary exiting the blade perpendicular to this interface not far aft of the de-icing boot. In order to simplify the calculations, no concentration or diffusion has been applied to the heat energy travelling through the blade from the point at which it leaves the neoprene/aluminium alloy interface till it appears at the metal/air or metal/ice interface.

Although this type of approach considerably simplifies the system compared with the actual flight case, provided that the area under study is reasonably close to the de-iced area in a chordwise sense, it may be considered sufficient for the scope of these estimations. The area of de-icing element transmitting heat energy into the blade is considerably greater than the internal area through which it escapes aft. Hence, in reality, at the beginning of a 'power on' de-icing cycle the temperature in the blade interior trapped on three sides under the de-icer element may experience a considerable temperature rise. Thus it will present a particularly attractive negative temperature gradient through the relatively short path to the blade surface just aft of the de-icer.

5.2.5 Composite Blade

Although the non-metallic composite blade carries the same de-icing 'boot' as its metal counterpart, the actual blade composition results in very dissimilar thermal characteristics. As briefly mentioned earlier, the polyurethane foam core of the composite blade has a thermal conductivity 300 times less than the aluminium alloy of

the metal blade. The overall effect is that the structure underlying the actual de-icer electrical heating element (ie. including the inner neoprene layer) is less thermally conductive than the outer protective (double thickness) neoprene layer. As will be appreciated from the figures in the sample calculation case studies that follow, this results in a much smaller flow of heat energy from the inner surface of the de-icer into the blade material than that flowing directly through the outer neoprene to the air (or ice).

The composite blade is manufactured by 'tacking' several sheets of dry glass and carbon fabric over an expanded polyurethane foam core. The structure is then formed by resin impregnation under a vacuum in a mould. Thence the blade is polyurethane spray painted, to which the neoprene de-icing boot is glued. In general the fibres of the fibre/resin composites run spanwise and chordwise within the blade such that directly beneath the de-icer (under the polyurethane paint) within the composite layer, approximately 50% of the fibres run chordwise. As the thermal conductivity of the fibre material is greater than that of the resin and the fibres represent a continuous path of homogenous material it was considered too limiting to apply isotropic thermal properties to the laminates in the analysis. Thus in the case studies an allowance is made by calculating a thermally preferable route from the relative values of thermal conductivity. Hence heat energy is allowed to flow along the fibres in a chordwise direction as well as directly into the blade perpendicular to the plane of its origin. The direction of such flow for the purpose of this basic one-dimensional estimative approach was calculated as follows:-

$$\theta = \tan^{-1} \left[\frac{k_1}{k_2} \right]$$

where:

θ = angular deviation from perpendicular to layer
 k_1 = thermal conductivity of glass or carbon
 k_2 = thermal conductivity perpendicularly through layer

and:

$$k_2 = k_1 \times F + k_r \times (1 - F)$$

where:

k_r = thermal conductivity of resin

F = fill fraction (ie. fibre volume fraction of composite)

As briefly described earlier, this one-dimensional analysis does not allow for thermal concentration or diffusion, ie. the heat flow streamlines, although being allowed to bend, are effectively of constant cross section, thermally speaking.

The composite blade is manufactured as described earlier to produce what is referred to as the 'stressed blade'. This is in fact the basic structural shape inboard necessary to carry the load of the rotating outboard part of the blade. The inboard part of the blade is thick (ie. of high thickness/chord ratio) but experiences small aerodynamic forces compared to the more radially outboard stations. Also, to fit the blade root into the pitch change mechanism requires a final 'root-end' circular cross section. Thus for structural integrity, the continuous spanwise fibres of the composite laminate layers of the blade construction cluster together at the root into the circular cross section to anchor into the root retainment wedge.

To effect a good weight:strength:load distribution, ie. only putting the strength and inherent weight where it is required, the solution is to produce the 'stressed blade' with the circular cross sectioned root and fit a dense polyurethane expanded foam 'cuff' over the circular (and near circular) area to form the correct aerofoils. The thermal conductivity of the cuff foam is almost identical to that of the blade core foam. Over the inboard leading edge area of the blade therefore this cuff, which increases to a considerable thickness toward the root end, and lies directly beneath the neoprene de-icing boot (except for the polyurethane paint) has the effect of providing such extensive thermal insulation that all structure under the cuff may be ignored with respect to heat energy flow considerations. This criteria is borne out in the numerical case studies (Section 17.4, "Sample Calculations").

In comparison with the metal blade therefore it can be seen that although some heat energy will flow aft within the blade to emerge from the blade downstream of the de-icing system, the magnitude of the flow will be much less than in the metal blade case (see case studies). This phenomenon has serious implications with regard to runback ice formation (detailed later).

5.2.3 Heat Transfer Coefficient

In order to effect a one-dimensional thermodynamic analysis, some relatively realistic estimation of surface heat transfer coefficient is required. Heat transfer coefficient is composed of the sum of the convection and radiation heat transfer coefficients. Firstly convection: To simplify the approach allowing more concentration on the material temperature comparison between metal and composite blades, rather than diverging into complex simulation of heat transfer coefficient at this time, a standard flat plate approach is adopted, (Ref.15), page 515, section 22.2, "Forced Convection in Laminar Flow Past a Flat Plate", Fig.22.6. For cases concerning surface areas of the blade in close proximity to the leading edge it may be assumed that the boundary layer is laminar. For points aft of the de-icing system, ie. considerably downstream (typically 20 - 30% chord), transition may be assumed to have taken place resulting in a turbulent boundary layer. In a similar manner to the way in which a flow velocity profile exists in an air flow velocity boundary layer, a temperature profile exists in the temperature boundary layer (Fig.90). The derivation of convective heat transfer coefficient is well

established and appears in (Ref.15) where the heat transfer coefficient in terms of Stanton number is given by:-

where:

$$h_{xl} = St \cdot C_p \cdot e \cdot U_s$$
$$St = \frac{C_f \cdot S}{2}$$

and

$$S = Pr^{-2/3}$$

h_x = heat transfer coefficient at station x (Fig.90)

St = Stanton number

C_f = Friction coefficient

C_p = Specific heat capacity at constant pressure

U_s = free stream velocity

x = surface distance downstream of leading edge

For Low Speed Laminar Flow

$$C_f = 0.664 R_{ex}^{-1/2} \quad (\text{Ref.19})$$

therefore

$$h_{lx} = \frac{0.664}{2} R_{ex}^{-1/2} Pr^{-2/3} C_p e U_s$$

which reduces to

$$h_{lx} = 0.332 Pr^{1/3} R_{ex}^{1/2} \frac{x}{k}$$

where h_{lx} = laminar heat transfer coefficient at station x

For Low Speed Turbulent Flow

$$C_f = 0.0146 R_{ex}^{-0.211} \quad (\text{Ref.19})$$

and turbulent Prandtl number approximates to 1 (Ref.19)

therefore

$$S = 1$$

and

$$h_{tx} = 0.0073 R_{ex}^{-0.211} C_p e U_s$$

where h_{tx} = turbulent heat transfer coefficient at station x

It was considered that the effects of compressibility on the temperature boundary layer skin friction coefficient would not be of significant magnitude to warrant introducing a different method of calculation in a few cases and thereby generate another variable amongst the case comparisons. Thus, for comparison of the

effectiveness of material layer thickness and composite material properties, the low speed formulae have been applied in all cases of the estimative calculations of Section 17.

Secondly radiation: The absorptivity of air is extremely low and the emissivity of a white surface is also low. The overall radiative heat transfer coefficient is a function of the temperature difference between the radiator and the absorber. In the cases of heat emission from the iced (or lightly frosted) surface to the atmosphere the temperature difference is relatively small (typically of the order of 20 - 40°C). The radiation heat transfer coefficient is given by:-

$$h_r = \epsilon_1 \sigma (T_2 + T_1) (T_2^2 + T_1^2) \quad \begin{array}{l} \text{(Ref.15), page 584} \\ \text{Chapter 23,} \\ \text{equation 23.36} \end{array}$$

where:

h_r = radiation heat transfer coefficient

ϵ_1 = surface 1 emissivity

σ = Stefan Boltzman constant

T_1 = surface 1 (emitter) temperature

T_2 = surface 2 (absorber) temperature

It is assumed in the derivation (Ref.15) that no heat energy is absorbed by air between the two bodies. In the cases studied here there is no second body, and if the airflow over the surface is taken to be the second body then it follows that the absorption rate will be negligible. Thus the radiation heat transfer coefficient is formed from a multiplication of several negligible values and is therefore itself negligible in comparison with the convective heat transfer coefficient. Therefore it may safely be ignored in these calculations, the total heat transfer coefficient being equal to the convective heat transfer coefficient.

The calculations of heat transfer coefficient appear in Appendix A (Section 17). A general summary is given below.

5.3 Concluding Remarks

5.3.1 Metal Propeller Blade

A detailed account of the study case calculations and results appears in Appendix A in Section 17.4. However, an overall general summary is given below.

The effect of stagnation temperature rise is significant in varying the heater power required to effect de-icing in spanwise and chordwise directions. This fact is clearly demonstrated in Cases 1.1 and 1.2 where the required heater power on the leading edge is only 42% of that required aft of the stagnation area. The use of a simple non-varied (during the "power-on" periods) value of heat output over

the whole of the de-icing boot will inevitably lead to a considerable "over-kill" situation at the leading edge when sufficient power is used to de-ice the trailing edge of the de-icing boot. Spraymat de-icing systems are actually designed with a 'stepped', varied, power output density with respect to chord, where the power level increases from the system trailing edge toward the leading edge. However, no allowance is made for the stagnation temperature rise at the leading edge.

Another factor of influence on the heater power required is the thickness of the ice accretion. As the ice accretion increases in thickness, thermal insulation increases thus reducing the power required to raise the interface temperature. Thus it is beneficial in power terms to allow the ice to accrete to the maximum permissible thickness, from an aerodynamic consideration, before de-icing. This phenomenon is clearly presented in Cases 1.3 and 1.4 (Appendix A, Section 17.4) where an increase in ice thickness from 2 mm to 10 mm effectively reduces the heater power required by 25% from 3.86 kWm^{-2} to 2.88 kWm^{-2} .

5.3.2 Non-Metallic Composite Propeller Blade

As expected the calculations clearly indicate the different thermal characteristics of the non-metallic composite blade compared with the solid metal blade. The overall effect is to reduce the required heater output to between 50 and 65% of that required for the metal blade.

The results show that the temperature drop "forward" and the composition of the blade under the sprayed polyurethane layer, are effective in determining the heater power required for de-icing. It is usual practice to modify the profile of the blade root by casting a dense polyurethane foam cuff over the basic structural blade. The effect of this cuff under the de-icing boot is to render the blade composition under the cuff irrelevant when calculating de-icing heater power, to a reasonable approximation. This is evident in Case 2.5 where the heat loss aft is typically reduced to less than 25% of the equivalent value where there is no foam cuff present. The effect of stagnation temperature rise on the heat output distribution spanwise and chordwise still applies as for the metal blade. The required heater output more than doubles when the heat transmission point is moved aft 15 mm from the leading edge.

5.3.3 Run-Back Ice

It is demonstrated in Cases 1.1, 1.3 and 1.4 that a positive aft blade surface temperature may be achieved on the metal blade in some circumstances. This is derived assuming no ice to be present over the aft surface. Thus if there were an accretion already existing over the aft blade surface (ie. aft of the trailing edge of the de-icing system), then it would have the effect of increasing thermal insulation, thereby raising further the aft blade surface temperature. Hence it can be seen that, for the metal blade, runback ice formations

may be removed by the action of heat from the de-icing heater element travelling aft through the blade.

It is obvious from the indications of the results, that little heat energy from the de-icer enters the composite blade. Thus, in the presence of run-back ice (Figs.F20-F22), mentioned earlier, there is no secondary heat flow as a result of conduction aft through the blade from the de-icer to deal with this ice. Therefore run-back ice formations on the blade aft of the de-icing boot on upper and lower surfaces, are not easily removed. This is borne out by actual flight experience, from which photographic evidence of the presence of run-back ice is available (Figs.F20-F22).

The very same problem was encountered on the Chinook helicopter during icing flight trials in Canada using a composite blade. The de-icing system employed involved a metallic electrical heater matrix sandwiched in glass fibre and epoxy resin, similar in some ways to the "Spraymat" system. The runback ice problem was fully overcome in a simple manner. A secondary heater matrix, constructed in the same way as the first, was employed aft of the primary de-icing area, and energised much less frequently than the primary, to remove the run-back ice formed by, and aft of, the primary matrix. If further run-back ice had formed in a similar manner aft of the secondary heater matrix, then it may have been removed by employing a third matrix aft of the second. As the degree of precaution increases aft along the blade chord, the magnitude of run-back ice formations decreases rapidly, such that it is unlikely that a third matrix will be necessary.

6 Two-Dimensional Computational Ice Accretion Prediction

6.1 Introduction

The necessity to improve and modernise the present spraymat design method has already been discussed in detail in the chapters entitled "Commercial Justification" and "Technical Justification". The basic components of the spraymat design system include prediction the ice catch area and catch efficiency distribution, followed by detailed electrical design of the actual heater mat pattern. This research programme is concerned primarily with the calculation of ice catch area and catch efficiency distribution. Research to improve the detailed electrical circuit design method will form a part of a subsequent research programme. There has been considerable progress in the technology surrounding ice accretion prediction since the development of the Lucas Aerospace approach emphasising past experimental test data from similar aerofoils, (Appendix B). Computer software capable of predicting aerofoil ice catch area and catch efficiency distribution has been developed and verified by a few aerospace organisations. For commercial reasons, this software created by other, competing, organisations such as NASA, Boeing, NLR, etc., is not available to Lucas Aerospace. However, a software system has been created at RAE Farnborough which is available to Lucas Aerospace. The RAE software was developed with the aim to predict helicopter rotor blade icing. Although useful to Lucas Aerospace in applications in its present state, it requires considerable development for use in engine air intake duct icing cases.

As detailed earlier ("Commercial Justification"), aircraft engine air intake duct de-icing system design and manufacture forms a large sector of the business of Lucas Aerospace at Luton. Hence, the second and final major part of this research programme is to develop the RAE software for ice catch area and catch efficiency distribution calculation in engine air intake duct lip cases. This will also yield icing rate and ice accretion shape information.

The objectives of this part of the research are detailed in the following section, after which the existing RAE software is described. Development of the existing software and a description of new created software follows this before its comparison with the 'old' Lucas approach and experimental tests.

6.2 Objectives

The overall major objective of this part of the research programme is to develop existing software and create new software where necessary, to predict icing catch area and catch efficiency distribution for engine air intake duct lips. Duct icing further aft of the lip, well inside the duct and perhaps as far downstream as the engine face, is to be addressed in subsequent research programmes. In order to effect this major objective, the following minor objectives were also addressed.

1. Convert the existing software to standard Fortran 77 from its existing state involving many VAX ('Digital') extensions to Fortran 77. It is the intention of Lucas Aerospace to install a computing system in the engineering department, capable of running the software system resulting from this research project. The new system will also serve all of the computing requirements of the department. This will eventually include: some CAD/CAM, PCB design, F.E. stressing, general Fortran, basic and Pascal, proprietary software packages (e.g. Lotus 123 spreadsheets), and already existing Lucas Aerospace software. Thus, as there are no VAX systems at Lucas (Luton), but several MSDOS operating systems to which the staff are already familiar, the new system will run under MSDOS in the short term. At a later date this will be superseded by the new OS/2 (multi-tasking DOS) operating system as it develops. By converting the software to standard Fortran 77 to enable running it under OS/2, means that it is still able to run under VAX/VMS, with only a few minor modifications, should the need arise.

2. Gain a full understanding of the existing software and comment it accordingly such that the software does not become dependent on one operator already familiar with the typical algorithms employed, but may easily be "picked up" and understood by a new user. This involves adding comments throughout the coding explaining each step within the coding, providing a notation key, and labelling all input/output points. Hence, what is first required is a full understanding of the functioning of the software.

The software was in the form of a single Fortran program having nineteen subroutines written by different authors, and compiled into one program by a single author. Hence there is a great deal of interface work between subroutines, involving much name changing of variables and "cross-overs" of data. This objective therefore became a major task.

3. Maintain a "simple aerofoil" version of the original software, adapted to run on the new computer hardware, to apply to helicopter rotor blade and other quasi-two-dimensional aerofoils.

4. Consider validation of the resulting new design tool. For financial reasons (detailed later), a specific experimental test programme could not be employed for validation purposes only. However, a longer term full validation programme is initiated using available experimental data. The intention (as described in a subsequent section) is to employ the new method in parallel with the 'old' on commercially financed tests until sufficient validation data is accumulated to justify using only the new method thenceforth. This is common practice in industrial engineering projects, where the financial resources required for immediate validation are neither available nor commercially justifiable in comparison with the aforementioned approach.

Additional validation is possible in this project from theoretical considerations in conjunction with the validation of the original RAE software (as described later).

6.3 Existing Software

The existing software obtained from RAE is in the form of a Fortran program computer model written by R. W. Gent (Acknowledgements). Its function is to predict ice catch limits, ice catch efficiency distribution, ice accretion rate distribution and ice accretion shape, for an arbitrary body of a profile not too dissimilar to a typical aerofoil. To clarify the previous statement; the body should not possess sharp corners, (except at the trailing edge), which introduce unacceptable errors in the flow prediction method. The approach applies to steady two-dimensional compressible flow.

Briefly, the program functions in the following manner. The orthogonal velocity components of the airflow (XS,YS) are determined (non-dimensionalised with respect to ambient flow velocity), at all points within the flow field (ie. the area in which the droplet trajectories will eventually lie). The droplet trajectories to yield the ice catch limits are calculated. This is effected using the equations of motion of the droplets, ignoring gravity due to infinitesimal mass relative to the magnitude of the ambient flow speed. Droplet inertia gives rise to orthogonal velocity components for the droplet relative to the airflow direction as the airflow deviates from the ambient direction, to flow around the body. The two major influences on a droplet therefore are its inertia (relative to the body) and drag from its velocity relative to the local airflow (calculated using the low Reynolds number Stokes Laws). The method uses a 'time-marching' approach applying the droplet equations of motion at each step. It starts from a point seven aerofoil chords ahead of the aerofoil leading edge along a line representing an upstream extension to the aerofoil chord. This line is deflected through an angle α , to simulate aerofoil incidence. The new position of the droplet is continuously updated at each time step, until impact with the aerofoil occurs or the droplet travels past 30% chord where a "MISS" trajectory is assumed (ie. the trajectory is assumed never to impact on the aerofoil). This assumption of no ice accretion aft of 30% chord is made simply to minimise the computer program run time, the limit itself actually being a variable in the case data, and not fixed at 30%.

Originally, a full CFD approach to calculating the flow velocities was adopted using the VGK (viscous Garabedian and Korn) software developed at RAE. VGK is not suitable for iterative procedures ie. to calculate the flow velocity at each point before calculating the droplet motion. This is carried out at every point in the flow which could be occupied by a droplet and this would lead to very long computer run times. Thus in a former version of the program "TRAJICE", employing this approach, the VGK program was first run separately, to develop a large matrix of stored flow velocity components at all points on a grid around the aerofoil. A major drawback to this method was that a large part of the matrix stored numbers never to be used. Only the relatively small droplet trajectory part of the whole flow field is actually required. Secondly, using this method, only the velocities at the grid points are calculated, requiring linear two-dimensional interpolation for the actual droplet

point velocities, thus introducing an error and requiring three separate grid point velocity sets to be calculated first.

Thus the second generation of the program developed at RAE, "TRAJICE2" employed a 'PANEL' method, written by S. Fiddes (Acknowledgements) in place of VGK to store "panel strengths" (flow circulation) for the aerofoil. From these panel strengths the flow velocity components may be quickly and relatively easily calculated in a time marching determination of droplet trajectory. The aerofoil is assumed to be constructed of a large number of small straight panels (typically around 150 in number). For each panel, the panel strengths GAM1 and GAM2 are stored. GAM1 and GAM2 are the panel circulation at 0° and 90° aerofoil incidence respectively. The overall panel circulation for a given aerofoil incidence (ALFA) is calculated using:-

$$GAM = GAM1 \cos\alpha + GAM2 \sin\alpha$$

In this manner subsequent icing predictions at different aerofoil incidences may be made without re-running the panel strength generation section of the program, thereby minimising computer run time. Thus the new program requires less storage space, runs faster and avoids the previously mentioned position/velocity error. As the droplet approaches the aerofoil flowfield in its march along a trajectory, the local flow velocities are calculated from the panel strengths, according to which panel has its perpendicular through its midpoint closest to the droplet. From this point, using the modified droplet inertia:-

$$K_0 = K \cdot \frac{\lambda}{\lambda_s} \quad (\text{Ref.14})$$

where: λ_s = range of a particle, diameter D, launched in still air with velocity V, assuming Stokes law holds.
 λ = actual range of the particle

$$\frac{\lambda}{\lambda_s} = \left[1 + 0.0967 \text{Re}_A^{0.6367} \right]^{-1}$$

$$K = \frac{c_D D^2 V}{18\mu c} \quad \text{Re}_A = \frac{c_A V D}{\mu} \quad \mu = \frac{(1.564 \times 10^{-6} T_\infty^{1.5})}{(T_\infty + 410.9)}$$

where: Re_A = Reynolds number for air

K = droplet inertia parameter
 μ = air viscosity
c = chord or characteristic length
V = freestream velocity
 c_A = air density
 c_D = droplet (water) density

and drag,

$$C_D = \frac{24}{Re} \left[1 + \frac{3Re}{16} \right]$$

the droplet new orthogonal velocities (US,VS) and thence new position (XS,YS) are calculated for the next time step.

Impact ("HIT"), or otherwise ("MISS") of the droplet with the aerofoil is determined. For impact cases, the location of the impact on the aerofoil is known from a comparison of the droplet location on its trajectory, and the aerofoil co-ordinates. The initial location from whence the droplet travelled ie. its "y₀"-ordinate seven chords ahead of the aerofoil leading edge, and its impact point on the aerofoil, plus similar values for a second droplet initiated close to the first are known. The relative difference in distance between the two impact points on the aerofoil measured over the aerofoil curved surface "d(S/C)" and that between the two start points "dY₀" (straight line perpendicular to ambient flow), yields the local catch efficiency ie. "S_{init}/S_{imp}". "S_{init}" is the distance between the start points and "S_{imp}" is the surface distance between impact points. Thus by employing a series of droplet trajectories between the upper and lower aerofoil surface ice catch limits, the catch efficiency distribution is determined. Catch limits are defined where impact is tangential to the aerofoil surface, or in other words, the droplet trajectory is parallel to the aerofoil surface within a reasonably fine tolerance, (less than 0.00001 Y/C from the latest "MISS" trajectory).

To calculate the ice accretion rate requires knowledge of the freezing fraction ie. the fraction of impacting water which freezes at the point of impact. The freezing fraction is determined from the thermal characteristics of the system, ie. kinetic heating, evaporative cooling, sublimation, etc.. Hence the surface heat transfer coefficient is required, which differs within the boundary layer according to whether the local flow is laminar or turbulent. The boundary layer transition point position depends on the surface smoothness. The smooth surface Reynolds number is given by:

$$Re_{\theta} = U_e \cdot \frac{\theta_1}{\nu} \geq 162 \quad (\text{Ref.14})$$

where:

U_e = velocity at the edge of the boundary layer

θ₁ = laminar boundary layer momentum thickness

ν = air kinematic viscosity

and using Thwaites formula:

$$\Theta_1^2 = \frac{0.452\nu}{U_e^6} \int_0^s U_e^5 dy \quad (\text{Ref.14})$$

where:

s = distance from the airflow stagnation position

and the rough surface Reynolds number is given by:

$$R_{ek} = U_k \cdot \frac{K_s}{\nu} \geq 600$$

where:

U_k = velocity at height K_s from the surface

K_s = equivalent sand grain roughness of the surface

and:

$$\frac{U_k}{U_e} = \left[2 \left[\frac{K_s}{\delta} \right] - 2 \left[\frac{K_s}{\delta} \right] + 2 \left[\frac{K_s}{\delta} \right]^4 \right] + \frac{\$}{6} \left[\frac{K_s}{\delta} \right] \left[\frac{1 - K_s}{\delta} \right]^3$$

where:

$$\$ = \frac{\delta^2 \cdot dU_e}{\nu ds} \quad (\text{Ref.14})$$

δ = boundary layer thickness, determined using approximation:

$$\delta = 8.5 \Theta_1$$

Thence the laminar heat transfer coefficient is calculated using:

$$h_1(s) = \frac{0.296\sigma}{\sqrt{\nu}} \left[U_e^{-2.88} \int_0^s U_e^{1.88} ds \right]^{-0.5} \quad (\text{Ref.14})$$

where:

σ = air thermal conductivity

and the turbulent heat transfer coefficient is calculated using:

$$h_t(s) = St \rho U_e C_p$$

$$= \left[\frac{C_f/2}{Pr_t + \sqrt{St_k} \cdot C_f/2} \right] \rho U_e C_p$$

where:

St = Stanton number

ρ = air density

C_p = air specific heat capacity

C_f = skin friction coefficient

Pr_t = turbulent boundary layer Prandtl number

St_k = roughness Stanton number

$$\frac{C_f}{2} = \left[\frac{0.41}{\ln \left[\frac{864\theta_t}{K_s} + 2.568 \right]} \right]^2$$

where: θ_t = turbulent momentum thickness, given by:

$$\theta_t(s) = \frac{0.036\nu^{0.2}}{U_e^{3.29}} \left[\int_0^s U_e^{3.86} ds \right]^{0.8} + \theta_{lt} \quad (\text{Ref.14})$$

and: θ_{lt} = laminar momentum thickness at transition

$$St_k = 1.92 \left[\frac{U_\tau K_s}{\nu} \right]^{-0.45} Pr^{-0.8} \quad (\text{Ref.14})$$

where: U_τ = shear velocity at the surface, given by:

$$\frac{U_\tau}{U_e} = \left[\frac{C_f}{2} \right]^{0.5}$$

Runback water is additional in the integration system for the next downstream point. Hence the actual remaining fraction of the impacting water, plus water which has run back from a further upstream point, is determined and frozen. Its volume is determined from a knowledge of ice density. Two methods of determining ice density are selectable within the program, one involving a continuous variation of density with temperature, and the other being the use of two discrete values (rime or glaze) dependent on temperature.

Once the ice volume is known and local catch area, the ice thickness follows and subsequent accretion rate. It is then only a

matter of extrapolating the ice growth rate over the time period spent in the icing conditions to derive the ice accretion shape. The desired 'time-in-icing' is an input variable to the program in input file TRAJICE2.DAT.

A further modification to the program caters for cases where the flow characteristics are essentially equal to those of a previous case, e.g. only a change of incidence or icing encounter duration time. The ice catch distribution, icing rate and accretion shape may be rapidly calculated from a set of gradients and intercepts of the ice catch efficiency distribution curve, (non-dimensional with respect to ambient flow velocity and aerofoil chord), stored in a data file during the previous case. For relatively long 'time-in-icing' cases, the airflow over the aerofoil may be changed considerably by the effect of the ice accretion on the aerofoil shape. In these cases the total 'time-in-icing' is divided into several periods based on some suitable criterion (such as a maximum single period of two minutes), and run as a series of consecutive cases. During the first case, the actual co-ordinates of the iced aerofoil (ie. aerofoil plus ice shape) are stored (ICEFOIL.DAT) for input as the "start" ('clean') aerofoil (CRD.DAT) for the subsequent case, and so on. Thus errors caused by the continuous employment of a 'clean' aerofoil are reduced to a level where the ice accretion shape prediction for icing times in excess of ten minutes compares well with experimental test cases (Bib.932).

The validation of TRAJICE2 is extensively and positively effected within (Bib.932), including its sensitivity with respect to Mach number, incidence, chord, water droplet diameter, flow liquid water content, ambient pressure and ambient temperature. The program is further validated using the results from other experimenters employing different software. Even though these different computer programs make use of entirely different approaches to the same problem, the results are "remarkably similar" (Bib.932), which adds considerable credence to the results from the RAE program. The reason for the use of other software to aid validation, as stated in (Bib.932), is the lack of relevant experimental or flight icing data.

6.4 Software Development

One of the stipulations of standard Fortran 77 is that file names must not exceed six characters in length. Thus the developed version of TRAJICE2 became TRAJ2. During its development the program has become quite sophisticated and not easily understood. It took a long time and close scrutiny to gain a full working knowledge of the details and a great many comments were added to the coding. These serve to aid its understanding by subsequent users and also, of greater importance during the research programme, to maintain a knowledge of its contents whilst further developing it and producing additional programs.

The aerodynamic panel method (briefly described earlier) is autonomous in subroutine FOIL, written by S. Fiddes ('Acknowledgements'). The panel method is based on flow circulation,

and thus one of the pre-requisites mandatory to the functioning of FOIL within TRAJ2 is that the aerofoil (or other body in consideration), must have a "closed" trailing edge, ie. the locus of the aerofoil co-ordinates must be continuous and have no end. Another requirement is that the trailing edge be 'sharp' in order to satisfy the Kutta condition, to fix the aft stagnation point at the trailing edge. TRAJ2 is designed to work with an aerofoil in a free stream, which may be rotated to a positive value of incidence, (negative incidence is effected by inverting the aerofoil).

The air intake lip is not a complete aerofoil, but usually takes a form similar to the "nose" part of an aerofoil. It has neither a sharp nor a closed trailing edge. Furthermore, the intake lip is not in a freestream flow. It experiences a "dual" flow, divided at the forward stagnation point, one air flow division travelling over the outside surface of the air intake and the other entering the duct to eventually flow through the engine. Thus the intake lip does not satisfy the requirements for FOIL or TRAJ2. To meet the requirement for a "closed" trailing edge, an afterbody must be added to the lip to form an aerofoil. This could be carried out by appropriate additional software within TRAJ2, but clearly a favourable approach is to compile a new program which is capable of reading the intake lip co-ordinates, creating an afterbody and presenting the total aerofoil co-ordinates to TRAJ2 in the appropriate data file (CRD.DAT). This approach is advantageous as TRAJ2 remains relatively unchanged as a useful origin to relate to.

Consider a two-dimensional elliptical body (or aerofoil with a rounded 'blunt' trailing edge) in a steady two-dimensional airflow of mid subsonic speed (Mach 0.5). The rounded trailing edge means that both the fore and aft stagnation points are free to locate themselves according to the flow circulation around the body. The relationship between the flow velocity distribution around the body and the incidence of that body to the freestream ambient flow direction is unique. That is, for an identical body, equal speed and equal incidence, the flow is identical. Applying a sharp trailing edge (ie. replacing the ellipse with an aerofoil), the aft stagnation point is fixed at the trailing edge (Kutta condition). Consider two bodies of identical 'nose' section and slightly different 'tail' section at the same incidence and speed. The previous relationship between incidence and the flow is no longer unique, but 'non-unique' to a level dependent on proximity of the test point to the leading edge (ie. away from the trailing edge). For moderate values of incidence, the distance between the natural location of a 'floating' aft stagnation point for a rounded trailing edge aerofoil and the actual trailing edge (assuming a Kutta condition), is very small. Hence for aerofoils of reasonable chord (ie. not excessively short) the error introduced in the flow velocities in the leading edge area for small values of incidence are small.

An aircraft engine air intake lip in flight experiences two flows separated by the forward stagnation point. The flow over the outside surface of the duct, ie. outside the locus of forward stagnation points, is equal to the ambient flow with associated influence due to

the presence of the body, (lip aerofoil). The flow to the other side of the forward stagnation point, ie. inside the duct is influenced by the function of the intake to provide the engine with the correct air mass flow rate at an acceptable flow speed. In a cruise condition, the intake reduces the flow speed within the duct, and conversely during take-off it increases the flow speed in the duct. This change in flow speed within the duct has the effect of changing the location of the forward stagnation point on the duct lip. The same effect may be achieved by a change in aerofoil incidence. If the duct is initially at zero incidence, then by increasing the incidence of the simulating aerofoil in a freestream flow until its forward stagnation point is in the same place as that on the lip aerofoil in dual flow at zero incidence, then the flow around the forward area of the simulating (freestream) aerofoil is identical to that in the same area of the 'dual flow' (actual) lip aerofoil. Comparing an aerofoil with an intake lip profile, there are small differences in the local flow velocities around the trailing edge regions, due to the Kutta condition which fixes aft stagnation at the sharp trailing edge in the 'free' aerofoil case. Hence the flow in the vicinity of the aftmost panels, (ie. close to the aft stagnation point), is different for the two bodies. Thus the overall flow is not quite identical as the actual local flow velocities at each point around the subsonic body are dependent upon the circulation around each and all of the panels. However, the level of dependence varies according to the distance of the panel from the point in question. Thus, in the short term first approach, and to the level of accuracy required for de-icer design purposes these differences are usually small and outside the area of interest. In the longer term towards the end of the project, and detailed later, the software was modified to allow a 'blunt' trailing edge afterbody in engine air intake cases by variation of circulation instead of incidence, thus freeing the aft stagnation point and eliminating this error.

6.5 New Software

The new software was introduced in two stages to better fit within the departmental work schedules of the sponsoring company. In the short term, to provide a current working ('approximating') solution by varying incidence of the simulating aerofoil, the main RAE program 'TRAJ2.FOR' remained effectively unchanged. A 'pre-processor' program 'PTRAJ2.FOR' was created to run prior to TRAJ2 (Fig.44(a)). PTRAJ2 takes the engine air intake duct lip geometry from input file 'LIP.DAT' and extends the lip aft to form a complete aerofoil. It then calculates the value of incidence necessary to apply to this aerofoil in order to move the forward stagnation point to a desired position. The stagnation point position required is input in the case data input file 'LTRAJ2.DAT' and is equal to that of the engine air intake duct, acquired either from experimental test or predicted from experience. Except for the case of an axisymmetric inlet at 0° incidence and 0° sideslip, due to the three-dimensional flow effects, it is not feasibly possible, within this two-dimensional software suite, to calculate the desired forward stagnation point ordinates.

In the longer term solution, employing variation of circulation rather than incidence, a different pre-processor program ('PTRAJ3.FOR') was created to run prior to a modified version of the RAE program, (now 'TRAJ3.FOR'). There are two basic differences between the long and short term solutions. PTRAJ3 differs from PTRAJ2 in that the intake lip is developed into an aerofoil with a 'blunt' (rounded) trailing edge, as opposed to the more usual 'sharp' trailing edge of PTRAJ2. In the PTRAJ3/TRAJ3 case, achievement of the desired positioning of the forward stagnation point is effected in the main program 'TRAJ3', whereas in the earlier PTRAJ2/TRAJ2 case, it occurs in the pre-processor 'PTRAJ2'. In the new version, the aerofoil incidence remains unchanged at the value input for the lip in the case data input file 'LTRAJ3.DAT'.

PTRAJ3 and TRAJ3 supersede PTRAJ2 and TRAJ2 for intake lip simulation cases, PTRAJ2 becoming redundant. TRAJ2 remains applicable to 'non-lip', normal, 'free-flying', single flow system, 'sharp' trailing edged, complete aerofoils.

6.5.1 LIP.DAT

This is an input file to the pre-processor(s) (PTRAJ2/3). It contains the geometry for the engine air intake duct lip. The co-ordinates may be entered to any consistent scale (as for CRD.DAT in conjunction with TRAJ2/3). The abscissae of the leading edge and lip trailing edges are also entered separately, in metres, for scaling purposes, (XLE, XTEU, XTEL), allowing the upper and lower surfaces to be scaled separately. This has proven a useful option for intake lips constructed from the upper and lower surfaces of different aerofoils for which the co-ordinates are available on different chord lengths. It also maintains flexibility for further modification, as the long term aim to employ the new de-icer design method to aid designing the duct (or other body) with de-icing in mind from the initial concept stage. It also allows the co-ordinates to be supplied in either dimensional or non-dimensional form. A further, and probably most useful advantage of this method of data storage is that it is suited to taking the curves from drawings using a digitising 'mouse'. The leading and trailing edge ordinate points of both surfaces are entered, (ie. the leading edge of the lip features twice in the file).

As for CRD.DAT, LIP.DAT caters for symmetrical lip profiles, where only the upper surface need be supplied.

ISYM = 0	asymmetrical
ISYM = 1	symmetrical

A symmetrical lip carries a further complication over a symmetrical aerofoil in that one surface may continue further aft (downstream) than the other. Usually the lower surface (intake inner surface) will be known to a greater partial length of the eventual simulating chord than the upper (Fig.46). These cases are catered for by employing "ISYM=1" to indicate symmetry is present. The data must be arranged such that the symmetrical parts of the profiles utilise the same data

point numbers aft of the leading edge (ie. have the same abscissae), and thus the difference in curve lengths is indicated by the different numbers of points entered for each curve, (ie. NU is not equal to NL).

NU = number of points on upper curve (including l.e.)

NL = number of points on lower curve (including l.e.)

The complete upper surface curve is entered. In the most common cases, where the lower surface curve is of the greater length, then only the additional curve is entered ie. x(NU+1) to x(NL) and corresponding y-values. Conversely, intake lips exhibiting a longer (streamwise) upper surface (intake outer surface) profile curve than lower, are dealt with by only entering the upper curve. The lower curve is derived by reflecting the first part of the upper curve as far aft as the number of points required for the lower surface (NL) indicates. It will be noted that in symmetrical cases, the lip leading edge only features once. XTEU and XTEL are always entered, irrelevant of symmetry and must be in metres to allow scale fixing. A sample LIP.DAT file appears in Table 10(a).

6.5.2 LTRAJ2.DAT

LTRAJ2.DAT (Table 10(b)) is the case data input file for PTRAJ2.FOR, taking the same format as the input file TRAJ2.DAT for TRAJ2.FOR, except that 'ALFA' (incidence) is replaced by 'XSTAG' (abscissa of the desired forward stagnation point), and 'CHD' (aerofoil chord) is replaced by 'CLE' (lip simulating aerofoil chord generation factor). A positive value of XSTAG indicates that stagnation occurs at XSTAG value of x on the upper surface of the lip, whereas a negative value indicates the lower surface. XSTAG must be supplied to the same scale as the lip ordinates of the surface to which it applies, ie. if stagnation occurs on the lower surface and the lower surface co-ordinates have been supplied in millimetres, whereas the upper surface co-ordinates have been supplied in inches, then XSTAG must also be supplied in millimetres. A zero value of XSTAG indicates that stagnation occurs on the leading edge. The leading edge, for co-ordinate geometry purposes, is somewhat arbitrary when differentiating between upper and lower surfaces for intake lip profiles, but should be chosen so as to form the lip 'highlight', ie. the furthest upstream point when at designated zero incidence. CLE is explained in the description of PTRAJ2, where it is employed.

6.5.3 LTRAJ3.DAT

LTRAJ3.DAT (Table 10(c)) is the equivalent input file to LTRAJ2.DAT for application to PTRAJ3(.FOR). It is unique to PTRAJ3 as is LTRAJ2.DAT unique to PTRAJ2. LTRAJ3.DAT takes the same format as LTRAJ2.DAT with a few minor changes involving deletion of some inputs and addition of others. ALFA, the intake lip incidence replaces XSTAG and XSTAG moves to an additional line of inputs. CHD (chord) is removed altogether, thus it not being necessary to input an unused 'fictitious' value as in LTRAJ2.DAT. An additional input is BLF which is variable between 0 and 1.

XSTAG has the same function in PTRAJ3 as in PTRAJ2, ie. the desired forward stagnation point abscissa (this time always in metres), positive on the upper surface and vice versa. As for PTRAJ2, CLE is a factor to vary the generated chord and takes typical values of the order 1.0 to 1.5. BLF is a factor to allow variation of the level of 'blunting' of the generated afterbody trailing edge. BLF varies between 0 and 1. A value of 0.0 results in the trailing 35% of the sharp trailing edged aerofoil chord being blunted. A value of 1.0 corresponds to 5% chord blunting. The variation between is linear.

6.5.4 PTRAJ2.FOR

PTRAJ2 (Fig.44(a),45), is a Fortran program to be used in engine air intake duct lip cases, acting as a pre-processor to TRAJ2. Its function is two fold. Firstly, to create an afterbody on the lip of LIP.DAT. This forms a complete 100% chord aerofoil, which is output to the aerofoil geometry input file for TRAJ2 (CRD.DAT - Table 11). Secondly, to calculate the incidence value (ALFA) to apply to this new aerofoil to effect a stagnation point at the desired stagnation point location specified (XSTAG) in the case data input file (LTRAJ2.DAT).

The afterbody profile is created in the following manner. A new chord length for the total aerofoil to be formed is chosen by predicting suggested values for the upper and lower surfaces. This is performed from a knowledge of the foil thickness (YU(NU)-YL(NL)), (YL is negative on the lower surface), and profile gradients (GRDTEU and GRDTEL for upper and lower surfaces respectively) at the aft limits (XU(NU) and XL(NL)) of the given lip. A relatively simple algorithm is employed to generate new chords, with four subcases to allow for positive and negative lip trailing edge gradients on upper and lower surfaces.

Surface	Lip t.e. gradient	Algorithm
Upper	+ve	$CHDU = CLIPU \times 3^{(CLE + GRDTEU)}$
Lower	-ve	$CHDU = CLIPU + (YU(NU) \times \frac{0.95^{(1/CLE)}}{GRDTEU})$
Upper	+ve	$CHDL = CL IPL \times 3^{(CLE - GRDTEL)}$
Lower	-ve	$CHDL = CL IPL - (YL(NL) \times \frac{0.95^{(1/CLE)}}{GRDTEL})$

where:

CHDU = preliminary upper surface aerofoil chord

CHDL = preliminary lower surface aerofoil chord
CLIPU = original lip upper surface chord
CLIPL = original lip lower surface chord
CLE = factor to allow chord choice variation (input in
LTRAJ2.DAT, typically 1.0 - 1.5), (Figs.P1-P5)
GRDTEU = original lip trailing edge gradient, upper surface
GRDTEL = original lip trailing edge gradient, lower surface
YU(NU) = ordinate of last point on original lip trailing edge,
upper surface
YL(NL) = ordinate of last point on original lip trailing edge,
lower surface

The greater of the two suggested values (CHDU and CHDL) is chosen as the new aerofoil chord (CHD), which is formed from an extension aft of the existing lip chord (ie. in the same direction : parallel), to the new calculated length (CHD).

Cubic splines are fitted on upper and lower surfaces from the lip trailing edges to the new aerofoil trailing edge. The splines emerge from the lip trailing edges with the same gradients and curvatures as the lip trailing edges, to form a smooth aerofoil. From these splines a series of co-ordinates are generated, 76 on either surface. It is intended to make this number a variable requestable within the input data. Due to the vast number of occasions and second order occurrences it affects within PTRAJ2, TRAJ2, PTRAJ3 and TRAJ3, this modification has been deferred until a later date. The generated co-ordinates (ie. those on the afterbody), correspond to abscissae located at equal divisions of θ on the transformation:

$$\cos\theta = 1 - 2x$$

such as to conglomerate points near the ends of the spline where the greater curvatures usually occur. This corresponds to the leading and trailing edges of the afterbody.

The spline fitting is carried out in subroutines "SPLINE" and "SPLINT" taken from "Numerical Recipes" (see PTRAJ2.FOR coding) where their functions are described thus. "Given arrays XS and YS of length N containing a tabulated function, ie.

$$Ys_i = f(Xs_i)$$

where the xs_i are ordered, and given values Yp_1 and Yp_n for the derivative of the function at the first and last points respectively, 'SPLINE' returns the array Y2(n), which contains the second derivatives of the interpolating functions at the given Xs_i . If Yp_1 and/or Yp_n are greater than 1.0 then the natural spline is selected, ie. zeroⁿ curvature at the end of the given range". Where in PTRAJ2.FOR:

upper surface XS array = TU array
 YS array = YU array
 Y2 array = YU2 array
 N = NU

$$Y_{p1} = 0.0$$

$$Y_{pn} = 0.0$$

lower surface XS array = TL array
 YS array = YL array
 Y2 array = YL2 array
 N = NL
 $Y_{p1} = 0.0$
 $Y_{pn} = 0.0$

"Thence given the arrays Xa, Ya and Y2a containing a function Y(X) and second derivatives respectively, and a value of X, 'SPLINT' returns the interpolated value Y via a spline fit", where in PTRAJ2.FOR:

upper surface Xa array = TU array
 Ya array = YU array
 Y2a array = YU2 array
 N = NU

lower surface Xa array = TL array
 Ya array = YL array
 Y2a array = YL2 array
 N = NL

The incidence required to effect the desired forward stagnation point is calculated.

$$ALFSTG(I) = ATAN2 (GAM1(I), - GAM2(I)) \times 180.0/\pi$$

where GAM1 and GAM2 are the panel strengths at each panel for aerofoil incidences of 0° and 90° respectively, as described in "TRAJ2.FOR". ALFSTG(I) is the aerofoil incidence necessary to locate the forward stagnation point at the point X(I),Y(I).

Panel strengths are determined in exactly the same manner as in TRAJ2.FOR using the same subroutine ('FOIL') from TRAJ2 in PTRAJ2. The new 'total chord' aerofoil co-ordinates are output to CRD.DAT for input to TRAJ2.FOR. For intake cases the two absent parameters (CHD and ALFA) required for TRAJ2 are supplied by PTRAJ2. The other case data required in TRAJ2.DAT is read from LTRAJ2.DAT and written to TRAJ2.DAT by PTRAJ2, maintaining the correct format for TRAJ2.

Also output from PTRAJ2 is a file containing the non-dimensional aerofoil co-ordinates, and panel strengths in a standard TEMPl.DAT file format (Table 12(a)), (Fig.44(a)), required by TRAJ2 for a "fast", "similar case" executed (as explained in "Existing Software"). There is also an option in PTRAJ2.FOR to only create the complete aerofoil and plot it out (PLOT.DAT), (Fig.44(a)), for prior inspection before attempting to calculate panel strengths.

6.5.5 PTRAJ3.FOR

As explained earlier, PTRAJ3.FOR is an updated modified version replacing PTRAJ2.FOR in the longer term solution. As in PTRAJ2, PTRAJ3 reads in the lip geometry from LIP.DAT and case data from LTRAJ3.DAT, (Fig.44(b)). An afterbody is created and added to the lip to form a complete aerofoil. The same subroutine 'AFTBDY' from PTRAJ2.FOR is applied to create a 'sharp trailing edge' afterbody. Then a further subroutine 'BLUNT' effectively replaces the aftmost part of the aerofoil with a 'rounded' trailing edge formed from parabolic arcs.

The degree of 'blunting' of the sharp trailing edge is determined by a control factor "BLF". BLF is input in LTRAJ3.DAT and varies from 0.0 to 1.0 corresponding to the aft 35% to 5% chord of the aerofoil becoming parabolic respectively, ie. 65% to 95% remaining the original afterbody profile of the sharp trailing edged version. The parabolas are fitted tangential to the existing lip trailing edges, and meet at the total aerofoil trailing edge perpendicular to the aerofoil chord. They are created using:

$$x = x_0 + \frac{2t(s_1(x_1 - x_0))}{(s_1 - s_0)} + y_0 - y_1 \\ + \frac{t^2(2(y_1 - y_0))}{(s_1 - s_0)} - (x_1 - x_0)(s_0 + s_1))$$

and

$$y = y_0 + \frac{2s_0t(s_1(x_1 - x_0))}{(x_1 - x_0)} + y_0 - y_1 \\ + \frac{t^2((y_1 - y_0)(s_0 + s_1))}{(s_1 - s_0)} - 2s_0s_1(x_1 - x_0))$$

where:

x_0, y_0 = start point

x_1, y_1 = finish point

s_0, s_1 = start and finish slopes (gradients) respectively

t = current distance on x-axis measured from x_0 .

but: $s_1 = \pm \infty$
 $y_1 = 0$

therefore:

$$x = x_0 + 2t(x_1 - x_0) - (x_1 - x_0)t^2$$

$$y = y_0 + 2s_0t(x_1 - x_0) - t^2(y_0 + 2s_0(x_1 - x_0))$$

where:

upper surface	$x_0 = XU (NU)$	
	$x_1 = CHD$	(chord)
	$y_0 = YU (NU)$	
lower surface	$x_0 = XL (NL)$	
	$x_1 = CHD$	
	$y_0 = YL (NL)$	

The second parabola is fitted from the new upper surface trailing edge (total aerofoil chord), perpendicular to the aerofoil chord line, to meet the lower surface afterbody profile tangentially at the same abscissa as the point where the upper surface parabola is tangential to the upper surface afterbody. This approach is adopted to avoid small 'steps' at the aerofoil trailing edge resulting from differential 'round-off' of converging curves from independent origins.

PTRAJ3.FOR contains subroutine 'FOIL' as in PTRAJ2, taken from TRAJ2. In PTRAJ3, FOIL calculates the panel strengths in a modified manner to that of TRAJ2 and PTRAJ2. A third panel strength 'GAM3' multiplied by a factor ψ is added. $\psi \cdot GAM3$ is a circulation applied to the panel irrespective of the onset flow. GAM3 is a constant circulation such that the total $\psi \cdot GAM3$ may be varied in magnitude by variation of the factor ψ . Thus effectively, the total panel circulation in the absence of any onset flow would be equal to $\psi \cdot GAM3$. $\psi \cdot GAM3$ is added to the GAM1 and GAM2 components of circulation in onset flow to achieve a new total circulation in onset flow where the forward stagnation point has moved to the desired location. Thus with the forward stagnation point at the correct required location, the total circulation in onset flow is composed of the three components: $GAM1 \cdot \cos \alpha$, $GAM2 \cdot \sin \alpha$ and $\psi \cdot GAM3$, ie:

$$k = GAM1 \cdot \cos \alpha + GAM2 \cdot \sin \alpha + \psi \cdot GAM3$$

where: α = aerofoil incidence

GAM1 = panel strength in onset flow with natural forward stagnation point location (ie. $\psi = 0$) at an aerofoil incidence $\alpha = 0^\circ$.

GAM2 = panel strength in onset flow with natural forward stagnation point location ($\psi = 0$) at an aerofoil incidence $\alpha = 90^\circ$.

GAM3 = constant circulation component which when multiplied by ψ and added to $GAM1 \cdot \cos \alpha$ and $GAM2 \cdot \sin \alpha$ forces the forward stagnation point into the desired position.

ψ = factor by which to multiply the constant circulation GAM3 to achieve the desired total circulation to effect the required forward stagnation point location.

The desired forward stagnation point location is input as variable 'XSTAG' in input file LTRAJ3.DAT, from which the factor is derived through a DO LOOP test similar to that applied in PTRAJ2, mentioned earlier, where the incidences required to make each point a stagnation point were developed.

The aerofoil incidence (ie. lip incidence) α input in LTRAJ3.DAT, remains unchanged.

An output file TEMP3.DAT of non-dimensional aerofoil co-ordinates and panel strengths is formed as in PTRAJ2 (TEMP1.DAT), but includes the extra panel strength GAM3, (Table 12(b)), (Fig.44(b)).

6.5.6 TRAJ3.FOR

TRAJ3.FOR with its pre-processor PTRAJ3.FOR replaces TRAJ2.FOR with its pre-processor PTRAJ2.FOR in intake lip cases. TRAJ2.FOR without pre-processor is required for 'free-flying aerofoil' cases, leaving PTRAJ2.FOR no longer needed.

To create TRAJ3, TRAJ2 was modified in the same manner as PTRAJ3 varied from PTRAJ2, to accept the new three component circulation. As in TRAJ2 the panel strength generation need only be run the first time when successive executions are required at varying values of incidence or time in icing.

6.6 Validation

As explained shortly, it was not possible to effect a full specific validation program during the life of this research project. The preliminary validation of both the short term (PTRAJ2/TRAJ2) and long term (PTRAJ3/TRAJ3) new computational methods for the derivation of icing catch area and catch efficiency distribution on aircraft engine air intake duct lips is in three parts. Some experimental icing wind tunnel test data were acquired at the Lucas Aerospace 'Artington' icing tunnel (Ref.3): various assumptions could be drawn from the validation of the existing RAE icing software (Bib.932), and the basic theory was tested by comparison of the intake lip predicted ice accretion with the RAE 'free' aerofoil prediction.

6.6.1 Icing Tunnel Tests

Ideally, the validation would involve carrying out a series of tunnel tests on a specific two-dimensional model designed for this purpose. The financial cost of effecting such an experimental test programme for these validation purposes and not to provide any other commercial benefit is prohibitive, and not commercially justifiable when compared with the annual income resulting from intake de-icing system design and other approaches to achieving a working solution. Icing tunnels within the UK are limited in number (Bib.1144) and costly to hire. The low speed, sea level, 'Artington' tunnel is reasonably economic but experiences a continuous timetable of operation for customers worldwide. Therefore a financially preferable

preferable approach, commonly adopted in commercially oriented industries, is to accumulate validation data for the new method during normal operational testing of projects financially supported by customers on regularly scheduled test programmes. Thus the 'old' method is continued in use with the new method introduced alongside, but not used 'alone' until a sufficient validation database is accumulated. By adopting this approach large validation costs are avoided and otherwise financially unjustifiable modifications are incorporated. Had there been sufficient data available from previous tests relevant to validation of the new method then it would be possible to introduce the new method (alone) immediately. However, as explained earlier, such data is not currently available.

Therefore it was not possible during the project to carry out a series of tests specifically for this research project. The interim solution was to utilise a scheduled series of air intake tests, with a short additional test to indicate the leading edge stagnation point locations in a few flow conditions using a typical 'wooltuft' arrangement (Figs.51-58). The only current air intake tests available for such treatment involved an intake which was not ideal for the purposes of the project (Fig.46). The inlet possessed a rather small mouth diameter to maximum wall thickness ratio (as low as 2.0 in one place), and short streamwise length relative to wall thickness. This presented a rather strenuous test for the method.

Approximating the velocity flowfield thickness, perpendicular to the simulating aerofoil, to that of a cylinder:

Using $q_t = U \sin \theta (a^2/r^2 + 1)$ @ $\theta = \pi/2$ (Ref.20)

q_t = tangential velocity r = axisymmetric duct opening radius
 a = cylinder radius U = ambient velocity
 t = wall thickness $\theta = \pi/2$
 D = duct opening diameter

For $\frac{q_t}{U} = 1.1$ at the axis, $\frac{D}{t} = 3.16$

and when $\frac{D}{t} = 2$, $\frac{q_t}{U} = 1.25$

ie. a good working minimum ratio of duct diameter to wall thickness to apply in future cases to avoid excessive 3-D convergence effects would appear to be approximately 3.2.

The scheduled tunnel tests were planned for certification purposes and thus employed FAR 25 specifications for intermittent icing flow, and use of the de-icing system throughout the tests. One of the tests allows the ice to be accreted on the inlet for two minutes before the de-icing system power is switched on, and thus provides some ice catch limit and ice catch area information (Figs.60-63), but ice accretion thickness and accretion shape were not effectively established. Thus it was not possible to carry out a complete detailed validation program during the life of this research

project. However, a degree of preliminary validation was still feasible from the icing catch area and production of the correct panel strengths for the computational method (discussed later).

The variation in cross-sectional profile of the wall of the inlet from the upper vertical (0°), to the lower vertical (180°) provided a reasonable range of shape from which three profiles were chosen for the validation, being those at 90° , 135° and 180° , (Figs.47-49). The inlet is symmetrical about the vertical centre plane. Profiles at stations between 0° and 90° were not chosen because of the close proximity to the spinner, and various intrusions which were made to facilitate equipment, instrumentation and installation within the tunnel. After the series of scheduled tests, the inlet was removed from the tunnel and fitted with wooltufts at known locations (10 mm intervals), (Fig.50), before re-installing in the tunnel. There was insufficient time available to lower the temperature to -20°C . in the wooltuft test which was carried out at -15°C ., but the effect of a further 5°C . reduction in absolute flow temperature on the stagnation point location is negligible.

The test was effected by achieving the desired tunnel speed (111, 185 and 200kt), then observing the wooltufts as the speed was varied from slightly below the test nominal speed to slightly above. The stagnation point is indicated by the wool tufts. 'Fine tuning' of the stagnation point location between the tufts is then achieved by observing the movement of tufts as the speed is varied slightly, (Figs.51-58). Additional stagnation point location data was available from photographs recorded in the early stages of some of the scheduled icing tests. Water which impacted on the duct lip and 'ran back' before freezing, in a direction dependent on its impact point location relative to the stagnation point, mapped the locus of stagnation points around the lip.

From (Figs.51-58) it is noted that the locus of stagnation points includes an inflection near 135° due to the effect of a thermal sensor under the surface coating which is just visible in (Fig.59), causing a change in contour. From the wooltuft test (Figs.51-58) the stagnation point locations for speeds of 120 and 180 kt were determined for the lip profiles at 90° , 135° and 180° around the inlet (Table 14).

(Figs.60-63) represent four sample photographs from the non-de-iced, (de-icing system switched off) icing test mentioned earlier, for comparison of catch area with calculated values (detailed in the following sections). (Figs.60-63) are comparable with Cases 15-18 (Figs.P23-P26, P117-P120). Table 16 (Appendix B) presents a quick reference guide when comparing (Figs.60-63) with equivalent output plots from the computational predictions.

Due to the nature of the photographs of (Figs.60-63) it is not possible to make any accurate quantitative measurements of ice catch limits. Unfortunately at the time of testing the tunnel was urgently required for other work and the few figures presented represent all of the data that was recorded. There was not time available to make

measurements on the actual body surface and accreted ice inside the tunnel. However, several trends are notable.

(Fig.P118) indicates an upper/outer surface ice catch limit for the 90° lip section slightly aft of the extent of the original lip section on the 0.662 m chord simulating, blunt trailing edged aerofoil. Observing (Figs.60-63) it can be seen that the ice catch limit does extend to the lip trailing edge. There is a small region virtually clear of ice at the very edge of the lip where it meets the cowl. This is caused by the presence of the nacelle meeting the lip profile almost perpendicularly and thus causing a rapid change in flow direction, which results in a small change in droplet trajectory direction in this area. It is unfortunate that only an intake with this sudden geometry change was available during the programme.

However, the lower/inner surface ice catch limit of (Fig.P118) is only 38 mm aft of the leading edge (measured over the surface) compared with 83 mm for the 135° lip section (Fig.P119). Thus the inner surface ice catch limit of the 135° lip section extends 2.2 times as far aft as that of the 90° lip section. This is clearly reflected in (Figs.60-63), indicating the ability of the software to react to the body profile change between the two lip sections in a manner at least similar to that occurring in the tunnel test.

(Fig.P119) indicates a software prediction of 40 mm outer surface ice catch limit for the 135° lip section where the actual lip body profile extends 48 mm aft (over the surface). (Fig.60) appears to indicate a somewhat lesser catch length. However, during the test the light source illuminating the body was situated over a tunnel window in the roof of the tunnel and was not adjustable. Hence a shadow is cast over the lower outer region of the lip which has the effect of throwing some of the ice accretion into darkness. As the lip body is black (Erocoat) the catch limit appears to terminate further upstream than is actually the case. By careful observation of the lip outer surface in the 180° section area, ie. the lower vertical outer region, where a little more light appears to have been present, (probably due to reflection off the frosted tunnel floor), it can be seen that the actual ice catch in this area extends further aft than is first indicated by the shadowed area. Hence, returning to the 135° lip section in (Fig.60), it is quite possible that the outer aft ice catch limit is 40 mm aft of the leading edge. If attention is now turned to the 90° and 135° lip sections at the starboard side of (Fig.61) are observed, where a larger camera aperture was employed and the photograph was taken at a later time during the test after accretion of more ice and hence a dense white covering. It will be seen that the outer surface ice catch limits of 40 mm for the 135° lip section (Fig.P119), which itself extends 48 mm aft, and 50 mm for the 180° lip section (Fig.P120), which itself extends 62 mm aft, are much more evident. (Figs.62 and 63) of photographs taken at an even later stage in the test using an additional light source beneath a window in the tunnel floor clearly present the 135° and 180° lip section outer/lower surface catch limits and corroborate the above suggestions that (Figs.60 and 61) hide the true ice catch limits in the shadow cast by employing only a single light source. The inner surface ice catch

limit prediction for the 180° lip section is 63 mm compared with 83 mm for the 135° lip section. All (Figs.60-63) indicate a further downstream catch limit for the 135° lip section compared with the 180° lip section, the difference appearing to be approximately of the same order as that predicted.

Now employing the 'old' PTRAJ2/TRAJ2 predictions of (Figs.P23-P26) it can be seen that due to the incidence applied to achieve the correct forward stagnation point location, as discussed earlier, the ice catch is under predicted on the upper/outer surface and over predicted on the lower/inner surface. Taking the 180° lip section. Although the difference from the lower/inner section of 74 mm using the PTRAJ2/TRAJ2 method compared with 63 mm using the PTRAJ3/TRAJ3 method is not clearly obvious in (Figs.60-63), the upper/outer surface difference between 21 mm and 40 mm for PTRAJ2/TRAJ2 and PTRAJ3/TRAJ3 respectively is obvious, (Figs.62 and 63) clearly justifying the latter PTRAJ3/TRAJ3 approach.

Similarly for the 90° lip section, PTRAJ2/TRAJ2 applied incidence to the simulating aerofoil in order to position the forward stagnation point thereby under predicting the upper surface ice catch and over predicting the lower surface catch. Due to the short streamwise extent of the actual lip body upper surface (38 mm) it is not possible to observe the upper/outer surface ice catch limit of the PTRAJ3/TRAJ3 prediction (which is aft of 38 mm) on the experimental test photographs (Figs.60-63). The PTRAJ2/TRAJ2 prediction of 37 mm does not fall short of the ice catch limit observable, thus also not being contradicted by (Figs.60-63).

However, regarding the lower/inner surface, the PTRAJ2/TRAJ2 and PTRAJ3/TRAJ3 ice catch limit predictions for the 90° lip section, measured over the surface from the leading edge, are 55 mm and 38 mm respectively. As mentioned earlier, the PTRAJ3/TRAJ3 result is clearly confirmed and the preference for the PTRAJ3/TRAJ3 result over that from PTRAJ2/TRAJ2 equally indicated.

In the case of the 135° lip section, firstly it should be noted that in (Figs.P23 and P25) the lower surface catch limit marker on the plots is partially masked by the plot lower horizontal boundary and thus is not immediately apparent. Again, for the upper/outer surface ice catch limit it is difficult to show a software system preference between PTRAJ2/TRAJ2 and PTRAJ3/TRAJ3 from (Fig.60) due to the shadow mentioned earlier. However (Figs.62 and 63) indicate that the catch limit in this case extends definitely aft of the 32 mm prediction of PTRAJ2/TRAJ2 and is of the order of the 40 mm predicted by PTRAJ3/TRAJ3. In this case PTRAJ2/TRAJ2 under predicts the lower/inner surface ice catch limit at 66 mm instead of 83 mm for PTRAJ3/TRAJ3. (Fig.60) clearly shows a preference for the 83 mm catch limit and cannot justify the 66 mm limit.

Thus although these experimental test results do not provide conclusive 'stand-alone' evidence to support the software predictions, they do not contradict the latest version of the software and may be used as supporting data in addition to further justifying material.

They also show a trend toward preferring the PTRAJ3/TRAJ3 method over the previous PTRAJ2/TRAJ2 approach.

6.6.2 Validation Against RAE Software

The RAE program TRAJ2.FOR (previously TRAJICE2.FOR) has been successfully and extensively validated against icing tunnel experimental data in a large, government sponsored test programme (Refs.10 and 16), where the results are quoted to be "remarkable" (Ref.10). The software results are validated against variation of flow speed, flow liquid water content, ambient temperature, ambient pressure, droplet diameter and aerofoil chord. TRAJ2 has also been validated against another icing prediction program from NASA employing a different mathematical approach (Bib.932), (Refs. 9 and 10). The derivation of ice catch limits, catch efficiency distribution and accretion shape is carried out entirely within TRAJ2 and TRAJ3 in exactly the same manner as in the RAE TRAJICE2. The panel strength derivation of PTRAJ2 is identical to that of TRAJICE2 and to validate it for autonomous use, separate from the other sections of the icing prediction software, the following test was effected.

A typical intake lip profile and set of conditions parameters were employed in LIP.DAT (Table 10(a)) and LTRAJ2.DAT (Table 10(b)) as input to PTRAJ2. This produced output files CRD.DAT (Table 11), TRAJ2.DAT and TEMP1.DAT (Table 12(a)) of non-dimensional co-ordinates of the complete aerofoil, conditions parameters with additional incidence and stagnation point data, and panel strengths with non-dimensionalised co-ordinates of the complete aerofoil, respectively. Employing "ITYPE=1" in TRAJ2.DAT to indicate input via CRD.DAT and TRAJ2.DAT (rather than TEMP1.DAT), TRAJ2(.FOR) was executed to produce versions of TEMP1.DAT, TEMP2.DAT, ICFOIL.DAT and the four PLOT files (Fig.44(a)). Comparison of this TEMP1.DAT output file (Table 12(c)) where the panel strengths are generated within TRAJ2 using the exact same routines as in the RAE TRAJICE2 shows in to be identical to the TEMP1.DAT output file produced by the pre-processor PTRAJ2 (Table 12(c)) where the panel strengths are calculated outside TRAJ2 in PTRAJ2. All other output files produced by TRAJ2 using the TRAJ2 only and PTRAJ2/TRAJ2 input approaches are also identical thus validating the separate use of the panel strength generation routine outside the main program.

This however does not validate the theory of positioning the forward stagnation point using incidence as the incidence calculated in PTRAJ2 was also applied to the TRAJ2 (only) approach in order to test 'like' cases.

Apart from the additional circulation in the absence of onset flow (described earlier) the panel strength derivation section of TRAJ3 is otherwise identical to that of TRAJICE2. However, it is not possible to carry out a similar test as the previous one with PTRAJ2/TRAJ2 in the PTRAJ3/TRAJ3 case as in the PTRAJ3/TRAJ3 method the panel strength generation section remains within the main program (TRAJ3). It is also not feasible to test panel strength generation from TRAJ3 against that from TRAJ2 exactly as (as explained earlier)

TRAJ3 employs a third panel strength (in the absence of onset flow). Also as TRAJ3 employs blunt trailing edged aerofoils this would not be acceptable to TRAJ2 which requires a 'sharp' trailing edged aerofoil.

A further more conclusive test of the theory was carried out to validate PTRAJ3 and TRAJ3 against TRAJ2 (TRAJICE2). An asymmetrical aerofoil section of 0.6 m chord (Fig.117) was applied as input (CRD.DAT) to TRAJ2 resulting in TEMP1.DAT and PLOT output files (Figs.117 and 118). The 'nose' 32% chord (0.194 m) of that aerofoil was applied as input (LIP.DAT) with the same conditions parameter values to PTRAJ3 employing 5% blunting and a CLE of 1.0 (Fig.120) resulting in TEMP3.DAT, TRAJ3.DAT, CRD3.DAT and PLOT.DAT output files. The output from PTRAJ3.DAT was applied as input to TRAJ3.DAT. The desired value of forward stagnation point abscissa supplied to TRAJ3 in TRAJ3.DAT (from LTRAJ3.DAT) was varied through numerous executions of TRAJ3 (Figs.119(a-k)) until the output iced aerofoil plot of TRAJ3 (Fig.119(a)) was identical to that of TRAJ2 (Fig.118).

Thus it has been shown that the ice accretions on the 'noses' of two aerofoils of very different aft sections are identical. For this to occur, the method applied in the second case to simulate the conditions of the first case in the aerofoil 'nose' area has been validated for this application. Thus the use of a third panel strength in the absence of onset flow to move the forward stagnation point in order to simulate the correct air flow and droplet trajectory patterns in the forward area is validated for use in similar cases.

6.7 Comparison of TRAJ2 and TRAJ3 Prediction Methods

6.7.1 Introduction

As detailed in the Figures Index, the results of PTRAJ2/TRAJ2 executions appear in (Figs.P1-P88) and PTRAJ3/TRAJ3 in (Figs.P89-P202). Twenty cases were studied using the PTRAJ2/TRAJ2 approach. This was then superseded by PTRAJ3/TRAJ3. The same 20 cases were executed for comparison with the previous method, and a further five cases (21-25) for variation of the factor BLF applied in PTRAJ3 and not applicable to PTRAJ2. BLF is an aerofoil trailing edge 'blunting' factor explained earlier ("New Software"). The summarised input and output parameter values for both methods, in all cases, appear in Table 17 (Appendix B) and are graphically presented for quick comparison in (Figs.102-116).

Input parameters varied in both approaches include:

Lip angle	lip profile (90°, 135° or 180°) Table 17(a), (Fig.100)
Air flow velocity	61.73 ms ⁻¹ or 92.6 ms ⁻¹ Table 17(a), (Fig.104)
Flow liquid water content	0.3 gm ⁻³ or 0.6 gm ⁻³ Table 17(a), (Fig.105)
Ambient air temperature	usually 20°C Table 17(a), (Fig.106)
Time in icing	usually variable to allow 2% chord maximum ice thickness Table 17(a), (Fig.107)
XSTAG	abscissa of desired forward stagnation point Table 17(a), (Fig.116)
CLE	developed aerofoil chord factor Table 17(b), (Fig.102)
BLF	(PTRAJ3 only), developed aerofoil trailing edge blunting factor Table 17(b), (Fig.103)

The droplet diameter remained constant at 20µm, and the ambient pressure constant at 74.808 kPa.

The three lip profiles were first input to PTRAJ2 to observe the created afterbody using a chord factor CLE of 1.0 (Figs.P1-P3). To gain some experience of the effect of varying CLE, the 180° lip profile was chosen as a base and CLE was varied from 1.0 to 1.5 (Figs.P3-P8). The flow in the trailing edge region at incidence is assumed not to affect the 'nose' region flow to any reasonable

extent. Thus the maximum thickness/chord (t/c) ratio should be small, without increasing the chord length so far as to reduce profile accuracy or greatly increasing computer run times in the streamwise 'time-marching' approach adopted. On reflection, after comparison with the results of the PTRAJ3/TRAJ3 method, it would probably have been advantageous to employ a larger value of CLE in PTRAJ2 cases of 1.5, to reduce the trailing edge flow dependence. This was remedied in the PTRAJ3 cases where CLE = 1.5 was employed (Fig.102).

The trailing edges of the original lip body profile are indicated on the developed aerofoil plots output from the pre-processors PTRAJ2 and PTRAJ3 by short lines perpendicular to the profile. The original lip is similarly marked on the droplet trajectory plots and, in the TRAJ3 case, they were also added to the iced aerofoil plots. On the droplet trajectory plots the ice catch limits on the upper and lower surfaces are marked with an 'x'.

Thus cases 1-20 were input, via LIP.DAT and LTRAJ2.DAT (Tables 10(a) and 10(b)), to PTRAJ2. This resulted in developed aerofoils (Fig.101) in output files CRD.DAT (Table 11) and non-dimensionalised with respect to the new developed aerofoil chords in files TEMP1.DAT (Table 12), and conditions data in files TRAJ2.DAT (similar to LTRAJ2.DAT - see "New Software"). The output from the PTRAJ2 executions was employed as input to TRAJ2 to produce the corresponding PLOT1.DAT, PLOT2.DAT, PLOT3.DAT and PLOT4.DAT output plot files. These were used to produce (Figs. P9-P28, P29-P48, P49-P68, and P69-P88) of droplet trajectories, droplet start ordinate against impact distance aft over the surface (Y_0 v S/C_{impact}), ice catch efficiency

distribution and ice accretion profile respectively.

It became apparent that the effect of varying aerofoil incidence to move the forward stagnation point may be producing a rather larger detrimental effect on the droplet catch area prediction than first realised. This error may have been reduced by increasing the developed aerofoil chord (by increasing CLE to 1.5 - mentioned earlier) in order to reduce the value of incidence necessary to apply to the aerofoil to move the forward stagnation point. However, as the mass density of the water droplets is effectively 1000 times that of the air flow, this would have been a theoretically unacceptable compromise. Although it may have presented a possible short term 'working solution', it is likely that, in the not too distant future, the method (PTRAJ2/TRAJ2) would be applied outside its limits of acceptable error tolerance. Thus a 'short chord' aerofoil would be raised to excessive incidence and a relatively large error in catch efficiency distribution prediction would occur. Evidence of the emergence of this phenomenon is apparent in (Figs.P11, and P14-P18).

Hence, as described earlier ("New Software"), a new approach was developed. It was, by this time, realised that the aerofoil incidence must remain unchanged from that of the lip profile or aerofoil nose such that the geometry of the aerofoil nose (catch area) does not change relative to the droplet trajectories. Two alternative

approaches to move the forward stagnation point without affecting the aerofoil nose geometry were considered.

The first method involved variation of aerofoil camber by 'cusping' the developed afterbody trailing edge. The second method involved the use of a third component of circulation, in the CFD panel method, around a blunt trailing edged developed aerofoil, as described earlier ("New Software" - "TRAJ3").

The second method was preferential as it did not require the generation and variation of actual body shapes within the software which would greatly increase computer run times for no increase in accuracy or applicability. This second method also left more scope for future development into multi-element bodies etc., with less software sophistication ("Continued Research").

Hence, the new approach (PTRAJ3/TRAJ3) was developed ("New Software") and applied to the same 20 cases for comparison with the previous PTRAJ2/TRAJ2 approach. As described earlier, a further five cases (21-25) were also executed with varied aerofoil blunting factor (BLF), required in PTRAJ3 (Figs.P183-P202).

As in the previous method, several values of CLE (and BLF) were applied to the lip generation into the developed aerofoil to gain some knowledge of their effectiveness (Figs.P89-P102). CLE is varied from 1.0 to 1.5 in (Figs.P89-P94). From experience with the previous method, a value of CLE of 1.5 was then applied to all further executions. The developed aerofoil trailing edge blunting factor BLF was then varied from 1.0 to 0.0 (Figs.P94-P102) from which it was deduced that a value of 0.0 should be made standard throughout cases 1-20 for comparison with the experimental test results, the existing Lucas method and the PTRAJ2/TRAJ2 approach. Cases 1-20 were then executed using PTRAJ3 and TRAJ3 to produce the output plots of (Figs.P103-P122, P123-P142, P143-P162, and P163-P182) corresponding to those mentioned earlier relating to PTRAJ2 and TRAJ2 (Table 17(b)).

6.7.2 Results Comparison

Studying Case 1, observing (Figs.P9 and P103) of droplet trajectories from TRAJ2 and TRAJ3 respectively. The catch area of TRAJ2 (Fig.P9) is seen to be placed slightly lower on the aerofoil nose than that from TRAJ3 (Fig.P103). Therefore the TRAJ2 upper surface catch limit is further forward and vice versa on the lower surface. This is due to the small value of incidence applied to the aerofoil by PTRAJ2, visible in the trajectories of (Fig.P9), to relocate the forward stagnation point. This phenomenon is also borne out by the plot of catch efficiency against S/C (over-the-surface distance aft of the leading edge non-dimensionalised with respect to chord) of (Figs.P49 and P143), and the resulting ice accretions of (Figs.P69 and P163). The icing rates derived from these latter figures are in mutual agreement.

Taking Case 2 and observing (Figs.P10 and P104) it can be seen that PTRAJ2 had to apply a negative incidence to the aerofoil to

achieve the desired stagnation point. Similarly TRAJ3 must have applied a third component of circulation in the absence of onset flow in a direction counter-clockwise (looking at the figure) so as to cause the deviation in air flow streamlines and thence droplet trajectories present in (Fig.P104). Thus the two approaches (TRAJ2 and TRAJ3) employing different theories corroborate each others results in Cases 1 and 2. (Figs.P50, P70 and P144, P164) support the results of the trajectory plots and further substantiate the two theories, there being the same shift in ice accretion and catch efficiency distribution due to the under prediction of the magnitude of negative incidence required by PTRAJ2.

If Case 3 is now studied, the relevant trajectory plots appearing in (Figs.P11 and P105), it will be seen that PTRAJ2 applied a positive value of incidence of rather large magnitude in order to achieve the desired forward stagnation point position. This large value is evidently supported as necessary in that the TRAJ3 result indicated that a strong clockwise circulation has been added to cause the trajectory deviations present in (Fig.P105) when making the necessary adjustment to the forward stagnation point. In this case the catch limits from TRAJ2 are further aft on both the upper and lower surfaces. The relatively large over prediction on the lower surface is due to the unrealistic incidence presented to the droplet trajectories as the air flow relationship is established. The much greater mass density of the droplets than that of the air (as described earlier) results in a much smaller deviation in droplet trajectory than air flow and hence the further aft catch limit on the lower surface. The slight discrepancy on the upper surface is probably an incidence under prediction by PTRAJ2 compared with the necessary circulation required to achieve the stagnation point. Thus again, the two methods agree in general trend and the differences in their results are attributable to the theory differences, the error obviously lying with the PTRAJ2 approach. This evidence is also supported in the accompanying catch and accretion plots of (Figs.P51, P71 and P145, P165).

Taking the 135° lip of Case 4 ie.(Figs.P12 and P106). In this case there appears to be a large disagreement between methods. PTRAJ2 applies a moderate value of incidence whereas TRAJ3 appears to have supplied little added circulation. However, when the unusual shape of the 135° lip section is accounted for, being more of the form of an inverted aerofoil, the results are more easily explained. The lines on the figures are droplet trajectories and not air flow streamlines. The natural forward stagnation point of the aerofoil at zero incidence is vaguely indicated by (Fig.P106) and the initial trajectory lines as they emerge from the left margin of the plot. Thence, due to the added circulation, the trajectories deviate in a generally upward direction lead by a much stronger change in direction of the airflow. Hence, using only aerofoil incidence in the PTRAJ2 method of (Fig.P12) requires a relatively large magnitude of positive incidence to achieve the same effect. Due to this large value of positive incidence the catch is somewhat largely over predicted on the lower surface by TRAJ2 as is indicated in the comparison of (Fig.P52) with (Fig.P146).

Throughout Cases 5-20 the trend is similar to that established in Case 1-4. In cases where the incidence supplied by PTRAJ2 and the third component of circulation supplied by TRAJ3 are of small magnitude, there is good agreement of results. The agreement deteriorates as the magnitude of additional incidence and circulation increases, such that the PTRAJ2 method over predicts the catch on the lower surface in positive incidence cases, and vice versa. In all 20 cases the two theories provide mutual support and indicate that the error is accountable to the PTRAJ2 theory incapability to correctly model the situation.

As introduced earlier, Cases 21-25 were carried out to examine the effect of variation of aerofoil trailing edge blunting on the overall ice catch and accretion results. The output plots (Figs.P183-P202) show that variation of BLF in this situation has no effect on the required output results. Hence, BLF remains a useful factor for modelling the developed aerofoil to achieve a reasonable shape without detriment to the results.

Hence in concluding this section, the PTRAJ2/TRAJ2 theory has been shown to give reasonable results for cases where the stagnation point effectively lies on, or near, the designated lip (and subsequent aerofoil) leading edge as input in the co-ordinate geometry, ie. when the additional incidence is almost negligible. In Cases where this is not applicable the PTRAJ2/TRAJ2 theory has been shown to produce unacceptable errors. However, the form of these errors is relatively reliable and reasonably predictable. Thus, through using a relatively large number of sample cases, the general trends of errors (differences between TRAJ2 and TRAJ3 output) render the PTRAJ2/TRAJ2 material useful as supporting validation of the PTRAJ3/TRAJ3 method in addition to the other validation evidence supplied. The PTRAJ3/TRAJ3 method has produced consistent results through a good number of cases and is mutually supportive of the PTRAJ2/TRAJ2 general trends.

6.8 Spraymat Existing Design Method

6.8.1 Description

The actual calculation sheets and figures for this approach appear in (Appendix B, Section 18.1). The theory from whence the formulae were originally extracted appears in (Ref.18).

From the drawings in the customers specification, the cross-sectional (streamwise) profile(s) to be presented to the icing flow are extracted. This profile is then compared with the following set of aerofoils.

Equivalent Aerofoil Sections

NACA 0006 - 64
65A004
65₁208
65₁212
65₂015

JOUKOWSKI 15 % t/c, cambered and uncambered

ELIPSOID, finess ratio 5:1
10:1

The closest matching equivalent aerofoil from the set are selected to represent the actual aerofoils in all subsequent calculations. With the aid of three calculation sheets of formulae ("Sample Calculations", Appendix B, Section 18.1), the limit of catch, rate of ice accretion and heat requirements are calculated from a knowledge of the required input parameters. These parameters include the actual and equivalent section chords, the equivalent section leading edge radius, ambient airflow velocity (T.A.S.), altitude, air density ratio for I.S.A. at that altitude, the effective angle of attack (incidence) of the aerofoil, the water droplet diameter, and the liquid water content of the atmosphere. These latter two are taken from FAR 25 Section C.

Limit of Catch

The limit of catch is calculated from the droplet Reynolds number, scale factor, and a series of charts of catch limit versus scale factor with lines of varying Reynolds number. There is a separate chart for each equivalent aerofoil and several values of incidence. Unless the number of incidence cases are restricted, then the number of charts required becomes large. Hence, in most cases there are only charts for two values of incidence, being 0° and 4° (positive). Should information at a value other than 0° or 4° incidence be required, then the accepted procedure is first to

determine the limit of catch at zero and four degrees incidence. For symmetrical aerofoils, the limit of catch at -4° incidence is determined by taking the 4° positive incidence value on the opposite face of the aerofoil. For non-symmetrical aerofoils, another equivalent aerofoil is selected from the set, having an upper surface contour similar to the lower surface contour of the primary equivalent aerofoil. The $+4^\circ$ catch limit of the secondary equivalent aerofoil is then used to represent the -4° value for the primary equivalent aerofoil. If data is only available at either 4° or 0° incidence, but not both, then the other is predicted by assuming the 4° upper surface catch limit to be 90% of the 0° value, and vice versa for the lower surface. From the catch limits at $-4^\circ, 0^\circ, 4^\circ$, a curve of catch limit against incidence is constructed, which is interpolated and extrapolated respectively to yield catch limits for other values of incidence. Hence it can be appreciated that, in this method, there is a considerably limited database from which to derive the required information. The droplet diameter used in the catch limit calculations is the FAR 25(c) maximum of 44.4 microns, as it is the largest droplets which impact at the furthest aft limit of icing. 44.4 microns is the maximum droplet diameter experienced on a reasonably regular basis in the atmosphere.

Rate of Ice Accretion

For the rate of ice accretion calculation, the droplet diameter used is the median volume diameter (MVD) taken also from FAR 25(c) of 20.0 microns. This is the diameter of the droplet with the median volume when considering the whole spectrum of droplet sizes found naturally in icing conditions, taken from associated atmospheric sampling data.

New values of droplet Reynolds number and scale factor are calculated using the new droplet diameter. The limits of catch on the upper and lower surfaces are calculated as before using the MVD droplet. From a chart of overall catch efficiency versus droplet inertia function (calculated on the heat requirements sheet, description to follow), having lines of varying scale factor, the overall catch efficiency is determined. The overall catch efficiency of the aerofoil at the particular incidence considered, is the percentage of water impacted over the catch area compared with the total amount of water passing through the plane perpendicular to the flow representing the aerofoil maximum thickness. Thence, knowing the liquid water content of the airflow (FAR 25(c)), and the maximum thickness of the aerofoil, the rate of ice accretion at the stagnation point is determined using the formulae on the calculation sheet, ("Sample Calculations", Appendix B).

Heat Requirements

For the heat requirements, the droplet inertia function is calculated, and also a new velocity and scale function using the droplet MVD ("Sample Calculations", Appendix B). From a chart of catch

efficiency at the stagnation point against droplet inertia function with lines of varying velocity and scale function, the catch efficiency at the stagnation point is determined for these new functions. The catch efficiency at the stagnation point is defined similarly to the aerofoil overall catch efficiency but taken over an infinitesimal area representing the forward stagnation point. From a chart of the heat transmitted to the water at 100 percent catch efficiency, and knowing the actual catch efficiency, the heat transferred to the water at that catch efficiency is determined. From another chart, the heat lost in convection and evaporation is determined and added to the heat lost to the water, to yield the leading edge power intensity required for anti-icing at the stagnation point. This complete design cycle is carried out for several cases (typically three or four) which are considered to be the limiting points. From the results, the worst case is extracted, ie. the greatest heating intensity. It is this value from which the heating intensity distribution is calculated using the worst case catch limit, ie. furthest aft, using the 44.4 micron droplet, shortened by 33% to exclude thin accretion extremities. From this information, the heat intensity distribution is tapered from stagnation point to factored catch limit, then 'stepped' into discrete, convenient spraymat element band widths (Fig.9) to form a histogram of the heat intensity distribution. The total power requirement of the heater mat is then obtained by integrating.

For de-icing cases (cyclic heating), a standard design curve is employed of heater power against ambient temperature (Watts x seconds v °C) such that for known values of heat output distribution (W.m^{-2}) and OAT (°C), the heater "power on" time is derived. The heater "power off" time having been determined from the ice accretion rate and maximum allowable ice accretion thickness, ie. the time to accrete the maximum allowable ice thickness. Lucas Aerospace manufacture three types of de-icing system cycle time controllers. The simplest employs a fixed, constant time interval determined for the worst regular case during design. Another employs three different cycle times based on OAT (ie. a step change function). The most complex type, most recently developed (fitted on the EH101 helicopter for main rotor blade de-icing), employs a continuously variable cycle time based on OAT, from a fixed design curve of time v OAT determined during design. The power intensity employed in de-icing cases is determined from experience dependent on application with an average of 15 W.in^{-2} (23.2 kW.m^{-2}), being increased to a maximum of 20 W.in^{-2} (31.0 kW.m^{-2}) in cases where short cycle times are required, (e.g. Tornado engine air intakes - eight seconds "power on" time).

6.8.2 Comparison with Experimental Test

Observing the calculation sheets for "Limit of Catch" (Section 18.1.1, Appendix B). Obviously there is a large over prediction of the ice catch limits on the outer/upper surface. This is attributable to the small dependence of the calculation of ice catch limit on aerofoil chord, using the existing method:

$$\text{Scale Factor} \quad \psi = 562 \frac{c}{d} \sigma$$

With this in mind then, it would be beneficial to employ similar aerofoils for calculation purposes which are of a similar chord length to the actual body under study. In engine air intake lip cases though a definite chord does not exist. Using the existing method therefore, the operator makes an estimation of the chord of the developed complete 'sharp' trailing edged aerofoil 'by default' when he chooses a simulating aerofoil from the list for which ice catch data is available, (see previous section). In cases such as the lip profiles used in the experimental tests described in this programme, with particularly 'blunt' leading edges, there are no aerofoils of closely similar 'nose' profile in the list. Thus the approach adopted is to use a rather large version of one of the available aerofoils, and hence the large chord. Therefore it can be seen that the existing method, with its limited number of 'similar aerofoils', is completely inadequate and unsuitable for these type of profiles.

Taking the lower/inner surface calculated ice catch limits of the existing method calculation sheet. Although the 90° lip profile value of 109 mm differs considerably from the experimental test catch limits observed in (Figs.60-63), the 135° and 180° lip section catch limit predictions are much closer. Considering that, in the 135° lip section case, the actual body profile length aft of the leading edge (measured over the surface) is 130 mm, the calculated catch limit for Case 17 using the existing method of 119 mm appears to over predict by only a small amount. Similarly the value of 122 mm for the 180° lip section which has a length of 126 mm is relatively accurate.

However, as indicated by the 90° lip section for the lower surface and 90°, 135° and 180° lip sections for the upper surface, there is no acceptable degree of consistency with which the accuracy of prediction experienced in the 135° lip section lower surface can be maintained. It should be remembered here that the existing ice catch limit calculation method was not designed for use in engine air intake cases and therefore, although having a limited capacity to cope with aerofoils at incidence, it carries no allowance for 'dual' flows with forward stagnation point displaced by the circulations resulting from them. It was also designed to operate with substrate shapes not too dissimilar to the aerofoil sections generally in use at the time of its composition, which bear little resemblance to some modern (often super critical) sections.

The existing method involves the use of a 44.4 µm diameter droplet for ice catch limit calculations. These limits are then factored by 2/3 to ignore the trailing third of the accretion which is assumed to be of negligible thickness. A 20 µm droplet is then employed to calculate the icing rate, (Calculation Sheet - Section 18.1.2). The ice accretion thickness at the leading edge is then calculated from the 20µm droplet icing rate and tapered (linearly) toward the new (cropped) catch limit, which was calculated employing the 44.4 µm droplet. This ice thickness distribution is then used to calculate de-icing system power output distribution. It is postulated

that it would be more realistic to employ the 20 μ m droplet (representing the volume median diameter and therefore a better 'flow average') to calculate the catch limits. These limits should not then be 'cropped', (or at least only by a small amount, say 5-10%). Thus, in this section, it was also decided to compare the 20 μ m droplet catch limits calculated using the existing method (Calculation Sheet - Icing Rate, section 18.1.2) with the experimental results of (Figs.60-63). This approach yields much better results than the 44.4 μ m version.

Studying the 90° lip section. The lip section actual body is 38 mm long on the upper/outer surface and 135 mm on the lower/inner surface. Thus, observing (Figs.60-63), It will be noted that the calculated catch limit of 48 mm for the outer/upper surface and 58 mm for the inner/lower surface present reasonably realistic predictions. In the 135° lip section case the upper/outer surface length is 48 mm and the lower/inner surface length is 130 mm. Therefore the catch limit calculations of 38 mm and 64 mm fall a little short. However, when it is noted that the largest droplets in the flow are obviously larger than the MVD droplet and thus will impact further aft than the 20 μ m MVD droplet, then these calculated values present a reasonably accurate picture.

The 180° lip section calculated catch limits of 66 mm on the upper/outer surface and 64 mm on the lower/inner surface compare well with the experimental results in the upper/outer surface case, but represent an under prediction in the lower/inner surface case. This under prediction may be explained in the same manner as that expressed for the 135° lip section as it is the lower surface catch which has the greater increase with droplet size when effectively at positive incidence.

Thus it has been shown in these cases that the existing calculation method does not provide acceptable results in its currently employed state. Adapting the existing method as described to use the 20 μ m droplet in the catch limit calculations renders considerable improvement, and in these cases provides reasonable results.

6.8.3 Comparison with Computational Method

As described above, the 20 μ m droplet existing method results (Calculation Sheet - Icing Rate, Section 18.1.2) are used in these comparisons. Comparing the 90° lip section results of Case 7 from the existing method with the new computational method (Fig.P109). Unfortunately there are no tunnel test photographic results for the lower speed (61.73 ms⁻¹), but the catch area at 61.73 ms⁻¹ will be less than that at 92.6 ms⁻¹. For the upper/outer surface, the existing method catch limit is 41 mm compared with 29 mm for the 'new' computational method. This difference is probably accountable to the large chord applied in the existing method (60 ins - 1.52 m) compared with that of the computational method (0.6 m), (Fig.117). It would not be possible to operate the existing method in this case using a 0.6 m

chord as there are no aerofoils in the list for which icing experimental data are available, having such a 'blunt' nose and short chord. Thus an aerofoil of thickness much greater than that of the 0.6 m computational aerofoil had to be employed and hence the large over prediction of catch limit in comparison.

On the lower surface, the existing method catch limit of 51 mm compares well with 56 mm for the computational method. The overall catch area difference indicates a position error of the catch around the aerofoil nose. Obviously this is caused by the fact that the existing method assumes the aerofoil to be at zero incidence in a 'free' flow with a natural 'free' aerofoil forward stagnation point position. In the computational approach the stagnation point is moved around the aerofoil nose and hence also the ice catch area.

In Case 16 (Fig.P118) on the upper surface, the catch limit of 48 mm from the existing method falls short of the 60 mm predicted by the 'new' method. The contrary is true on the lower surface where the 'old' and 'new' methods predict 58 mm and 38 mm respectively. The comparison between the 'new' method and the experimental results (Figs.60-63), (see previous section), is good. The extra catch length in the 'old' approach is probably due to the extra foil thickness from the large chord applied.

Moving now to Case 8 for the 135° lip section. In this lower speed (61.73 ms^{-1}) case, the 'new' method predicts catches of 54 mm and 32 mm on the upper/outer and lower/inner surfaces respectively, compared with 30 mm and 56 mm for the 'old' method. The lower surface ice catches are in reasonably good agreement, but there is a large difference between the upper surface values. For the higher speed

(92.6 ms^{-1}) Case 17 the 'new' method upper and lower surface catch limit predictions are 40 mm and 83 mm respectively, compared with 38 mm and 63 mm for the 'old' method. Obviously again there is a good agreement for the upper surface, and reasonably large error on the lower surface. As the speed increases from Case 8 to Case 17 the catch limits using the 'old' method (on a 'free' flow aerofoil) move aft as expected. Using the 'new' method, as well as a general increase in catch area, the catch area moves round the aerofoil nose in a sense such that the stagnation point moves in a positive incidence type direction. Hence, although at first appearance, the differences between the 'old' and 'new' method results for these two cases seem inconsistent, when they are viewed as general trends and total catch areas, their explanation becomes more obvious.

Finally Cases 9 and 18 of the 180° lip section (Figs.P111 and P120). For the lower speed (61.73 ms^{-1}) Case 9, the new method predicts upper and lower catch limits of 40 mm and 63 mm respectively, compared with 58 mm and 56 mm for the 'old' method. This may be explained as an increase in upper surface catch due to the thicker aerofoil produced as a result of employing a large chord, plus the same stagnation point movement related catch area 'shift' around the aerofoil nose described above in previous cases. In the higher speed

(92.6 ms⁻¹) Case 18, the 'new' method predicts upper and lower surface catch limits of 50 mm and 63 mm respectively, compared with 66 mm and 63 mm for the 'old' method. Once again, the same explanation is applicable of increased aerofoil thickness in the 'old' method and a catch area shift to position the stagnation point in the 'new' method. The general trend however in these cases is toward a smaller error, particularly on the lower surface, probably indicating a smaller stagnation point move applied by TRAJ3, which is most dominant on the lower surface.

Therefore it may be concluded in this section that although there is an overall trend in the magnitude and sense of errors, using the 'old' method as opposed to the 'new' method, the magnitude in some cases becomes unacceptable for design purposes. The 'old' method theory is rather basic and has accumulated a great deal of validation data for use in 'free' flow aerofoil cases closely similar to those from which its icing database was generated. The 'new' theory predicts results which are of the same order as the 'old' method, with catch area magnitude and position changes easily attributable to phenomena experienced due to employing the 'old' method outside its limits of applicability. Thus two overall conclusions have emerged from this comparison. A preference for the 'new' icing prediction method for air intake, modern aerofoils and in fact any aerofoil except those actual body profiles (and conditions) for which the previous experimental icing data is available. Secondly, the general agreement, with associated allowances for degree of acceptability, mentioned above, between the two icing prediction methods means that the results of the 'old' method provide some supportive evidence of the validation of the 'new' method.

6.8 Implementation

6.8.1 Computer System

Introduction

An integral part of this research programme is to establish at Lucas Aerospace, a computing facility within the engineering department for the running of the software resulting from the research programme. The current 'mini' computer operated at Lucas Aerospace is not capable of effectively running TRAJ2/3 (the larger, more demanding of the programs) and is already fully utilised. The IBM PC XT micro computer, currently in the engineering department, with 640 kb RAM and 20 Mb store would be unable to manipulate one of the large arrays of TRAJ2/3 within a sensible time period, and thus is completely impracticable for running the whole program. Hence it became necessary to procure a completely new computer system to satisfy the needs of the Spraymat design section. Therefore, the task was to assess the requirements of the new system for this purpose, investigate all viable offerings within the market, make a decision on which system to purchase, and install it within the department.

However, the cost outlay of such a system was not economically justifiable for spraymat design alone and it soon became apparent that

a more suitable approach was to provide a system which would serve the whole of the engineering department, which was currently in need of improved computing facilities. Thus the task expanded to an extensive investigation, assessment, and 'bill of materials' study (Appendix B), to result in the progressive procurement (blocks 1 to 7) of a complete IBM 'Token Ring' network of PS/2 PC's operating OS/2 (Fig.64).

6.8.2 Software

Toward completion of the research programme the new de-icing system design method containing the new software was employed alongside the 'old' method in commercial projects to answer incoming design enquiries (see "Conclusions"). This gradual approach to implementation, as detailed later, enables the accumulation of validation data without extensive cost.

7 TECHNICAL IMPLICATIONS OF THE RESEARCH

7.1 Product Improvements

By more accurate design of the product in respect of the application, to yield a power output distribution tailored to fit the conditions, the efficiency of the product is improved. This results in reduced total power requirement and reduced local maximum temperatures as heat is not supplied to areas where it is not required and therefore not absorbed by the ice accretion or airflow. By reducing the peak temperatures, the de-icing system is not thermally stressed to the same level as previously, and therefore will sustain a longer fatigue life. The reduced temperatures result in less 'overkill' heating and thence reduced runback water and subsequent runback ice. A secondary effect of reduced heat output is a reduced thermal stressing of the materials underlying and overlying the spraymat de-icing system. On large spraymat systems such as large complex engine air intakes on the same aircraft as large spinners and spraymat de-iced tailplane and fin leading edges, the overall power requirement reduction resulting from a combination of small savings in a large number of small localised areas may become quite significant, (a 5% saving could yield a power saving of four or five kilowatts).

7.2 Design Method Improvements

There are four basic areas of improvement to the design method. The main improvement in accuracy is due to the ability to employ the actual body co-ordinates instead of an existing aerofoil from a limited selection for which icing data is available.

The more detailed results of the computerised method are able to present distribution data for the true body, such as ice shape or ice catch efficiency distribution. This is converted into spraymat heat output distribution, to replace the standardised simple distributions applied to a single leading edge value in the 'old' method. To improve the accuracy of the overall design arrived at, to satisfy the complete flight envelope (or rather, conditions envelope) which the de-icer will encounter, the new system benefits from the ability not only to look more accurately at each case study (each condition), but to examine a great many more cases. Thus the new method may explore the whole envelope and therefore reduce the risk of omitting an extreme but relevant case not immediately apparent to a designer limited to choosing say three design cases. The software system may be run without operator after initial input, until the results are established, the operator being 'free' to set up the next case (and in fact under the multi-tasking operating system proposed - "Computer System", may run up to ten case studies simultaneously). Thus the overall design time required need not be increased beyond that of the 'old' method for three cases, when studying 20 cases using the 'new' system. There is also a facility to run, say 20 cases, consecutively, in batch mode, overnight after establishing all 20 sets of input data and initiating the command program once only. A further improvement to the relevance of each case in addition to the employment of actual

body co-ordinates, is the use of actual conditions parameters. Such criteria as convective cooling, evaporation, sublimation, ice/water phase changing, runback, etc. are determined 'real time' from the actual applied input data, thus leading to more accurate and therefore more relevant results.

Considering the actual design method of computerising the approach, as mentioned in "Technical Justification", there is a reduction in human errors created at each calculation stage by the 'hand calculated' method due to accumulative 'round-off' and simple incorrect use. As described in "Continued Research and Development", the computerised method has the scope to take over more of the previously 'hand calculated' parts of the 'old' method, to derive results closer to the final design required data, ie. requiring less 'hand' manipulation and interpretation. Thus, after further development, it may be feasible to output the Spraymat electrical power histogram at the end of the computer software execution. The computerised method also has the advantage of not requiring an operator to have a detailed knowledge of the mathematics of the system, leaving him free to better understand the application and design aspects.

By effecting a better design, the level of post design development is reduced and therefore also the amount of experimental test and re-test work. This translates to a direct reduction in development engineering design work and physical icing wind tunnel testing time (financial implications of which are detailed in "Commercial Implications of the Research").

8 COMMERCIAL IMPLICATIONS OF THE RESEARCH

An advantage of the new approach is that it is still independent of the type of de-icing system employed regarding ice accretion, and will only be specific to thermal systems when developed to determine the heat output distribution required of the system. Hence, should the Company wish to investigate other types of system, then the design method is still applicable.

8.1 Product Image

The overall effect of this research programme on the product image observed by a potential or established customer should be one of modernisation towards a more "high tech.", "state of the art" approach. However, the actual level of modernisation effected is by no means as visible to the customer as the image portrayed by advertising literature and brochures. For the purposes of this product and the attributes in question, ie. the level of technology to imply in the promotion, the customers tend to fall into one of three categories. It should be noted however that the customer is almost always a large engineering organisation employing many people covering all of the categories, and hence the small number of employees dealing with the acquisition of the de-icing equipment or specification of supplying manufacturer of that equipment, will often include engineers from at least two of the three categories. Thus the literature has to be capable in one version of satisfying all three categories without severely dissatisfying any one of them. The categories are:-

1. Definitely seeking "state of the art".
2. Definitely avoiding "state of the art".
3. Not really interested in the level of technology involved, he just desires the results to his standards.

Obviously, as an engineer, category three has homed in on the criteria of prime and only real importance in the matter, whereas categories one and two have been side-tracked onto a related yet secondary subject not directly involved in achieving their true aim. However, we must provide a facility to satisfy all three types. By increasing the amount of "state of the art" technology employed in spraymat design, we have hopefully avoided a rejection from customer one. By maintaining the level of experience required in implementing the basic design criteria, and to derive actual usable heater patterns from 'required heat output' data, we have maintained the interest of customer two.

When considering the introduction of a more modern "state of the art", "up to the minute technology" computer assisted design approach, the use of the icing tunnel to verify the results is an advantage of great importance to customers two and three. Customer one is the least

affected but the knowledge that some physical testing is effected to verify the results will further assure him.

The greatest influence of this icing tunnel verification falls upon customer two who seeks as much evidence of physical testing as possible and has no real interest in the modern computer approach. He trusts and relies heavily on the 'tried and tested' approach. He will accept that it is often necessary to involve computers to deal with some aspects of complex projects, but definitely is reassured by physical testing and certainly would choose a design system involving a ratio of physical testing to theoretical computation in favour of the former.

Thus, to satisfy this customer without effecting a rejection in customer one, it is preferential to include a little of the modern computerised approach in the advertising literature whilst maintaining a balance in favour of the 'tried and tested' technique. Customer three is re-assured to see evidence of both approaches complementing one another. He is impressed at the completeness of the approach in that the theory is checked and verified in situations akin to the conditions under which the equipment will serve.

Thus, the 'computer aided design' aspect of the method only deserves a word or two mention in the promotional material. It will probably impress customer one, but need not necessarily be included in detail in 'first encounter' material. Customer two will not be interested in this aspect of the matter in most cases, but it may help to convince him of the necessity for computer assistance, as he may appreciate how difficult it would be to access detailed interface temperature information with confidence in a physical test. Should such testing be considered, it would be more costly and time consuming than the computerised method. Another point in favour of the mathematical approach to analysing point or layer temperatures at depths in the material, over physical testing, is the difficulty in determining the location of a temperature datapoint. It is difficult to assess which layer a film thermocouple placed between two different material layers in a composite plate, records the temperature of. Again customer three is satisfied by the comprehensive approach with all related phenomena considered, and impressed by the additional capabilities offered by the new method. He realises the need for a computational technique in this subject much more readily than customer two.

Considering the four P's (Ref.11, pp.3) being, "Product", "Price", "Promotion" and "Place", as they relate to the marketing of spraymat. The company releases two brochures to its potential customers in which spraymat is featured (Refs.12 and 13). (Ref.12) "Product Range" devotes one double page to spraymat in presenting the range of products available, and presenting no more than one double page to any other of its products in the range. (Ref.13) "Ice Protection Equipment", devotes all of its three double pages to spraymat and related equipment. It can be seen that these two promotional tools make use of most of the advantages of the spraymat system, (listed earlier - Section 2.2.4). The approach portrayed in

the literature when considered in conjunction with the photographs, is one of skilled labour, a specialised product, low volume sales, process dependence, high quality, and manufacture with a high degree of testing and inspection throughout. Therefore the promotional literature presents a true picture of reality and makes full use of the companies virtues, as well as those of the product. This creates the correct image for selling the product to a potential customer looking for a reliable effective and efficient de-icing system, without himself requiring a vast detailed knowledge of his own requirements. The aim of the promotion is to convince the customer to trust the organisation to deal with all of the detailed work, leaving him free to make a somewhat vague request, knowing he will receive the system best suited to his application, whilst satisfying all relevant rules, regulations and certification standards to which the system must comply.

The more specific of the two promotional brochures (Ref.13), is completely dedicated to ice protection equipment and bears that name, unlike the "Product Range" brochure which dedicates two pages to spraymat and a further page to de-icing system ancillary equipment and service support. The "Ice Protection" brochure devotes five pages to the spraymat product and a sixth page to briefly mention ancillaries and service support. Some of the photographic presentations are the same as in (Ref.12) which detracts from an opportunity to present more material to the potential customer, having already acquired advertising space in his catalogue library. A better approach would be to present more applications of the product, which would add to the customers impression of the product versatility. However, the additional text of (Ref.13) over and above that of (Ref.12) is different to that in (Ref.13) in its approach. It gives mention to more of the advantages of the product, this time concentrating on more technically detailed statements such as the inter-laminar strength, ratio of heated to unheated area, thermal efficiency, fault detection, modulus of elasticity, compatibility with the substrate for increased fatigue resistance, etc..

Points mentioned are the 25+ years of experience in ice protection system manufacture, the consistency of spraymat to out-perform alternative systems during the whole 25 years and its wide range of applications. Thus this promotion draws well on past experience and virtues developed over a number of years. On the penultimate page is a list of technical specifications allowing the customer to check that his requirements are suitably catered for (customer three), thereby assuring the customer of the manufacturers confidence in the product.

In order to maintain the established product image, 'high tech.', 'state of the art', material should be minimal, to assist the existing brochures. A single picture and statement such as an engineer sat at a computer work station, having a heat output distribution graph portrayed on the screen could be presented. The text might read "Computational Fluid Dynamic computer design software works alongside icing tunnel experimental tests in comprehensive design studies".

8.2 Company Image

Many of the implications of the research for the product image apply to a lesser extent to the company image. The overall company image, once the new spraymat design method is established and new computer system installed, will benefit from the same modernisation. This modernisation of the company image is making a gentle introduction which will probably accelerate to a reasonable level during the next decade. This is the most effective manner in which to modify the company image thereby avoiding confusion amongst customers resulting from the changes, and maintaining the well established reputation for "experience". Acceleration of this modernisation will come through computerisation of design methods in all the other product areas of the company. Plans for computerisation of all other areas are already in the development stage.

8.3 Cost Benefit Analysis

Research Programme Financing

First Two Years

	1000's
1. Research engineers time at 'charged out' rate 2 x 1681 hrs @ 19.00 per hr	63.9
2. Cranfield student registration	3.6
3. Ice adhesion test rig manufacture	2.0
4. Adhesion rig operation	0.2
5. Stationery (including magnetic media)	0.1
6. Support Committee (meals, travel, time)	1.5
7. Travel and time - student	2.0
8. Travel and tuition - tutor	3.0
9. SERC grant	-5.6
10. Short course accommodation	1.0
11. Visits - travel	0.5
Total	<hr/> 72.2

Final Year

1. Research engineers time at 'charged out' rate 1681 hrs @ 19.00 per hr	31.9
2. Cranfield student registration	1.8
3. Stationery (including magnetic media)	0.1
4. Support Committee (meals, travel, time)	0.5
5. Travel and time - student	0.3
6. Travel and tuition - tutor	0.2
7. SERC grant	-2.8
8. Short course accommodation	0.4
9. Visits - travel	0.1
10. Icing tunnel observation - travel and accommodation	0.3
11. Photographic and thesis	0.2
Total	33.0

Total research programme cost = 105.2
Charging engineers time at salary + o/h, = 54.4

The argument for charging the research programme engineers time at full 'charged-out' rate is that if not employed on this research programme, he could be earning the full rate for the company on another scheduled regular engineering project within the department. However, if this were the case, then the research programme could not have also been effected. If the full rate on another project were to be earned in addition to effecting the research programme, then another engineer would be required, and thus the cost would not be a part of the research programme costs. Thus, it is postulated that the research programme is an additional manned project, and not an alternative one to work that could be effected 'instead'. Therefore it is correct to replace the full rate with the research engineers salary plus overheads (say 15.0 pa) resulting in a total programme cost of 54.4. The computer hardware/software costs have not been included as they are well justified by the numerous other applications to which they relate. The computer time spent on spraymat design is only a small fraction of the total computing time utilised by the department.

Cost Savings

Assuming that the option is taken to increase the detail given to each spraymat design proposal in preference to effecting a time saving for the current level of detail, the main areas for creating savings

are in reduced testing and development, and increased design proposal acceptance rate.

For obvious commercial reasons, it is not the intention of Lucas Aerospace to relate detailed information regarding design proposal success/failure rate. It is sufficient to say that the cost savings generated by a simple reduction in icing tunnel testing of one week on each of six projects will compensate the total cost of the research programme, shown earlier in the cost benefit analysis. Should the improvements to the design method brought about as a result of the research programme, effect a successful proposal where previously it would have failed, then the financial implications for one reasonably large order are capable of compensating the whole research programme costs several fold.

Assuming a reasonable increase in proposal success rate brought about as a result of the research programme, then in addition to the potential savings, there will also be an increased margin of choice when deciding which specifications to act upon. Hence, the risk involved in determining which projects to accept is reduced, which on a statistical basis in the long term will yield a lower acceptance of 'risky' projects. The actual financial savings generated as a result of this reduced risk and increased ability to choose are difficult to estimate, being probability based, but are potentially large should an unprofitable project be avoided.

Also difficult to estimate on a financial basis, are the long term increased income benefits of improved product and company images described in previous sections within "Commercial Implications of the Research".

9 CONTINUED RESEARCH AND DEVELOPMENT

The progressive development of the design method established in the research programme is subdivided into short term and long term projects.

9.1 Short Term

The timescale over which "Short Term" refers to in this context is estimated to imply 'during the twelve months following completion of this research programme'.

9.1.1 Multi-Element Bodies

The 'panel strength' approach of the CFD panel method adopted is sufficiently flexible that, with a modification probably of the order of complexity and magnitude as the 'floating aft stagnation point' modification described previously, multi-element bodies could be accommodated. Thus a configuration of more than one body, such as the two air intake lip profiles at opposite faces of the duct, could be simulated simultaneously. This assumes a reasonable duct mouth diameter to duct wall thickness ratio exists, or that a part of the duct which may be considered two-dimensional, such as the central part of a typical 'chin' intake opening, is under consideration. Thus the influence of each body on the flow circulation around the other body (or bodies) is effective in the calculations. Complex three-dimensional boundary layer interactions such as those situated at the wing root, or wing/nacelle interface are not accommodated, but relatively simple quasi-two-dimensional arrangements such as slotted flaps, wing/slat, etc. should present no major problems.

This modification would also prove useful as an addition to some of the long term more complex modifications described below, where a section through the complete configuration results in an arrangement of several bodies, e.g. a 'splitter' web, strut, propeller shaft tube or diaphragm inside an air intake duct.

9.1.2 Specific Experimental Test

Should the financial resources become available, the design system would benefit from a specific validation test schedule. This would take the form of a series of icing wind tunnel tests at the Lucas Aerospace 'Artington' facility on a model intake duct designed for the tests. Thus the model would be an axisymmetric duct of reasonable duct mouth diameter to duct wall maximum thickness ratio of say 6:10, a constant wall section round 360° of arc, and extending sufficiently downstream to define the simulating complete aerofoil as far aft as its maximum thickness. Therefore the defined duct wall streamwise length to duct mouth diameter (across the highlights) ratio should be of the order of 3:5, and the duct wall maximum thickness

should occur before the trailing edge of the 'true' part of the duct model.

The tests themselves, in order to fully validate the new computational method, rather than be based on FAR 25 specifications for intermittent icing flow, should be comprised of continuous icing flows of constant liquid water content and droplet diameter. The model does not require a de-icing (or anti-icing) system, as it is the ice accretion catch area and accretion shape which are of importance in these tests, without the influence of a de-icing system. As it is not possible to produce an icing flow of single droplet diameter, it would be advantageous to correlate the ice catch limits with the maximum droplet diameter present in the flow, taking the catch limit at the extreme aft limit of rough, dispersed, light accretion. However, for ice accretion shape (and accretion rate) purposes, the droplet median volume diameter (MVD) should be employed, as normal.

These tests should be carried out each with constant parameters of temperature, pressure, liquid water content (LWC), droplet MVD and airflow speed, for a range of values of each individual parameter. Thence it would be possible to produce curves of relationships between parameters. At the end of each test (after a predetermined 'time in icing'), a recording must be made of the ice accretion shape. This would be effected either by spray paint silhouette, as used by R. Gent at Artington (Bib.932), or by constructing a mould on the ice accretion and subsequent production of a full three-dimensional permanent replica for observation and measurement. This has been successfully achieved by the Artington icing tunnel staff on previous occasions using a silicon moulding material.

The results of such a comprehensive test schedule would provide useful reference data for future design studies as well as validation of the computational method. As detailed earlier, there is very little comprehensive engine air intake icing experimental data available to date. The major reasons as to why such extensive experimental test data is not abundantly available are that such a comprehensive programme would take of the order of two weeks of tunnel testing (at two tests per day), including two for 'setting up' and one for 'pulling down'. That is, assuming only two values of LWC and MVD with five values of temperature and speed, and two values of time-in-icing. It would be much more effective to consider a minimum of three values of LWC and MVD with five values of temperature and speed, and three values of time-in-icing, giving over 50 different values of droplet inertia parameter and scale factor ("Sample Calculations"). It will be appreciated that a more feasible test programme would include eight to ten tests over a period of one week, of check point values of the parameters for comparison with theoretical predictions. This approach would require the 'TEMP1.DAT' file comparison support as before. It is the long test time and test cost resulting in a lack of design data which originated the requirement for effective computational theoretical approaches used as design tools (see "Commercial Justification" and "Technical Justification").

9.1.3 Heat Output Calculation

To render the output of TRAJ2/3 more directly employable in spraymat design, it would be useful to reduce the level of results manipulation effected outside the software by the engineer (manually), by extending the degree of processing to which the software currently extends. Therefore the icing catch efficiency and ice accretion growth rate data would be employed in a 'post-processor' to TRAJ3 to develop 'heat required' data. The heat output (from the outer surface of the body) required to melt the accreting ice and/or evaporate the water running over the surface (including accumulative runback water) could be calculated to yield a heat output distribution. By incorporating the core methods of the one-dimensional (and possibly two-dimensional) thermal transient programs (from RAE), this information could be used to generate a spraymat area and heat output 'map' ie. at a finite depth within the composite laminate, including heat lost to the body in both 'inward' and 'outward' directions. Thus the final output to spraymat design from the software system, would be a contour map showing the spraymat area, shape and heat output distribution.

This approach is better suited to anti-icing cases where quasi-steady-state conditions may be employed. However, by employing a few general assumptions regarding the shedding efficiency such as the percentage of the total ice accretion effectively shed at each cycle, or the number of cycles required to completely remove the accretion, it is not inconceivable that the method could be extended to include de-icing (cyclic heating) cases.

9.2 Long Term

The timescale over which "Long Term" refers to in this context is estimated to imply 'during the three years following completion of this current research programme' ie. during the two years following the 'short term' projects.

9.2.1 Heat Transfer Coefficient Experimental Test

Existing information on heat transfer is located in the Bibliography.

The heat transfer coefficients (HTC's) used presently are developed from cylinder values based on Reynolds number. Once an initial fine ice layer has been accreted, then the 'rough surface' heat transfer coefficient algorithm is adopted to replace the 'smooth surface' version employed before the ice begins to accrete. Heat transfer coefficients are predictable from cylinder values for bodies not too dissimilar to a cylinder, but decrease in relevance as the authenticity of the similarity deteriorates. Thus a range of values of HTC for intake lip profile body shapes of varying wall thickness to leading-edge-to-maximum-thickness chord, ratio for ranges of values of LWC, droplet MVD, temperature and speed would be useful.

As for the experimental icing data, this would require a long test programme. No ice accretion is required in order to calculate the 'clean body' HTC. Given the relationship between clean body and iced body HTC for a cylinder and values of clean body HTC for the non-cylindrical bodies, predictions could be made, aided by experimental data at a few test points, of the iced non-cylindrical body HTC's. In order to determine the clean non-cylindrical body HTC, only a short time is required for each test, ie. for the temperatures to stabilise. A large number of tests may be effected in a day. Assuming five minutes per test or 50 tests per day, allowing for five values of airspeed and temperature, two days setting up, one day pulling down and say six icing test runs, the test programme need not extend over more than eight days (excluding the model design and manufacture time).

A further compromise allowing investigation into the required power output distribution and magnitude from the de-icing system might be to employ a standard (non-icing) wind tunnel and static full-scale model of the de-iced area of the body. To enable simple observation and measurement, an 'opened out' section of the intake duct (or other body) may be employed, provided the correct flow conditions are reasonably accurately simulated by adjusting the speed and incidence. For a propeller or helicopter rotor, the velocity and angle of flow of the oncoming air over the rotating blade may be simulated by increasing the tunnel air flow velocity and by adjusting the angle of attack of the blade between tests so as to test one radial band of the twisted blade at a time. Alternatively, should it prove economically preferential, it may be advantageous to manufacture an untwisted blade allowing the whole radial extent to be analysed in one test.

As the body will not carry an ice accretion, the de-icer surface will be visible for heat output measurement during the test rather than hidden beneath the ice. It will also be possible to record response times of the de-icing system to reach predetermined temperatures at the de-icer surface in the applied wind tunnel flow temperature. This could be correlated with the temperature which would be achieved during actual flight icing conditions. That is to say, the temperature difference produced by the de-icing system and its speed of response to achieve that temperature increase could be measured and compared with that required during flight in icing conditions with some allowance for altitude, Reynolds number and humidity.

The results from wind tunnel tests could then be used to confirm theoretical results, highlight differences and develop adjustment factors and constants for application to the theoretical formulae to yield practical heat transfer coefficients for design purposes. It may also be possible to use the recordings of one or more previous flight trials on other work to support the validity of the experimental tests which, in turn would support the theory. No flight trial heat transfer coefficient measurement test reports have been located during the bibliography search to date.

Once installed, this design system could not only be employed in determining de-icer power levels and distributions tailored to intake

designs, but in design comparisons between different types of de-icing systems.

9.2.2 Spraymat Power Calculation

Once the "Heat Output Calculation" modification is successfully implemented in the software and validated, an additional modification would be to employ 'required heat output' data to determine the spraymat element electrical power distribution. The 'Watts per unit area' heat power output of the spraymat is converted to 'Watts per unit area' electrical power input to the spraymat. This is effected by employing a suitable 'band width' for the elements then converting the curve of power against distance aft of the leading edge into a histogram. The original 'smooth' curve joins the minimum values of the histogram. Thus there exists a slight 'overkill' but no under estimation. It may also be possible to develop an option within the software, whereby the spraymat band width is generated rather than input. This width would be a function of proximity to the leading edge of the body, radius of curvature of the surface and rate of change of spraymat power distribution with distance. Obviously a small radius of curvature, or rapidly changing power distribution with distance would require a narrow band width, and vice versa. However, many spraymat systems are a combination of anti-icing and de-icing element patterns. Anti-icing is employed at the leading edge to form a 'breaker strip', to split ice accretions which 'wrap over' the leading edge, to prevent them from remaining in place under air pressure once debonded from the substrate surface. De-icing elements are employed thence aft to the aft de-icing limit. This type of combined system would dictate to some extent the band width in the leading edge area by specifying the location of the division between elements of anti-icing and de-icing operation. Provision for such a breaker strip could be incorporated in the software.

For the de-icing elements of the spraymat, by employing a de-icing cycle time, the element power to melt the ice at the bond interface could be calculated. As for the element band width, an option for cyclic timing generation within the software could be provided dependent on element power level, ambient temperature and allowable maximum ice thickness. The allowable maximum ice thickness could be presented as an input within the input data files, chosen from a list of default values based on application, or even assessed from drag or weight increase considerations which are calculable from the information already held within the software.

9.2.3 Ice Shedding

An area for improvement and expansion of the existing knowledge, is in the study of the shedding characteristics of accreted ice from a substrate in flight. This is difficult to effect due to the problems associated with observation of the phenomenon. Thus, should the theory be developed, its validation would prove difficult. Differences between applications would make generalisation to reduce the data

required, just to cover all typical design cases, difficult and uneconomic.

The theory would require knowledge of the fracture mechanics of ice accreted on air intake ducts which would require a good knowledge of the physical characteristics of the ice, and their variation with ambient conditions and applications. The behaviour of ice under mechanical loading is well reported in the literature (Bib. - 1), but its behaviour, on a crystallographic scale under the influence of centrifugal and aerodynamic loads is not well covered. Hence the a European icing/de-icing research project to investigate the physical and mechanical fracture characteristics of 'aeroice' in addition to adhesion and thermal properties is currently in the initialisation stage, and will include input from all major European aerospace industries. Thus the three major areas of this research programme; ice adhesion database compilation (and bibliography); preliminary 1-D study of the thermal characteristics of ice accreted on a heated non-metallic substrate; and, development of an available 2-D accretion prediction code for application to engine air intakes; will continue to be researched and their combination to form a new modern de-icing system design method will continue in subsequent icing research projects.

9.2.4 3-D Trajectories and Design

Three-dimensional droplet trajectory programs are beginning to emerge (Bib.- 9.2) but are not commercially available yet. The development of a full three-dimensional icing software package within the sponsoring company would require a great deal of effort and time. Additionally the operation of such software as operated by other organisations (e.g. Boeing/NASA) requires 'CRAY' type supercomputers. The purchase of such a computer system at Lucas Aerospace is not conceivable within the next five years, but the rapidly advancing technology of personal transputers could open up definite possibilities for running 3-D CFD software in the engineering department at Lucas Aerospace, Luton.

It is predictable that before such a task of producing the 3-D CFD software 'in-house' (at Lucas Aerospace) could be accomplished, relatively well established and validated packages will become commercially available capable of 3-D trajectory data generation. The increasing importance given to, and interest taken in, the effects of aircraft icing worldwide (as described in "Commercial Justification"), may soon lead to the commercial availability of complete 3-D icing and even engine air intake 3-D icing software packages for use on PC's equipped with transputer boards. Therefore it is considered that this aspect of the progression is not economically viable for internal (within the company) creation, but may be satisfied in the future by simple commercial acquisition or employment of the services of a computer hardware/software bureau.

9.2.5 Spraymat Element Pattern Design

Another design aspect for inclusion in the software system could be spraymat electrical element pattern design, presently carried out manually. The variables concerned are element band width, element thickness, element band length, system area, overall power, and voltage, electrical phasing of various area partitions of the de-icer and the physical metal spraying limitations such as spray angle, coating thickness, coating material, inter-element separation, substrate material, etc.. All of the variables are interrelated. Another consideration is the accuracy of calculation of surface area, or band length, width and area on a three-dimensional surface with often complex curves, relatively sharp radii, reflexes and occasional relatively sharp edges and corners. Currently this is not satisfied by any of the relatively less costly hardware/software systems available, especially considering the complete element pattern 'lay-up'. This is presently effected within the company by physical design construction using a full-scale model of the body and adhesive tape. Furthermore, it is arguable that if such a software package became available in the near future, unless extremely 'high level' (ie. a 'SMART' system), the time and effort required to gather arrange and input the data, run the system, and interpret the output, would be greater than that required to effect the existing manual approach.

However, quasi-two-dimensional bodies, ie. three-dimensional bodies of relatively constant section, such as helicopter rotor blades present a much simplified task to the software compared with complex three-dimensional engine air intake ducts. Thus complete spraymat element design by the software on these bodies may present a viable area for research. It must be noted though, that the current manual element pattern design method for these bodies is equally simplified over the three-dimensional engine intakes and therefore the economic advantages of effecting the operation by computer must be analysed first.

9.2.6 Viscous, Compressible and Transonic Flow

As the detail and accuracy of the software CFD package is developed, the criteria of viscous flow effects, compressibility and the transonic flow regime must be effectively addressed. These topics have been considered to some extent in conjunction with CFD and to a lesser extent with additional icing considerations (Bib.1314,1316). They are fully incorporated in the 3-D icing suites developed by some major aerospace organisations, but result in a complex and inherently large software system requiring a 'supercomputer'.

The introduction of these criteria to quasi-two-dimensional systems is not unrealistic as a long term modification for development of the software in continued research in this area of interest.

9.2.7 Duct Internal Flow

Most aircraft engine air intake ducts are not of simple shape. They tend to possess reflex curves, corners, constrictions, diffusions, bifurcations, flow separators, debris collectors, cross members, etc... Thus the assumption that between the duct leading edge lip and the actual engine face IGV's (inlet guide vanes) is a simple 'tube' gently 'blending' the inlet mouth shape to a circle, is far from valid.

Almost all of the above mentioned complications to the basic straight tube shape of the duct result in ice accretion. Even the actual construction of the walls of the duct, such as ridges produced at the intersections between components, often result in ice accretion. An 'out of wind' ridge, although not as severe in accreting ice as an 'into wind' ridge, results in a local pressure reduction in the 'cavity' just aft (downstream) of the ridge and subsequent local temperature drop. The pressure and temperature reduction often causes droplet impingement and freezing, causing ice accretion and producing a subsequent ice ridge which grows 'into wind' and provides 'anchorage' for relatively rapid ice accretion growth inside the duct.

All leading edge obstructions within the duct such as flow separator vanes, IGV's, internal shaft tubes (viz. typical turboprop unit), debris collectors ('Bird Catchers'), etc. tend to accrete ice in the same manner as the duct lip except in areas where the flow has already abandoned its water content to other substrates. Where a flow is turned through a bend in the duct, the 'into wind' (kinetic pressure rise) face of the bend is an obvious contender for trajectory impact and therefore ice accretion. However, for the same reasons as applied to the 'out of wind' ridge, the 'out of wind' kinetic pressure (and temperature) reduction face of the duct may also be an ice collector in some combinations of conditions (e.g. where the total temperature of that part of the airflow falls below 0°C. for the first time).

Thus it may be appreciated that to investigate icing well into the duct and take account of all the previously mentioned duct design possibilities, then modifications to consider 3-D CFD, 3-D trajectories, 3-D ice accretion, flow compressibility and flow viscosity must have been successfully achieved including transonic effects in cases where the flow speed reaches this regime, (at or not far aft of the lip in transonic and supersonic aircraft applications).

9.2.8 Rotating Bodies

The term 'rotating bodies' in this context applies to aircraft propellers and helicopter rotor blades (including tail rotors). There are two major fundamental differences to consider over and above those of a non-rotating body regarding icing predictions. The rotating 'in-flow' of the approaching air, and the centrifugal force experienced by impacting water and accreted ice have to be taken into account.

The airflow just upstream of a propeller with positive pitch, or just above a helicopter main rotor with positive collective pitch, experiences a degree of swirl in 'anticipation' of the disc rotation, analogous to upwash ahead of a fixed wing, but is three-dimensional due to the centrifugal effects on the airflow and therefore contains some 'spanwise' flow velocity components. This 'pre-swirl' rotation will therefore result in a motion of the water droplets relative to the flow streamlines and hence 3-D swirling droplet trajectories. Thus it can be seen that the droplets will impact the body at an angle to the free stream in the plane perpendicular to that in which incidence occurs.

The centrifugal force acting on impacted water causes it to runback in a direction having a strong spanwise component in addition to the streamwise component, thus generating ice accretion shapes considerably different to those for non-rotating bodies. This is immediately apparent from observation of the runback ice accretion on propeller blades (Figs.F20-F24, F42-F44). The centrifugal force also affects the runback water produced from ice melted by the de-icing/anti-icing system in a similar manner but not possessing the inertia of oncoming flow, merely the drag of over-flowing air in the predominantly streamwise direction. Thus the impinging runback water has a much stronger spanwise component of velocity and therefore potential for spanwise accretion than the runback meltwater, and thence leads to thicker accretions towards the blade tips. From considerations of over-stressing and fatigue inducing vibration of the blade considerations this is undesirable and thus its consideration at the design phase to produce a de-icing system to cope with it would be advantageous.

A further consideration regarding rotating bodies, particularly aircraft propellers in tractor configuration, is the effect of shed ice and water on downstream structures. The trajectories of water droplets shed from a propeller either through not freezing on the propeller, meltwater from the de-icing system, or water droplets within the influence of the propeller but not actually impacting on it, are different from those outside the influence of the propeller (or its swirling flow). Therefore these droplets may impact in areas considerably removed from the catch area of 'non-influenced' droplets. To predict the catch areas of such droplets is rather complex but not beyond the scope of a full 3-D CFD trajectory software system. Regarding ice shed from the propeller, the knowledge of its impact point on downstream structure is useful when considering the protection of equipment such as engine compressor blades, antennae, landing gear, canopies, etc.. Trajectories will prove difficult to predict for the non-spherical shed accretions where their trajectory is influenced by the aerodynamic effects of lift and drag forces created as a result of their form.

To effectively investigate shed ice trajectories, a knowledge of ice adhesion strength to the substrate is required to predict when the ice accretion will shed, or consequently, its size or mass upon shedding. To this application, the adhesion data of the "Ice Adhesion Study" would prove useful.

9.2.9 Active De-Icing/Anti-icing System

All currently existing actively controlled de-icing/anti-icing systems are controlled by either ambient air temperature (most cases) or icing rate sensors (few cases), which detect the presence of ice either by microwave or ultrasonic wave deflection or resistance, a structure resonant frequency variation, or the torque required to drive an iced rod against a chisel which removes the ice accreted on the rod. By using the CFD approach to design the anti-icing/de-icing system, the relationship between the complete aerofoil flow and the ice accretion rate or thickness at the point where the sensor to drive an active system will be installed, may be determined. The effects of the ice accretion on the aerofoil lift and drag, and local flow perturbations such as separation onset, is calculable from the information already derived within the existing software. Thus, from the knowledge gained within the computerised design system, an icing detector could be placed so as to effectively control the de-icing system dependent on the actual flow considerations derived from its local icing rate. Thus, the de-icing system could be controlled in a manner so as to comply with aerodynamic criteria as is of primary concern rather than simple ambient temperature estimated resultant ice accretion thickness. A further aspect of using the CFD approach to de-icer design is that it could be employed to position controlling sensors in areas where they will not detriment the flow and cause undesired ice accretion, or in areas where unrealistically low or high icing rates occur on a localised basis, in order to monitor a true environment. However it may prove useful to place them in a slightly artificially high water content area (due to flow interactions) in order to over predict, providing a safety margin to increase icing clearance confidence (at the risk of increased runback ice).

10 CONCLUSIONS

1. A bibliography has been compiled, citing over 1350 references, of research work associated with aircraft icing and de-icing. Such a facility was not available before the commencement of this research programme, the quantity and dedication of aircraft icing literature existing being unknown. The bibliography now forms a part of the Technical Library within the sponsoring organisation and is to be continuously updated. It has already been employed in the new European multi-national aircraft icing research consortium ('CAPRI' - Acronyms) programme, as well as throughout this research programme.
2. A comprehensive database of ice shear and tensile adhesion strength to various materials and surfaces has been compiled and combined with data derived from photographic results of flight testing. This type of survey was also previously unavailable and proved useful to the project. Continued research within the sponsoring organisation, and as a part of the CAPRI programme, is to include a large amount of ice adhesion research. Lucas Aerospace are heavily involved in the CAPRI programme and will therefore make good use of this survey. As for the bibliography, it is the intention that the ice adhesion database also be continuously updated.
3. An ice shear adhesion test rig has been designed, manufactured and operated. This involved a survey of all previous rigs to benefit the new design from past experience. Results produced using this rig were found to be consistent with those of the database. A consolidated library of ice adhesion test rigs did not previously exist, which led to the recent involvement of a few unsuccessful test rig designs by various organisations interested in ice adhesion testing. Reference to this survey indicated, in all known cases, that the problems experienced had been encountered in past designs and could therefore have been avoided. As for the bibliography and adhesion survey, this test rig survey will also prove useful during the early stages of the CAPRI programme, where an ice adhesion test rig is to be designed and built.
4. A preliminary one-dimensional study of the thermal characteristics of ice accreted on a heated non-metallic composite aircraft propeller blade in flight was effected. From this study useful knowledge and experience emerged for employment in ensuing research. At the time, within the sponsoring organisation, this type of study had not been effected in such a manner as to highlight the differences between the modern non-metallic composite and solid metal propeller blade regarding its thermal characteristics. The results were useful in supporting the justification for more complex computer prediction code application to the research.
5. An existing two-dimensional aerofoil ice accretion prediction computer program was adapted and additional software composed, to

enable ice accretion prediction on aircraft engine air intake duct lips in flight. The validation of the software has been initiated and continues as commercial projects provide the necessary financial support for experimental test work. Previously, an aerofoil ice prediction code was not available for employment on a PC, and required the use of a large, and inherently costly, mainframe computer. A two-dimensional air intake lip icing code did not exist before this research programme capable of execution on a simple PC. Hence, within the economics of the sponsoring organisation, having no mainframe computer, there is now a computerised facility to predict icing on aerofoils and intake lips.

6. This research programme, as described earlier, forms the first stage of a long term commitment by the sponsor towards a large 'in-house' icing research project. That first stage is now complete. The 'in-house' programme will continue with the research work cited in "Continued Research".
7. The 'non-technical' marketing and other commercial implications of the research programme have been investigated and the research commercially justified. Thus, the requirements of the "Total Technology" programme have been addressed and the research forms an active part of the business of an industrial and commercial organisation. The ice physics and adhesion work is already in use in further research work and the computer software resulting from the programme is already in employment in de-icing system design on actual commercial projects. Therefore the sponsoring organisation is directly benefiting from the research and its justification was valid.
8. A computer system has been justified, specified, purchased, installed and operated to run the developed software for ice accretion prediction on aerofoils and intake lips. The system is also proving useful in many other roles besides Spraymat design and continues to increase in power and size to form a large network throughout the sponsoring organisation. The technical and commercial benefits already provided by this system, resulting from this research programme, more than justify its acquisition.
9. The new ice accretion prediction and thence de-icing system design method has been incorporated in the procedures of the sponsoring organisation and employed (in parallel with the 'old' method) to answer design enquiries from a commercial customers. The initial response from the marketing section indicates a strong preference for the new design method which has now been permanently adopted. Also indicated is an improvement in the product and overall company images projected to the customer, in presenting a modern computerised approach to design, supported by engineering experience in the field.

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R1 - R17 Adhesion test rig design study options

R18 Test Rig Operation

Literature Survey Results

Figure	Test parameter	Substrate
L1	Shear adhesion	- Stainless steel
L2		- Titanium
L3		- Brass
L4		- Aluminium
L5		- Steel
L6		- Teflon
L7		- Polystyrene
L8		- Polyacetal
L9		- Rubber
L10		- Polyethylene
L11		- Neoprene
L12		- Viton
L13		- Lubricated Aluminium
L14		- Lubricated Stainless steel
L15		- Lubricated Steel
L16		- Lubricated Brass
L17		- Lubricated Teflon
L18	Tensile adhesion	- Stainless steel
L19		- Steel
L20		- Aluminium
L21		- Brass
L22		- Polystyrene
L23		- Polyethylene
L24		- Teflon
L25		- Lubricated Brass
L26	Tensile strength	
L27	Shear adhesion	- Metal
L28		- Hard non-metal
L29		- Soft non-metal

L30 - Lubricant
L31 - General (all substrates)

Flight Test Photographs

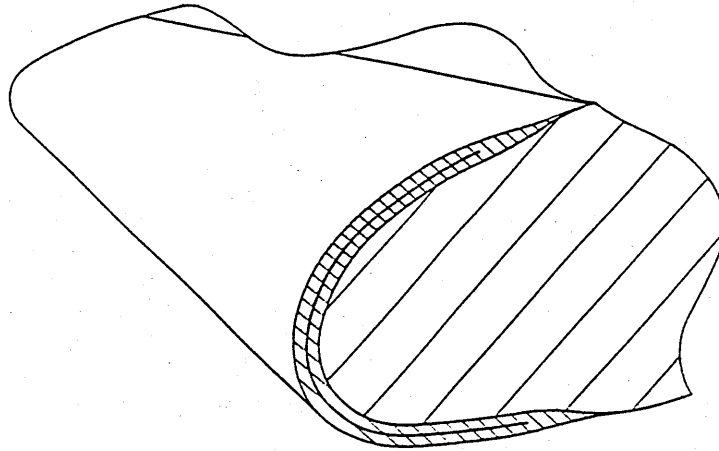
Flight	Test	Figures
952	952	F1 - F11
332	3517	F12 - F19
335	3527:1	F20 - F24
335	3527:3	F26, F27
335	3527:4	F25, F28 - F32
341	3533	F33, F44
349	3534	F34 - F36
	3543:1	F54
	3550:2	F37 - F43, F45 - F48
	3552:1	F49, F51, F52
	3552:2	F50, F53

Computer Icing Prediction Plots

P1 - P8	Developed aerofoils,	(PTRAJ2).
P9 - P28	Droplet trajectories,	(TRAJ2).
P29 - P48	Y_0 v S/C impact,	(TRAJ2).
P49 - P68	Catch efficiency distribution,	(TRAJ2).
P69 - P88	Ice accretion,	(TRAJ2).
P89 - P102	Developed aerofoils,	(PTRAJ3).
P103 - P122	Droplet trajectories,	(TRAJ3).
P183 - P187		
P123 - P142	Y_0 v S/C impact,	(TRAJ3).
P188 - P192		
P143 - P162	Catch efficiency distribution,	(TRAJ3).
P193 - P197		
P163 - P182	Ice accretion,	(TRAJ3).
P198 - P202		
P143 - P162	Catch efficiency distribution,	(TRAJ3).
P163 - P182	Ice accretion,	(TRAJ3).

FIGURES

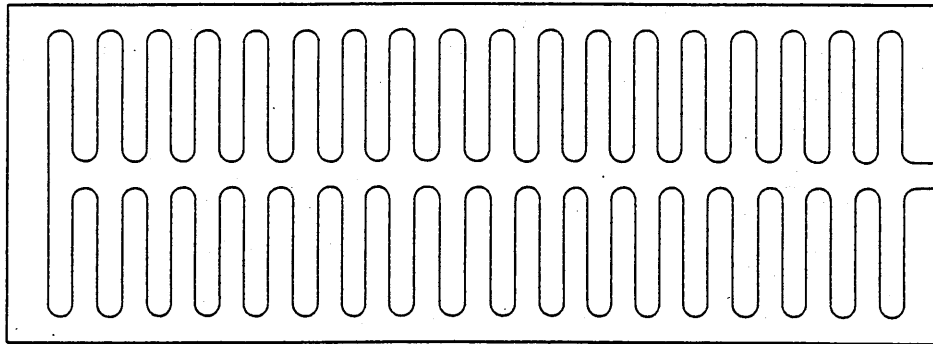
Electrothermal Rubber Overshoe



solid
non-metallic
composite
body

Fig.1(a)

Electrical wire element array



constant
section,
constant
resistivity
wire,
sewn into
glass cloth

Fig.1(b)

Pneumatic Rubber Overshoe

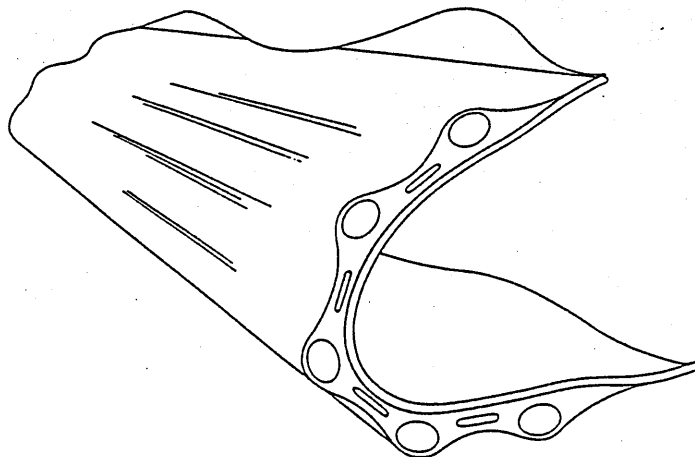


Fig.2(a)

Internal inflatable tube matrix

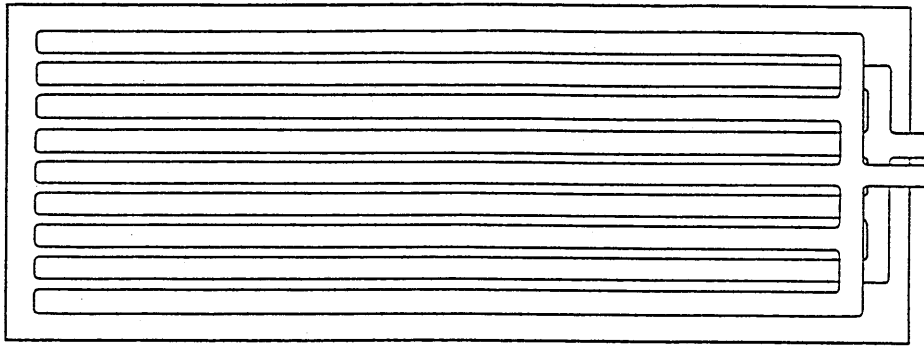


Fig.2(b)

Fluid De-Icing System

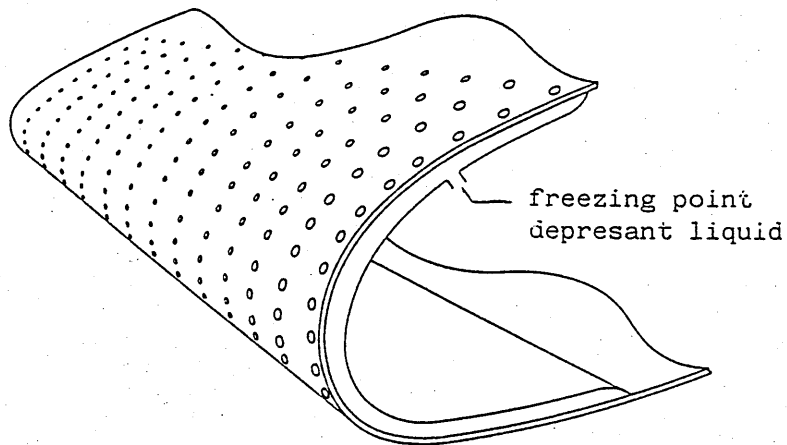


Fig.3

Hot Gas De-Icing System

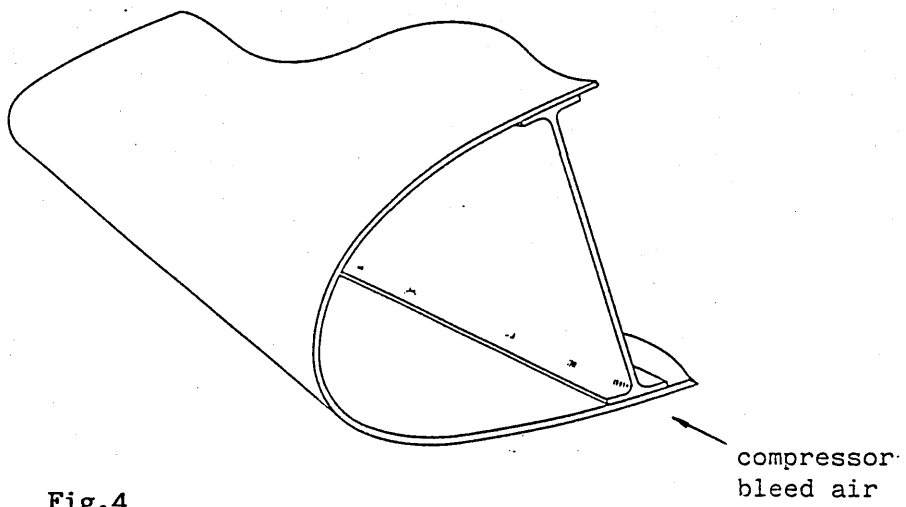


Fig.4

Electro-Impulsive System

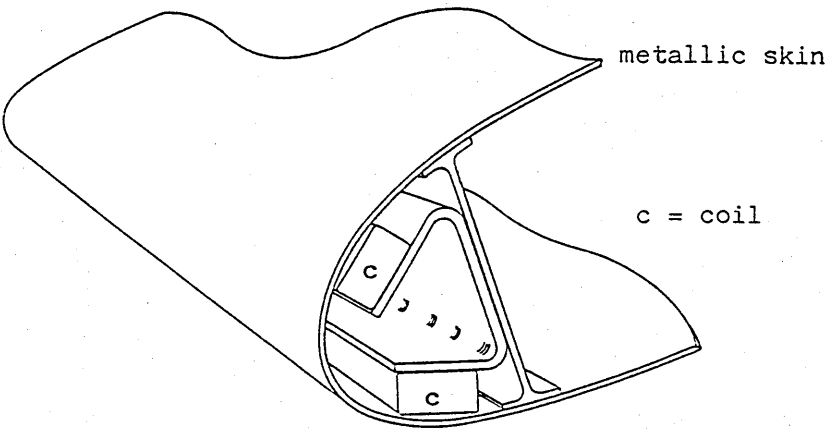


Fig.5

Electro-Expulsive System

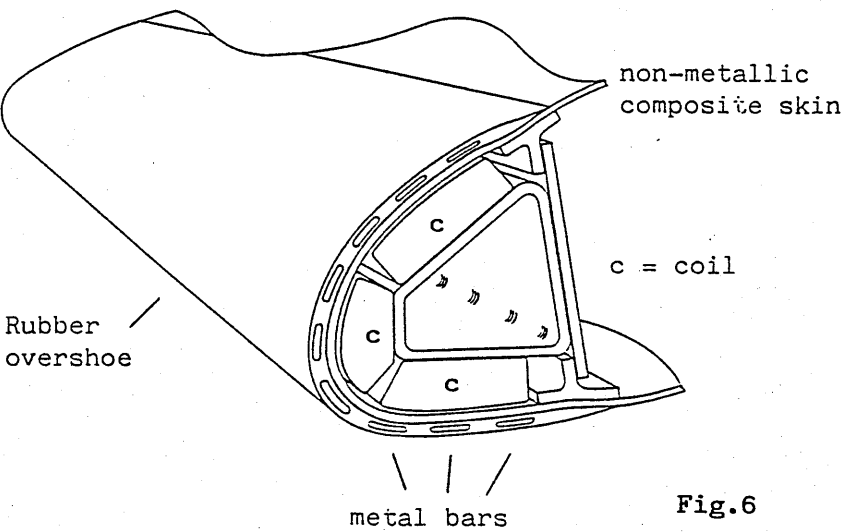


Fig.6

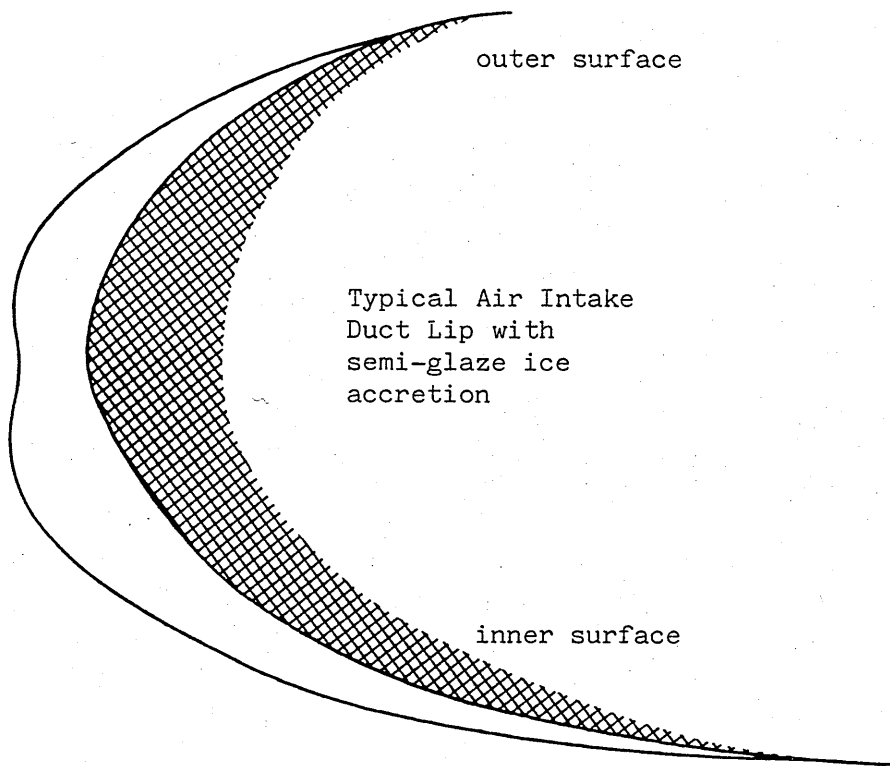


Fig.7

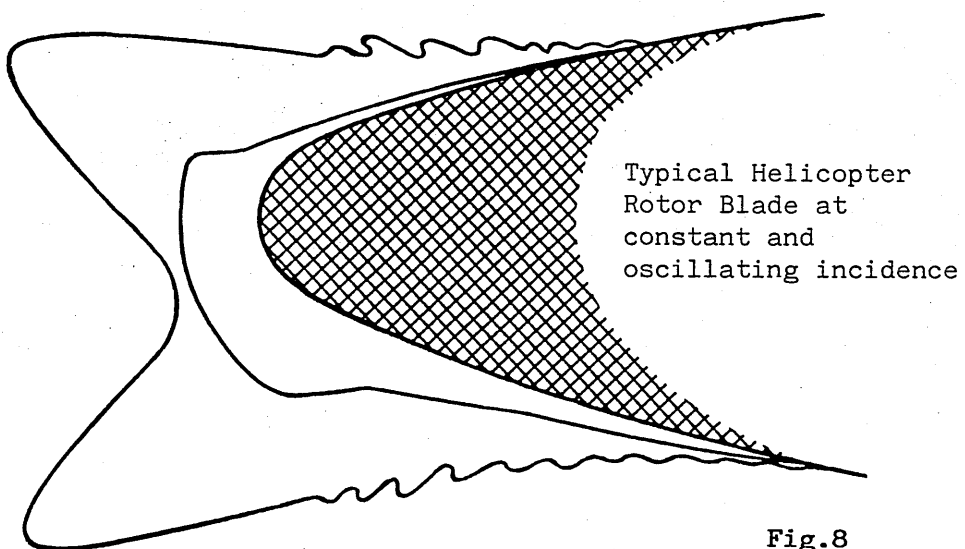


Fig.8

Spraymat

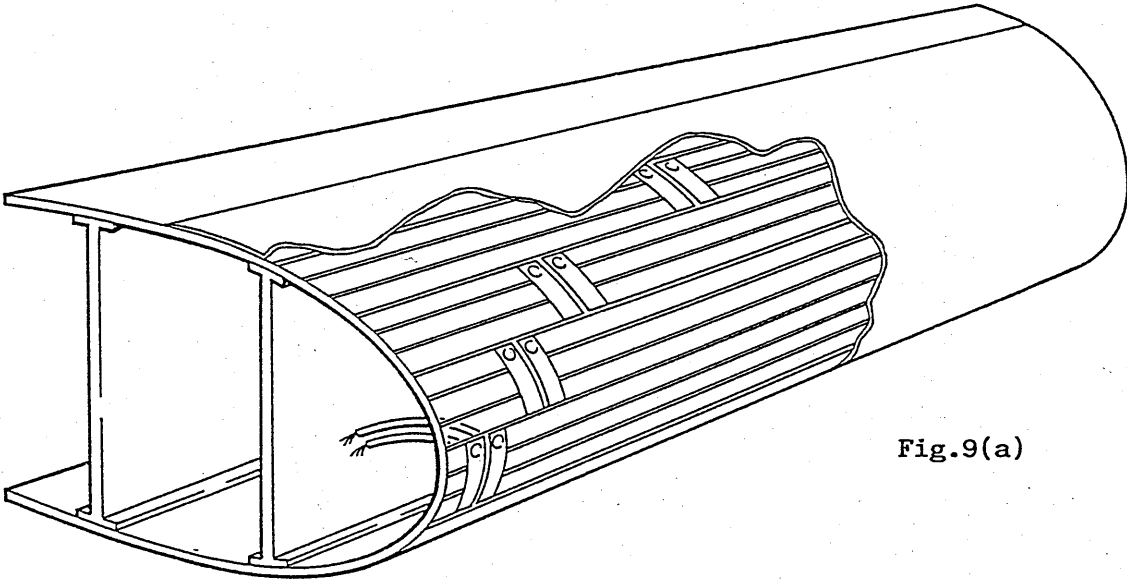


Fig.9(a)

Heat Output Distribution

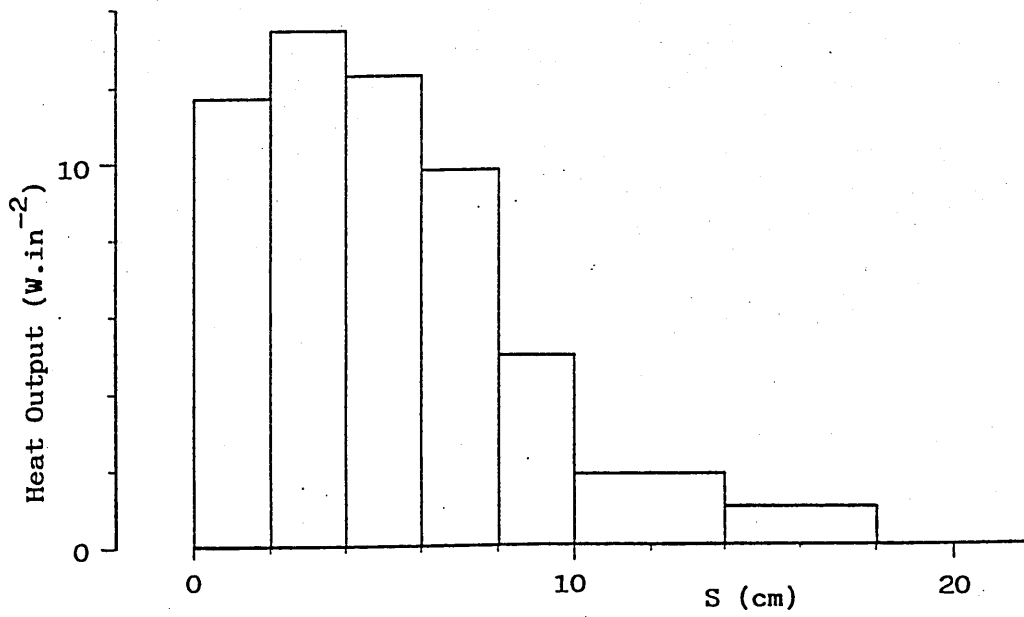


Fig.9(b)



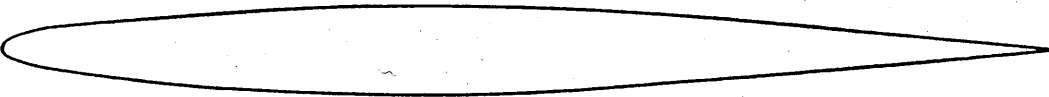
NACA 64A 006

Fig.10(a)



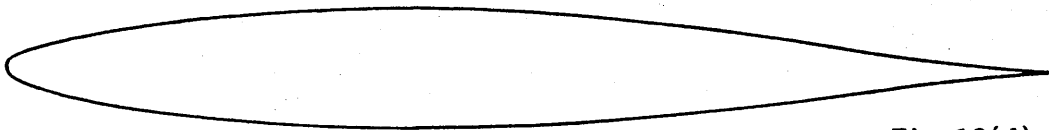
NACA 65-006

Fig.10(b)



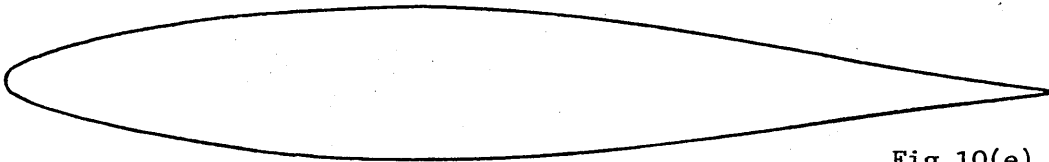
NACA 65-009

Fig.10(c)



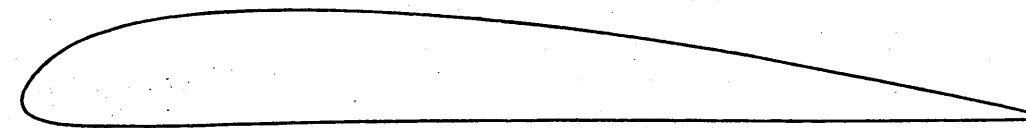
NACA65₁ 012

Fig.10(d)



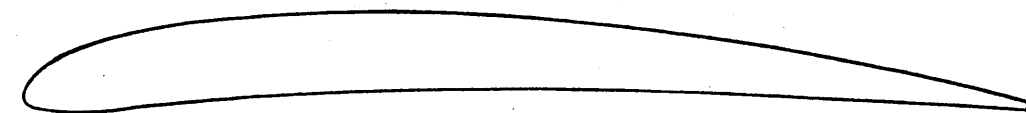
NACA 65₂ 015

Fig.10(e)



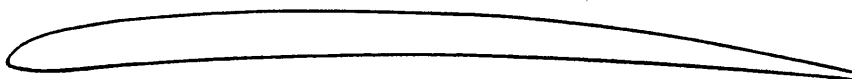
ARA-D

Fig.10(f)



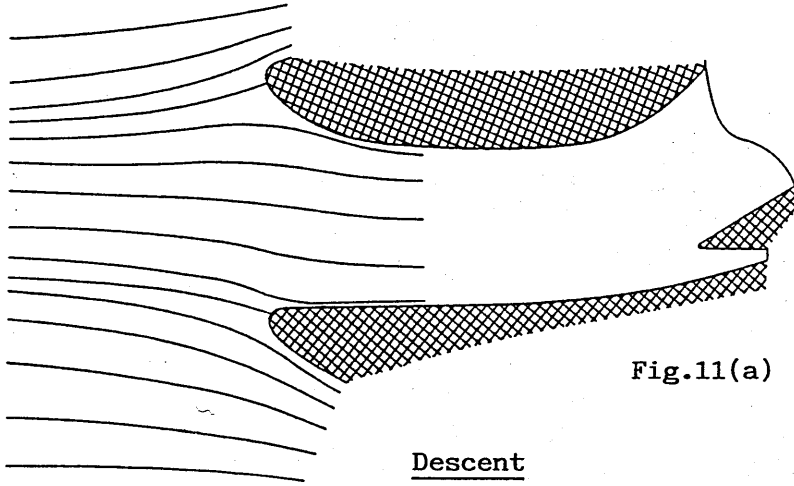
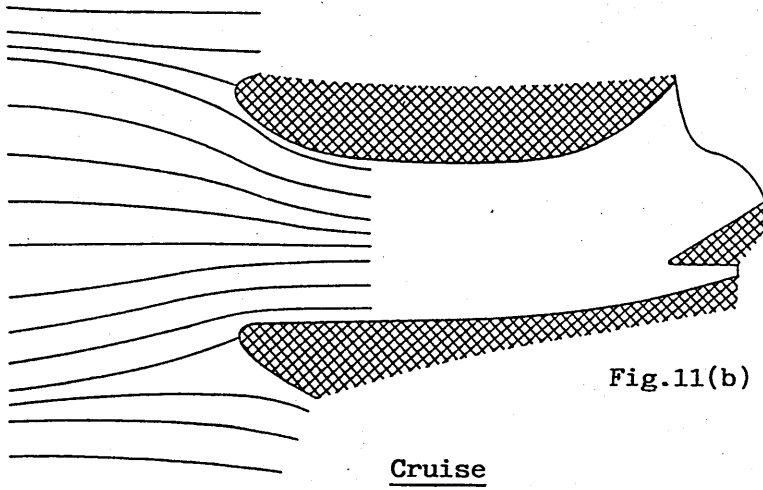
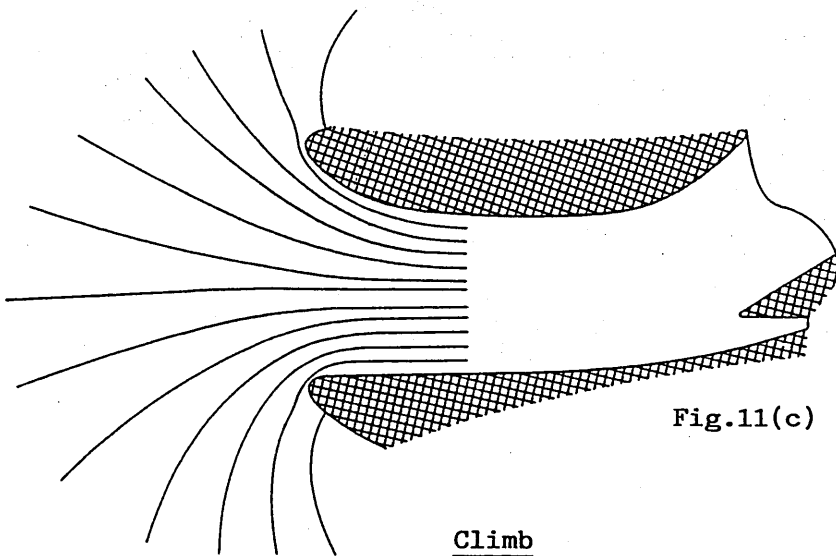
ARA-D

Fig.10(g)

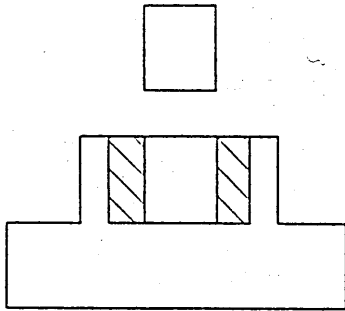


ARA-D

Fig.10(h)

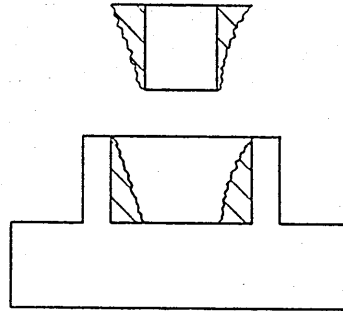


Ice Shear Adhesion Test Rig Operation



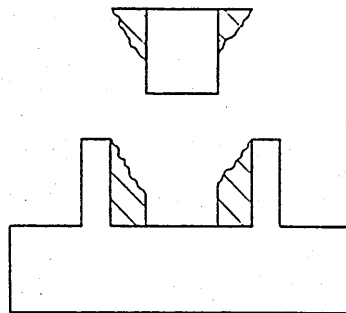
Adhesive Failure

Fig.12



Cohesive Failure

Fig.13



Mixed Failure

Fig.14

Test Rig Bullet/Breech Sealing

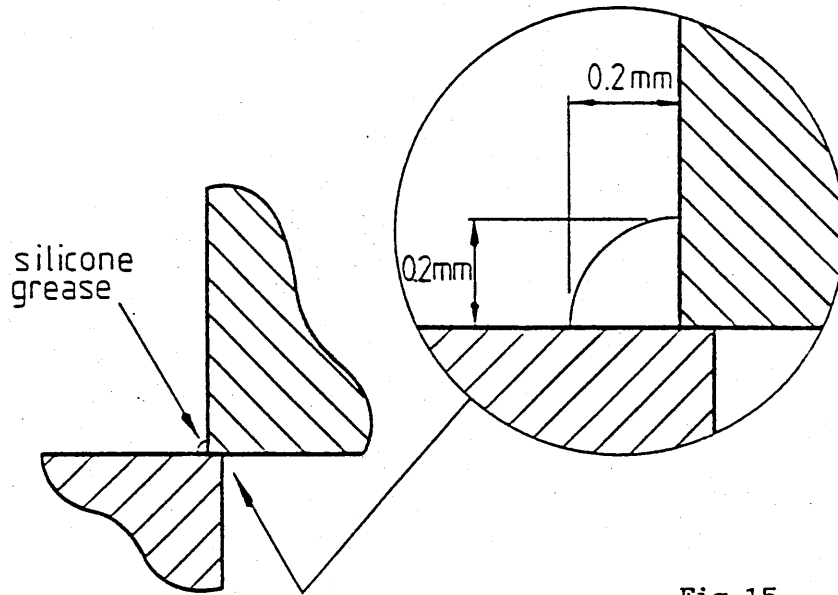


Fig.15

Ice Internal Bubble Formations - Cross Section, Side Elevation

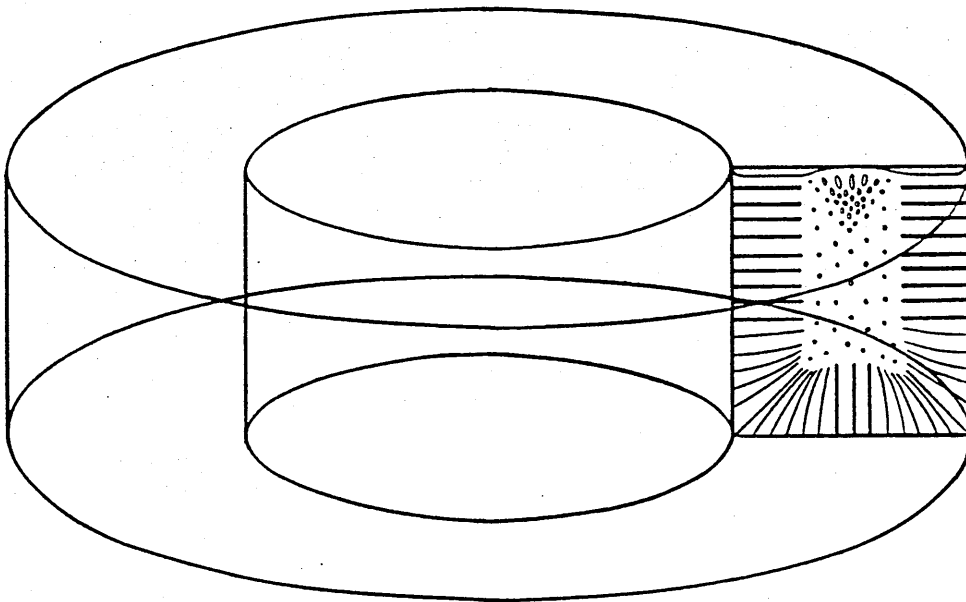


Fig.16(a)

Ice Internal Bubble Formations - Plan View

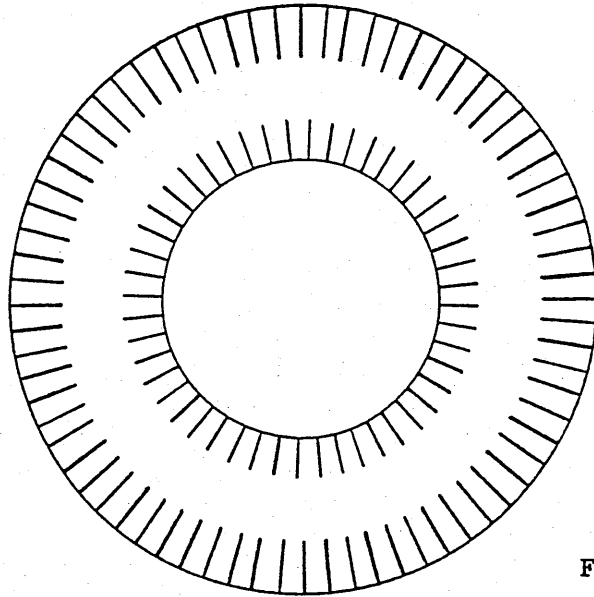


Fig.16(b)

Air Trapped During Freezing

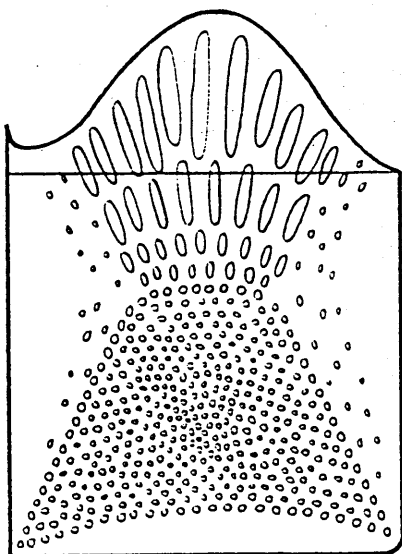
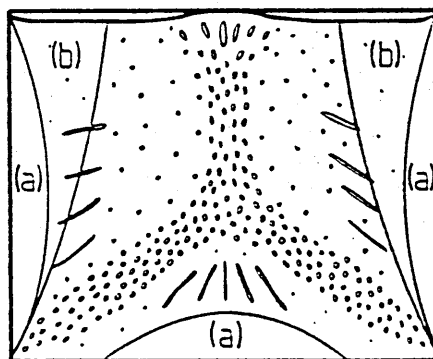


Fig.17



(a) = bubble-free zone

(b) = almost-bubble-free zone

Fig.18

Air Trapped During Freezing

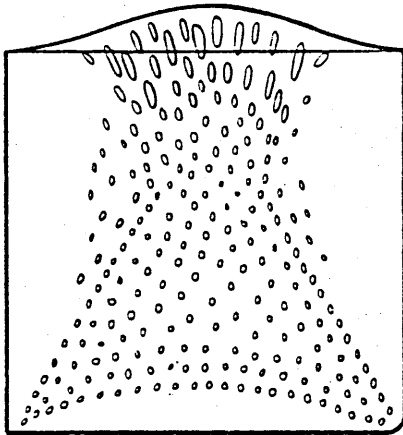
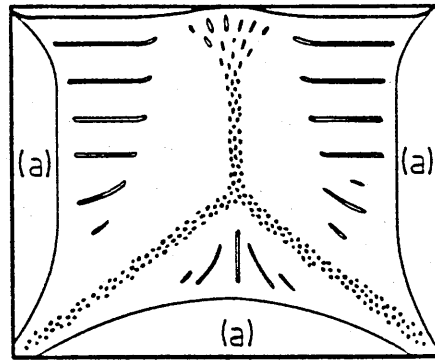
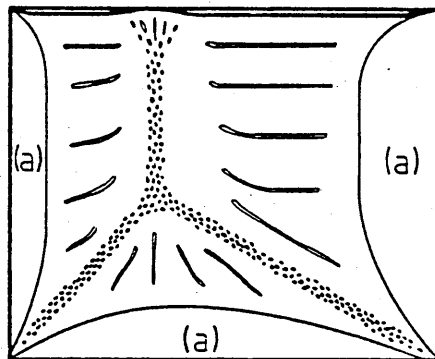


Fig.19



(a) = bubble-free zone

Fig.20



(a) = bubble-free zone

Fig.21

Layered Freezing

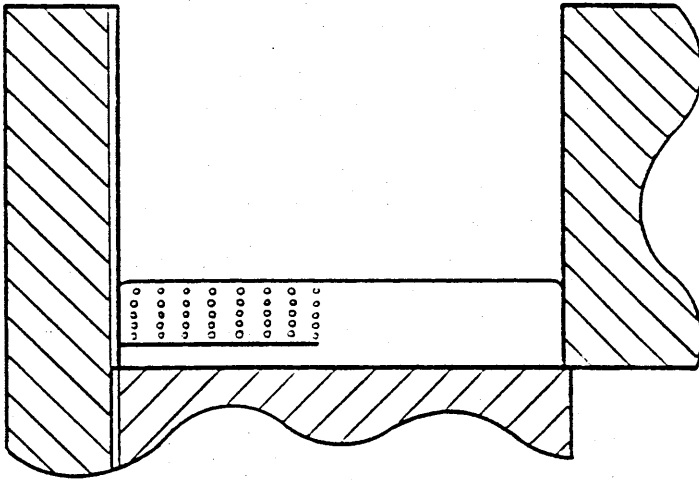


Fig.22

Flat Free Surface

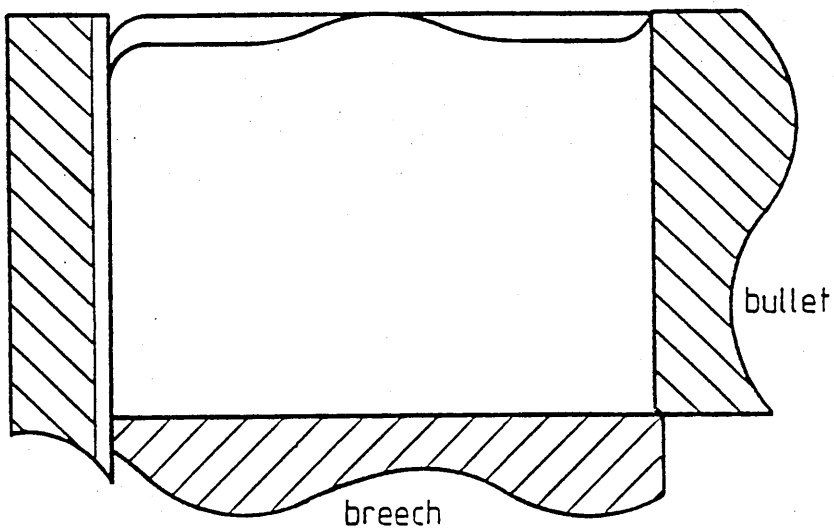


Fig.23

Free Surface Ice Crystals

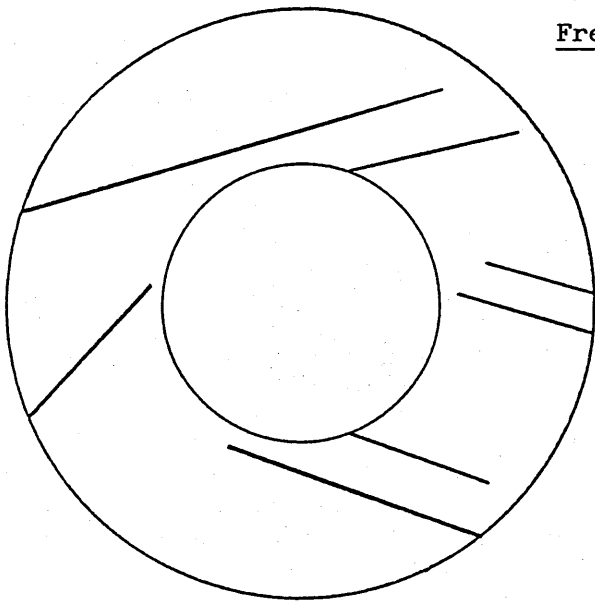


Fig.24

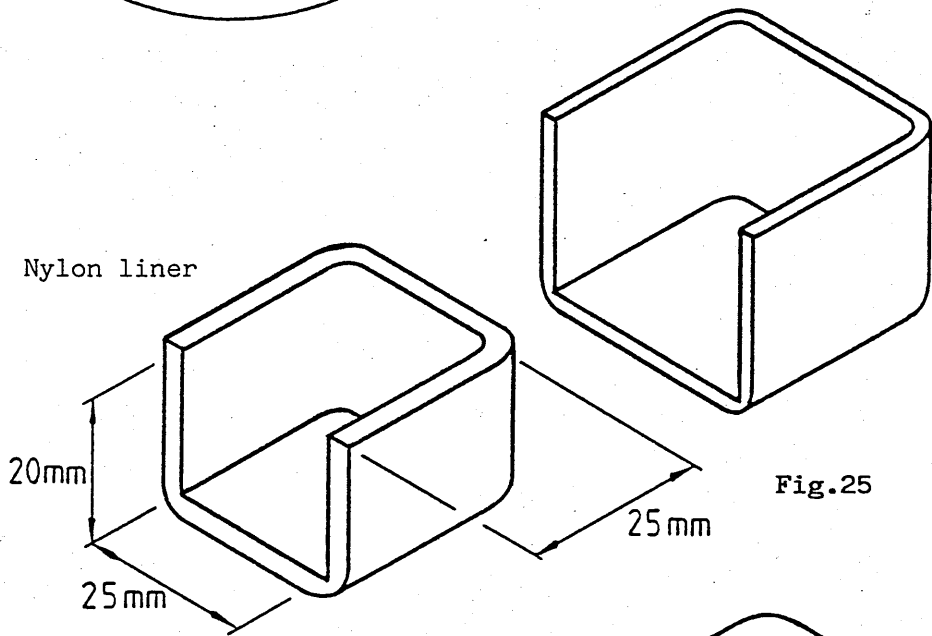
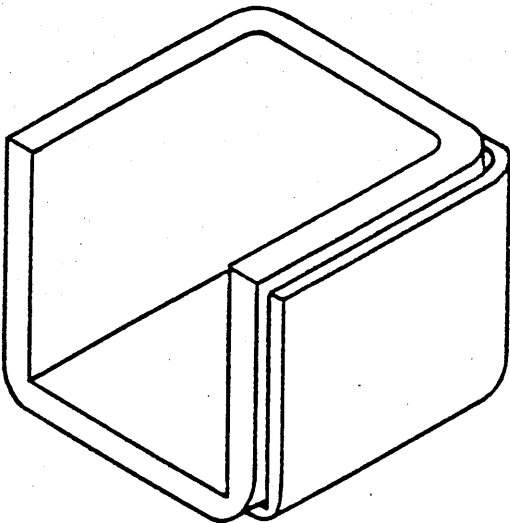


Fig.25

Ice Forming Cup

Fig.26



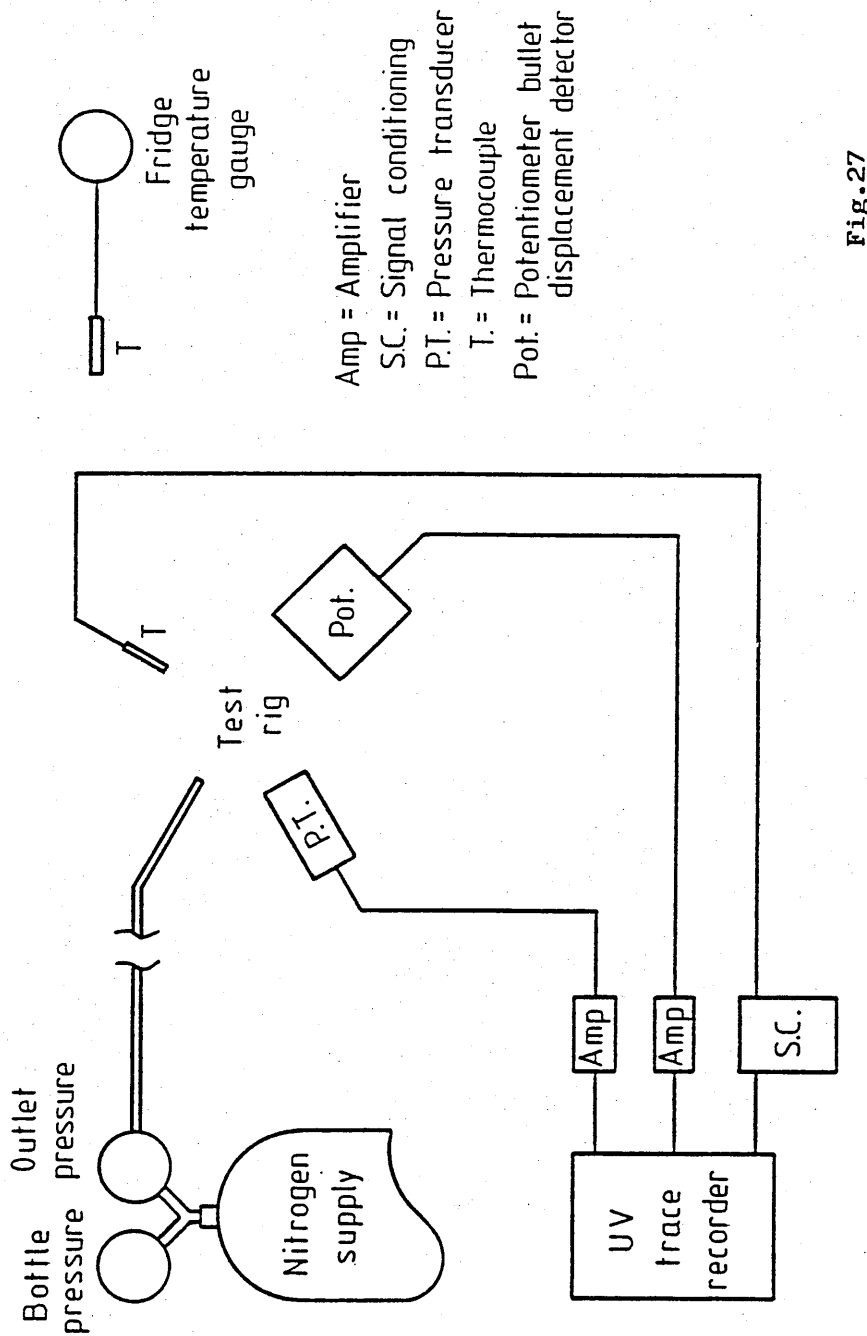
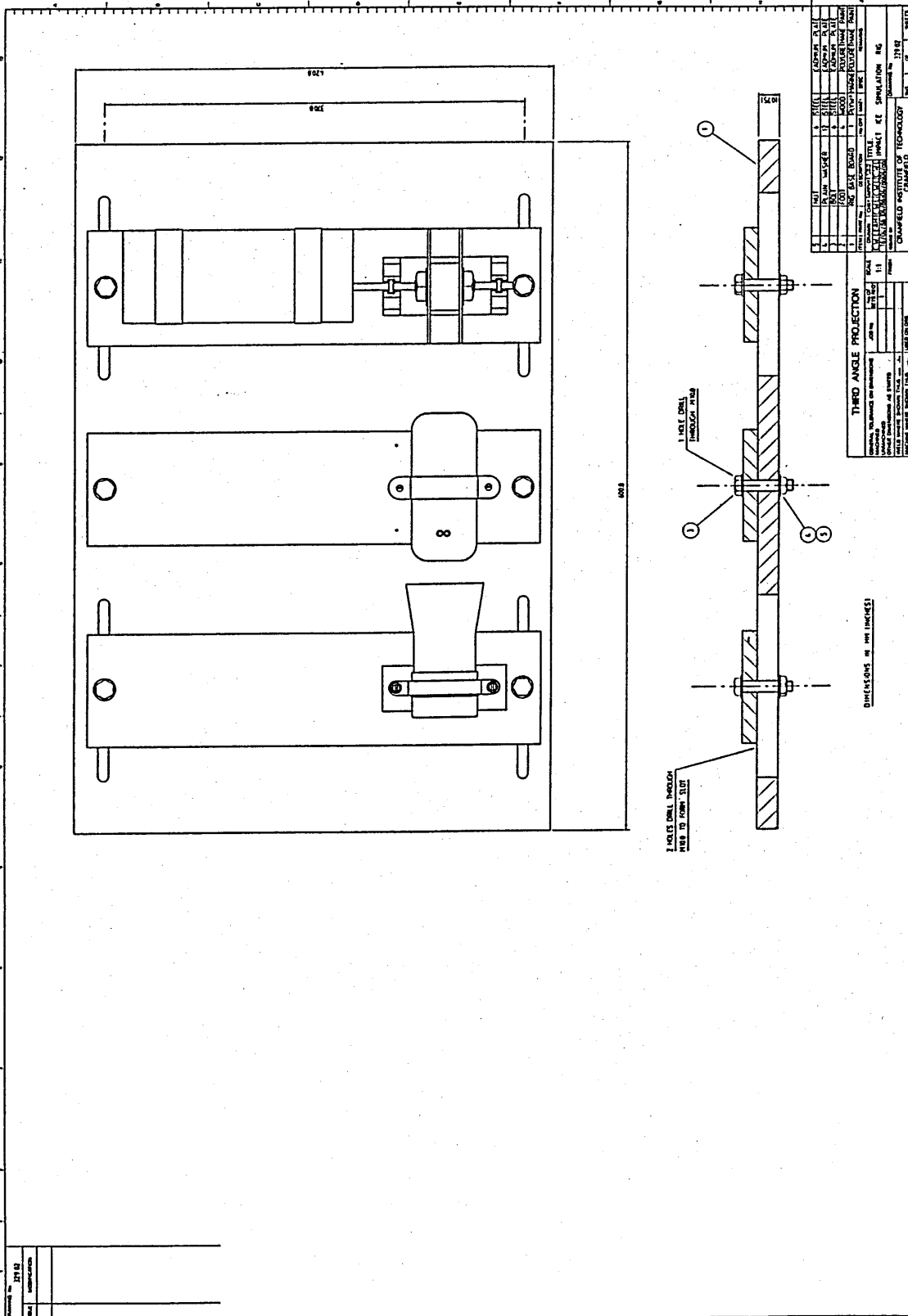


Fig.27

Test Rig Equipment Layout



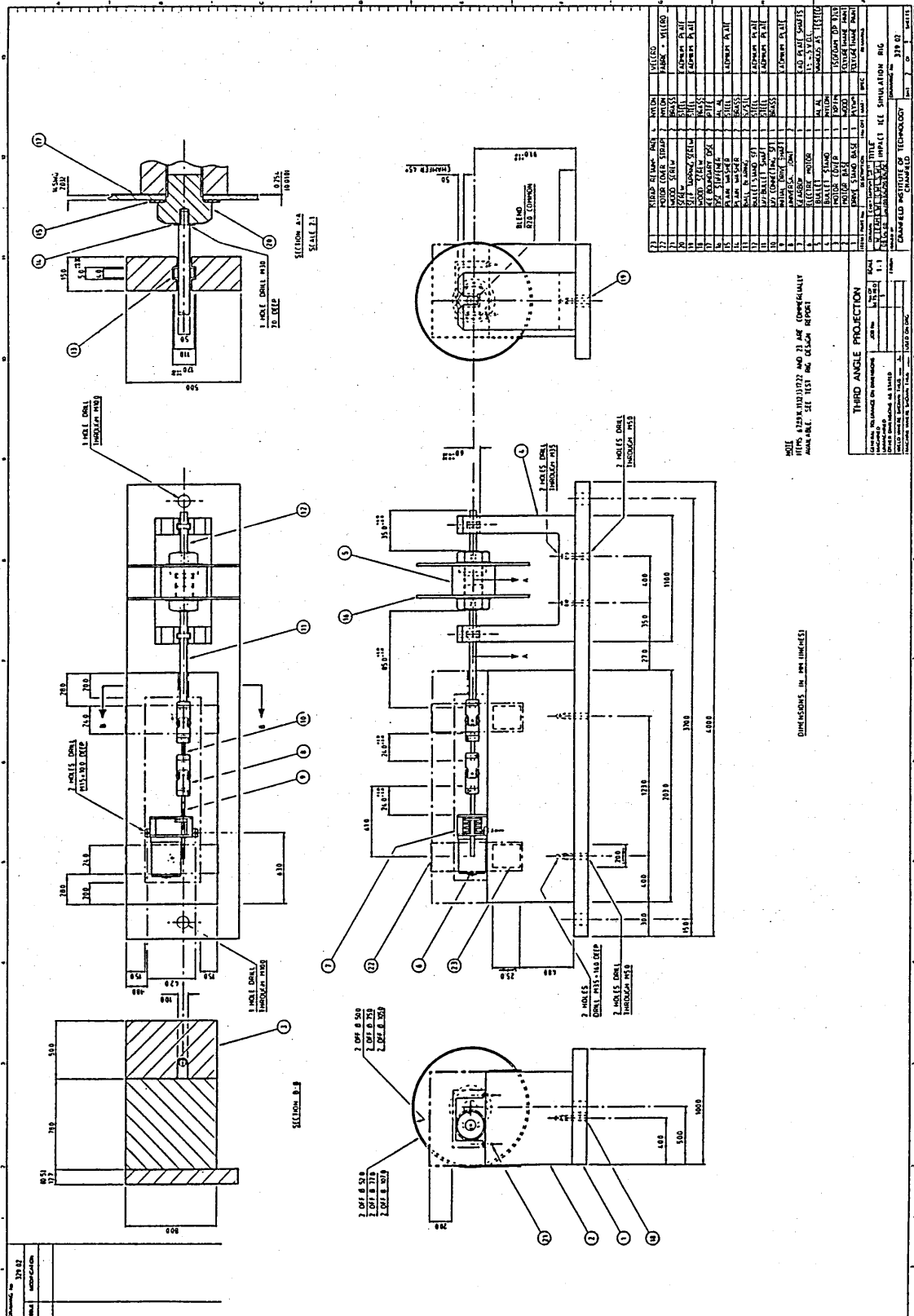
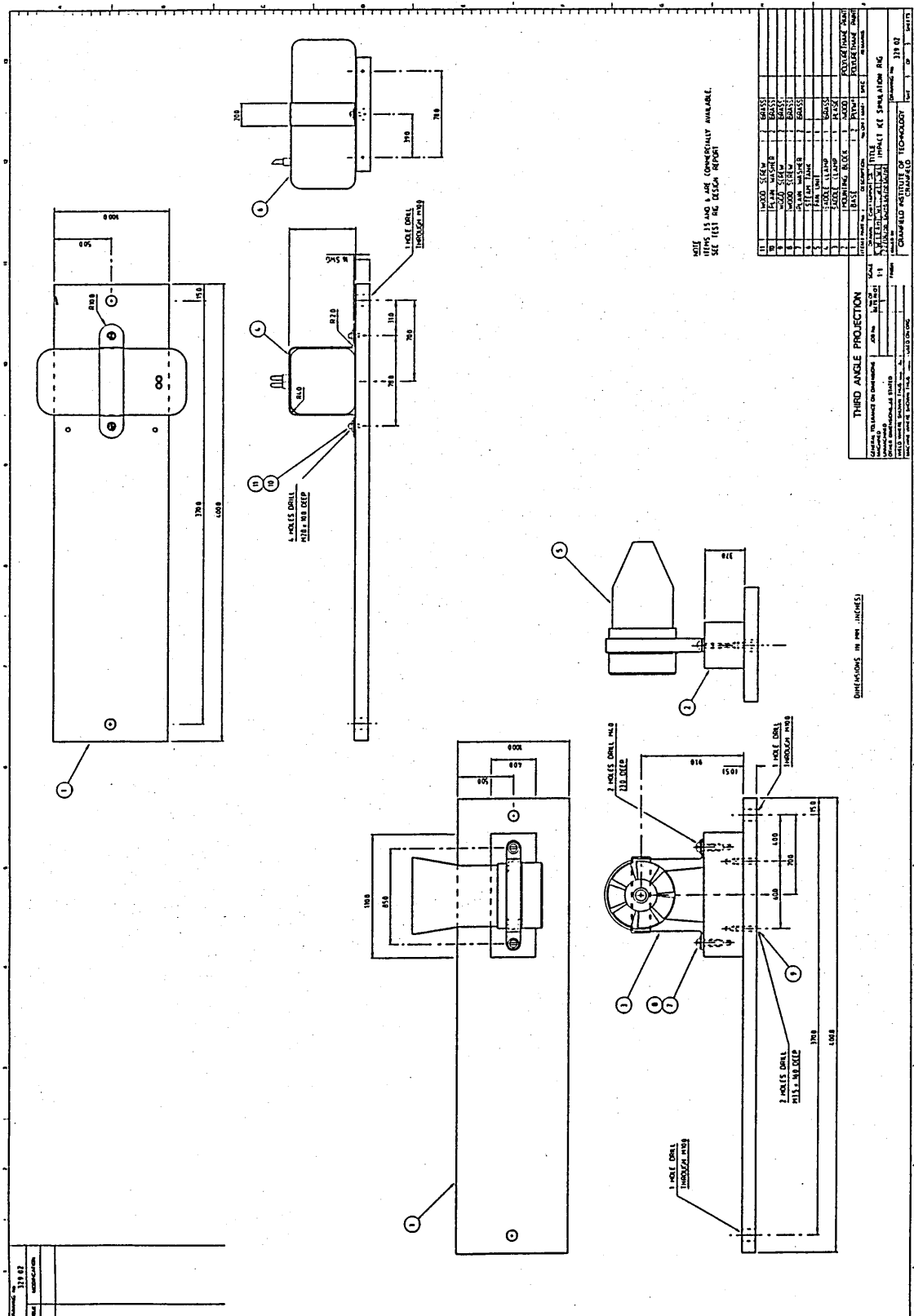


Fig. 28(b)

Rime Ice Sample Production Rig (Sheet 2 of 3)



Rime Ice Sample Production Rig (Sheet 3 of 3)

Fig. 28(c)

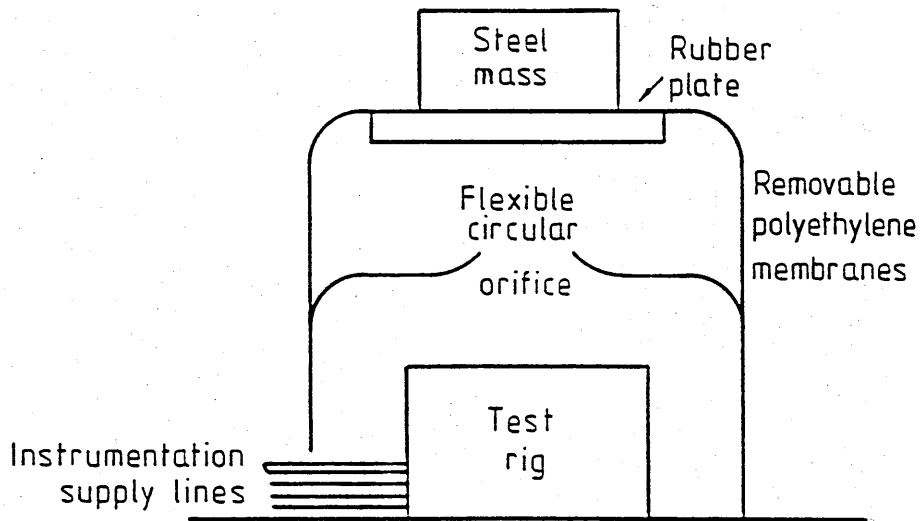


Fig.29

Bullet Retention System

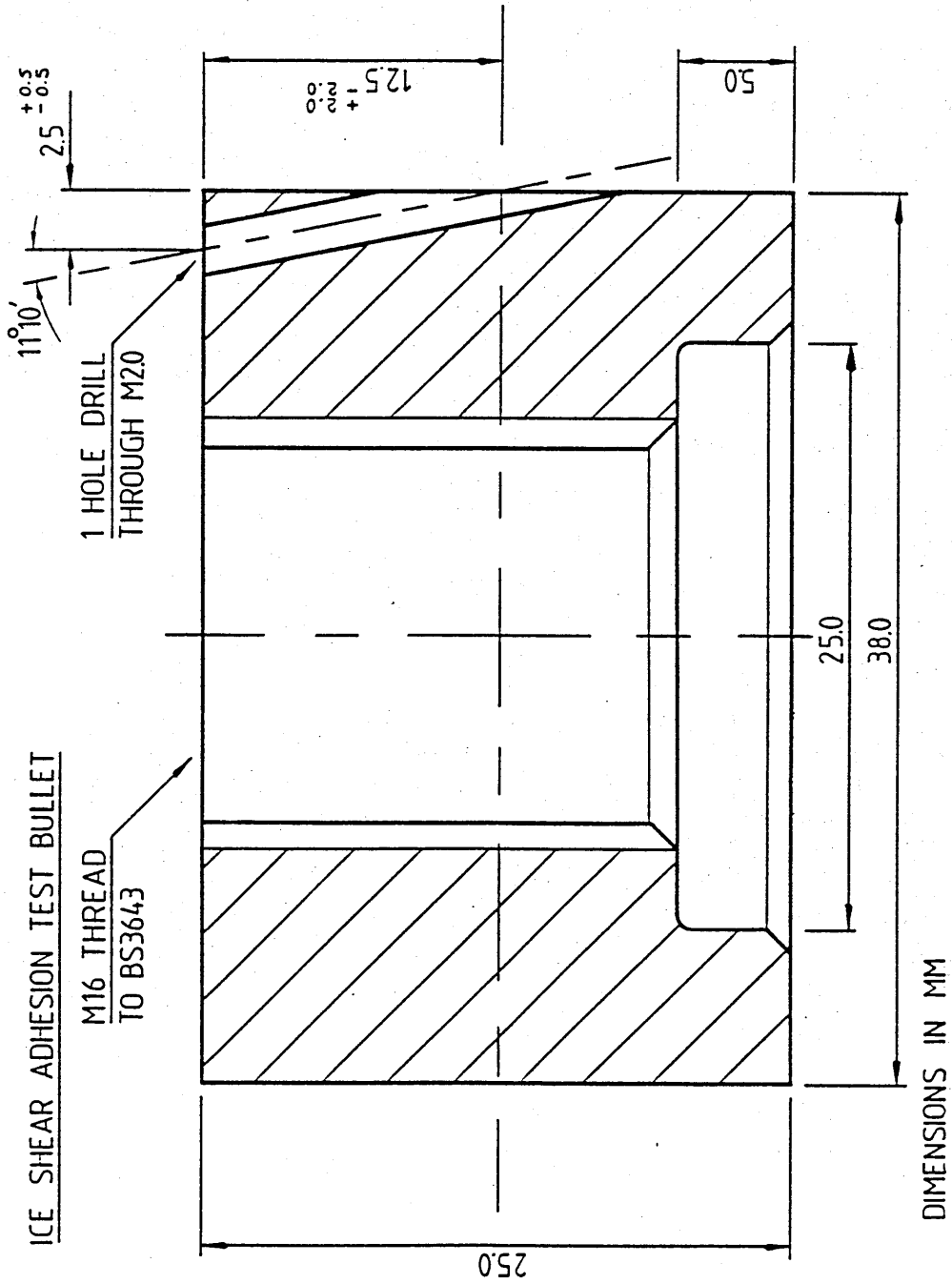
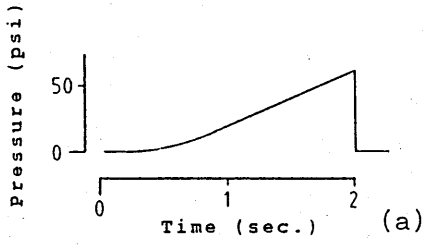
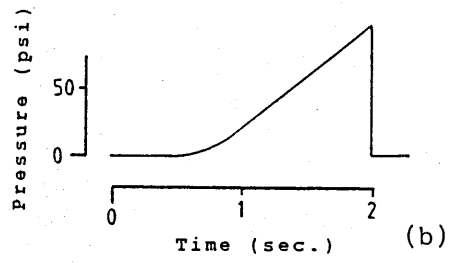
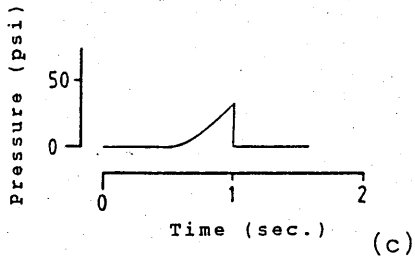
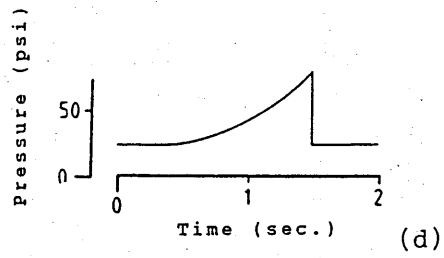
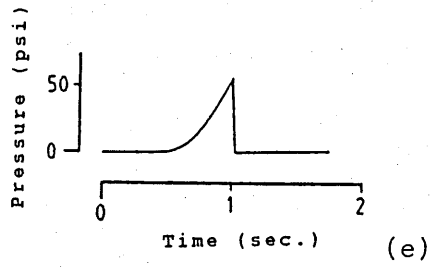
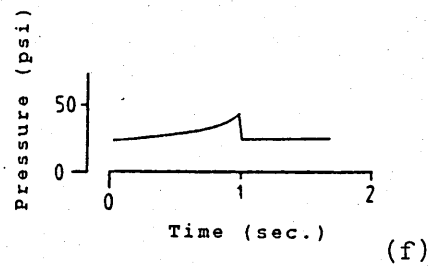
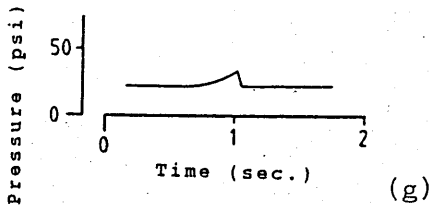
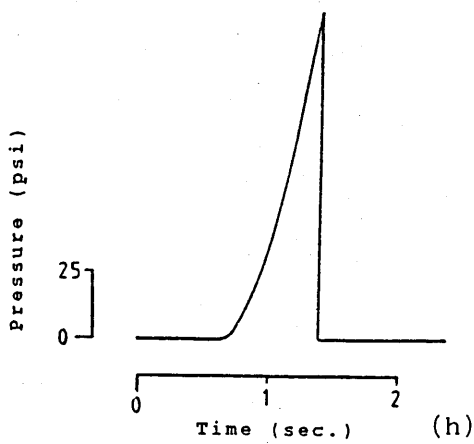
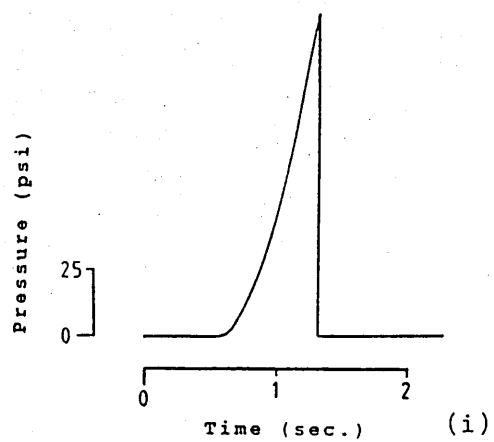


Fig.30

Pressure v Time

Fig.31



Ice Bond Loading Results

Cracks in Test Rig Ice Samples

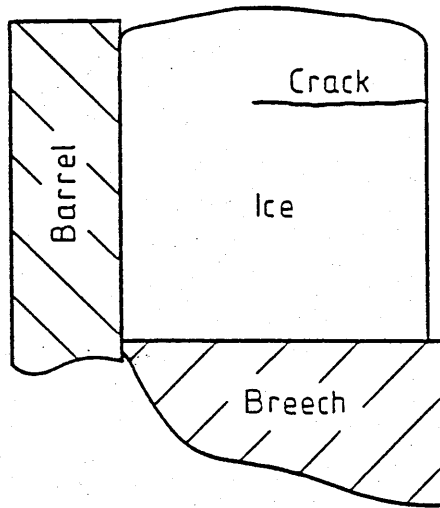


Fig.32(a)

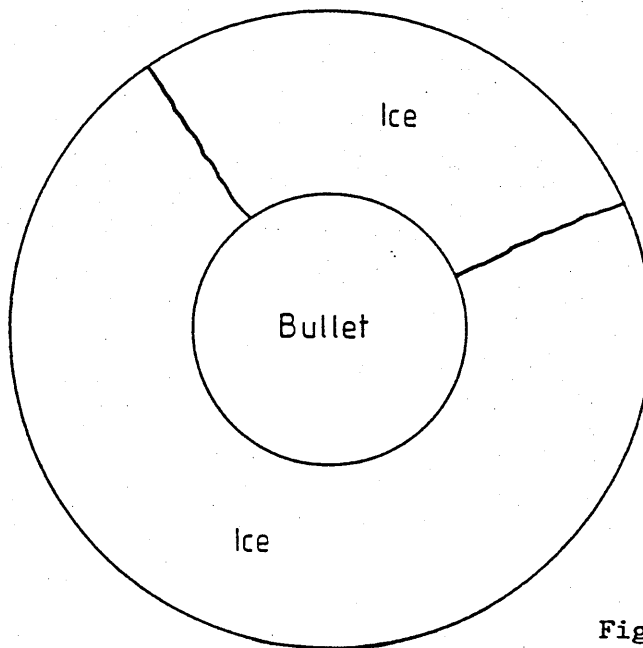


Fig.32(b)

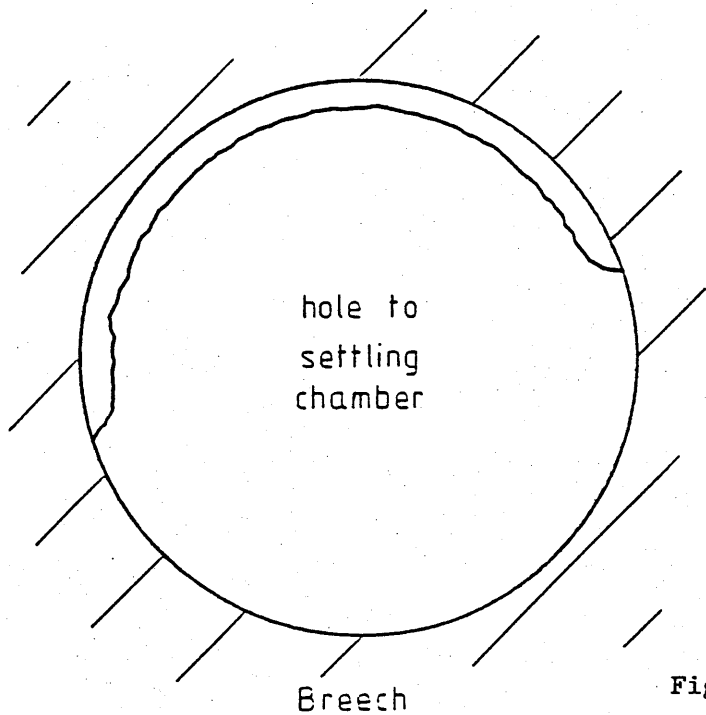


Fig.32(c)

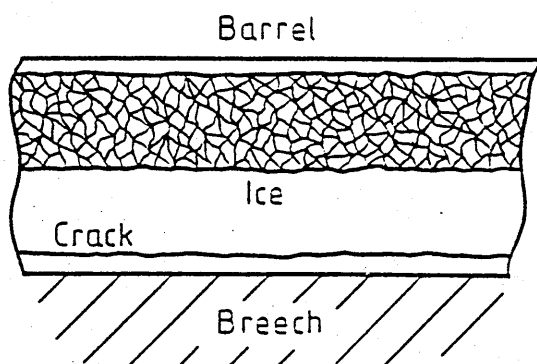


Fig.32(d)

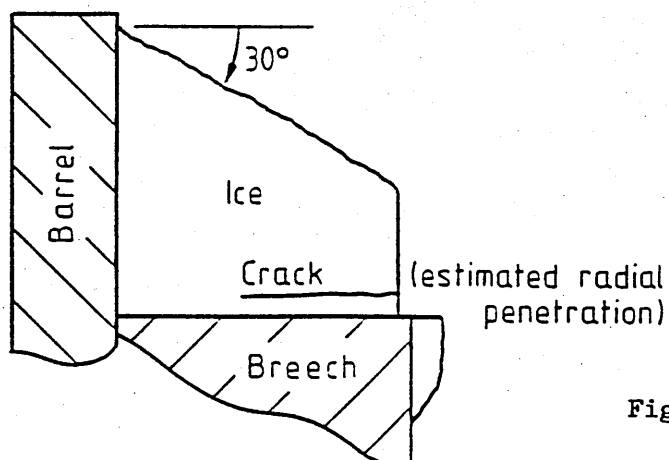


Fig.32(e)

Ice Shear Adhesion

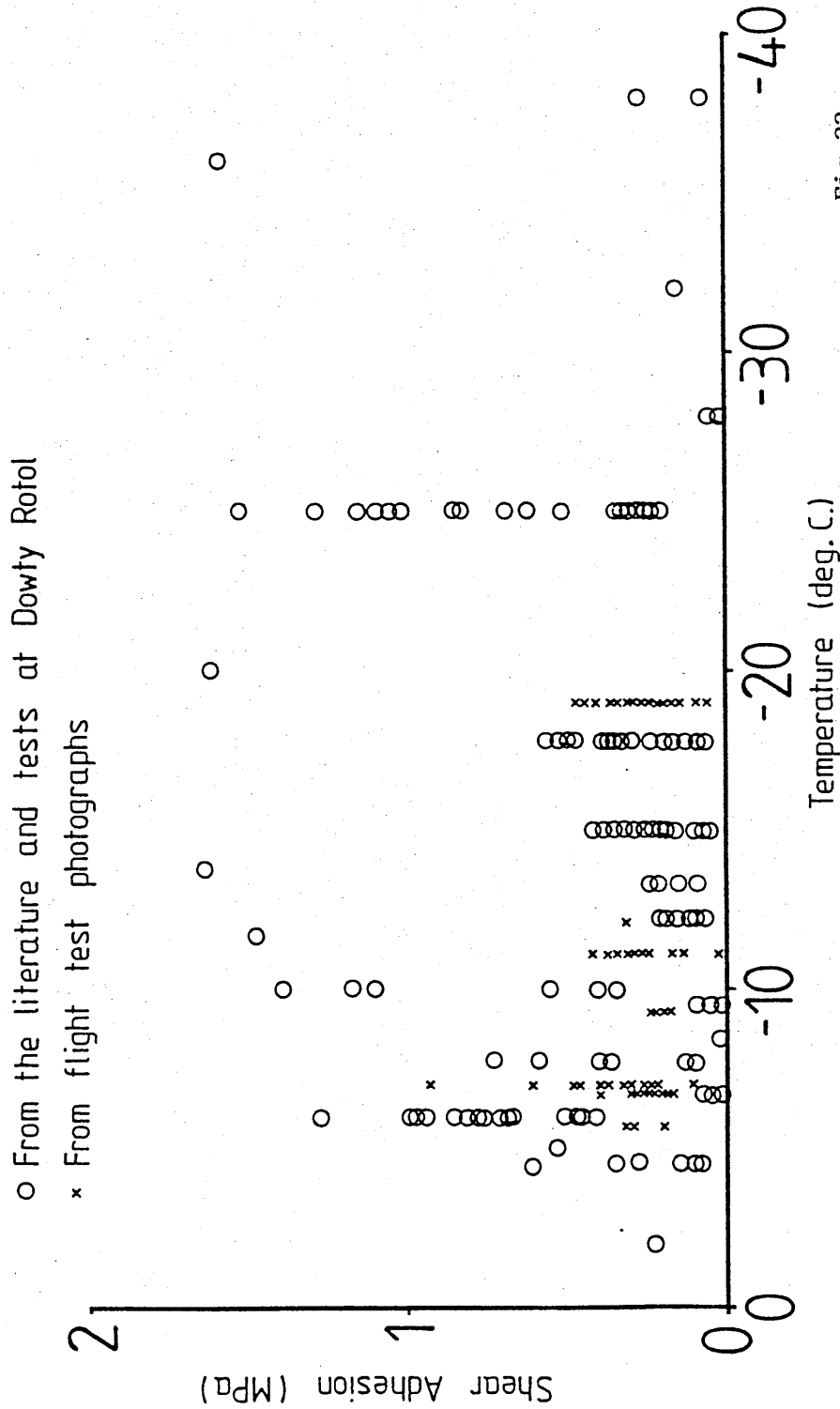
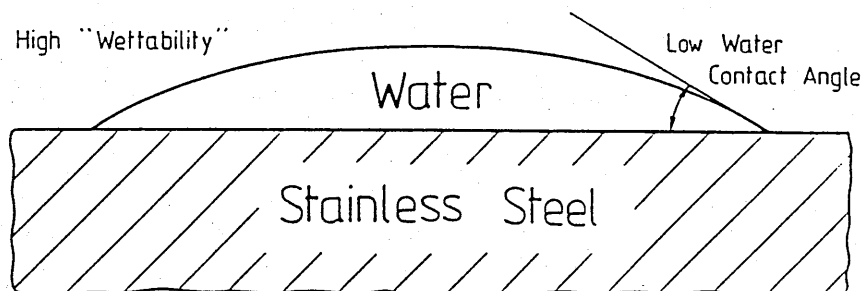


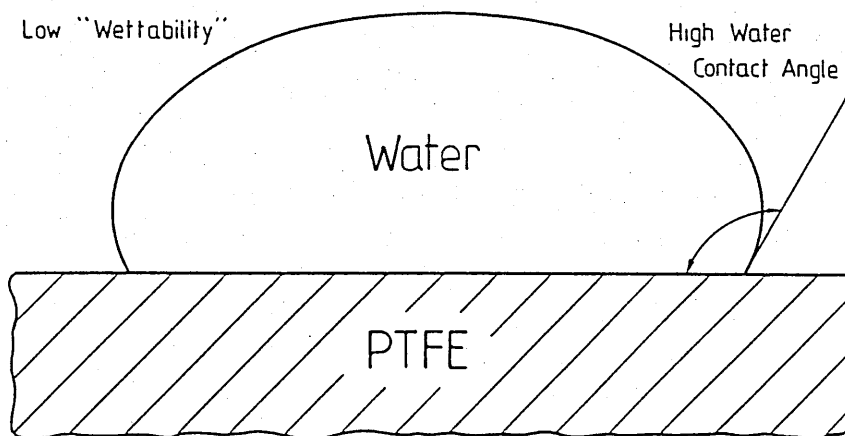
Fig.33

Surface Wettability



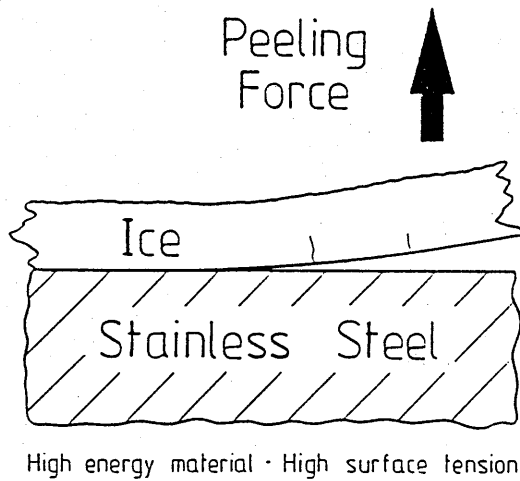
Low energy material - High surface tension -
High water attraction

Fig.34



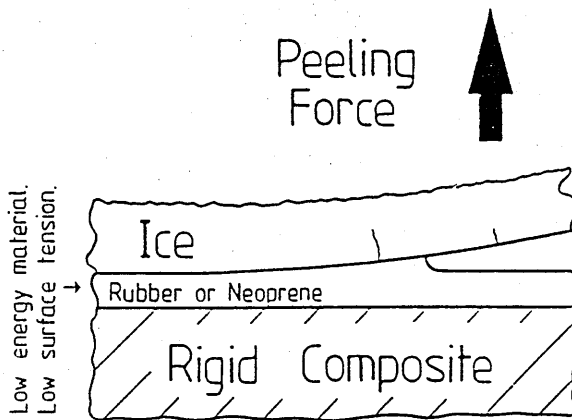
Low energy material - Low surface tension -
Low water attraction.

Fig.35



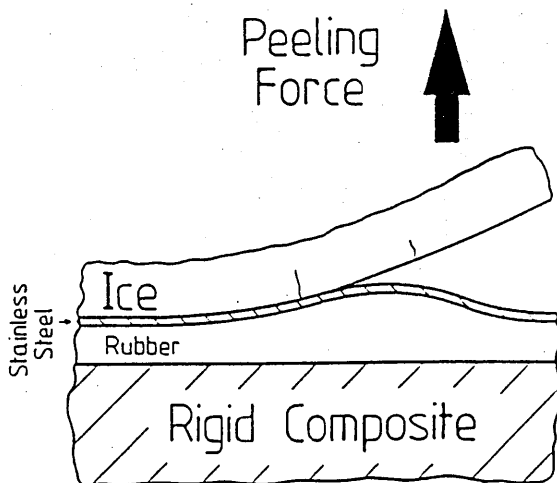
Sharp crack with small tip radius, high stress concentration, rapid crack propagation, small peeling force.

Fig.36



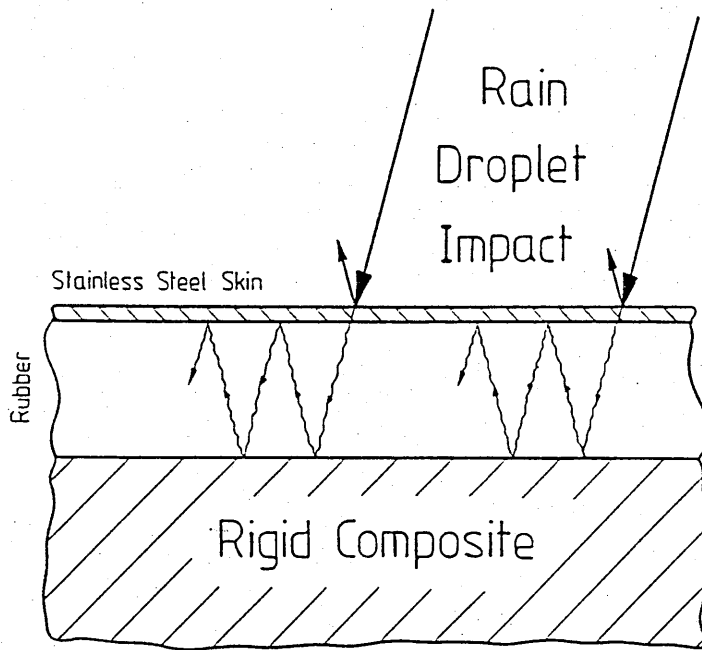
Plastic deformation of substrate at interface, large crack tip radius, low stress concentration, load diffusion, slow (or zero) crack propagation.

Fig.37



Large elastic interface deformation promotes initial cracking. High energy skin layer maintains sharp crack tip radius and rapid crack propagation.

Fig.38



Impact shock waves are reflected by hard surfaces and trapped in rubber causing rapid degradation leading to total material breakdown.

Fig.39

Polished Aluminium Alloy

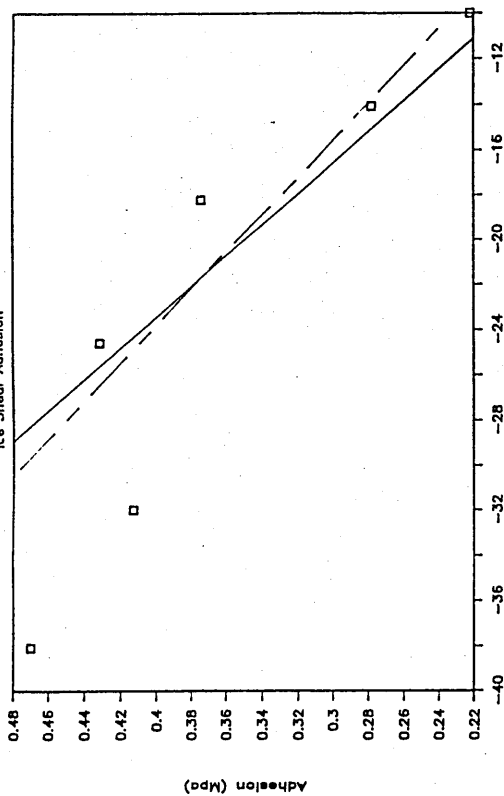


Fig. 40(a)

Clear Polyurethane Paint

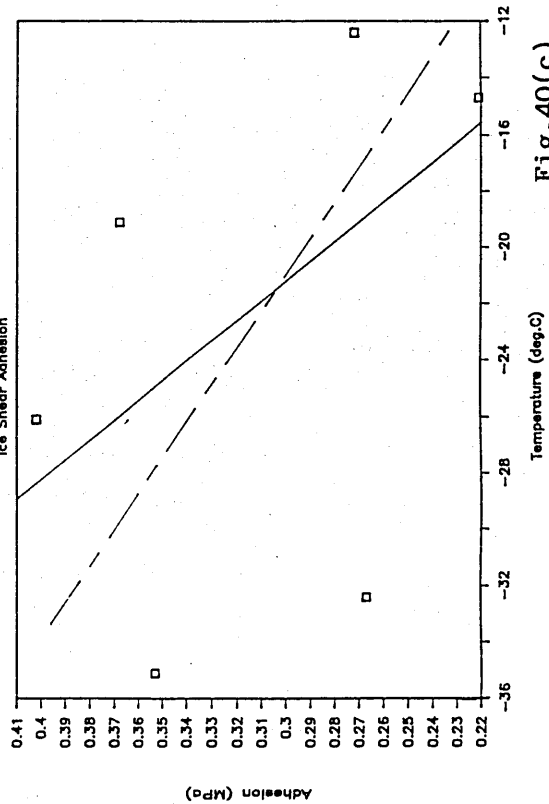


Fig. 40(c)

Machined Aluminium Alloy

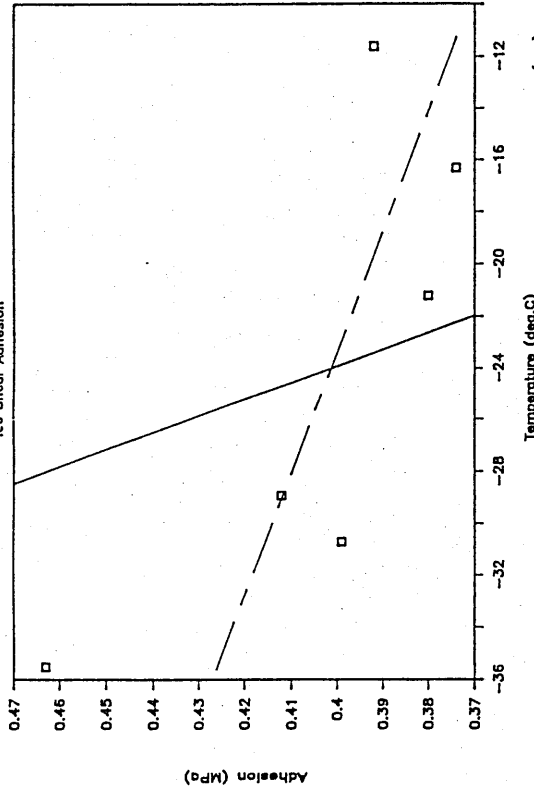


Fig. 40(b)

Machined Stainless Steel

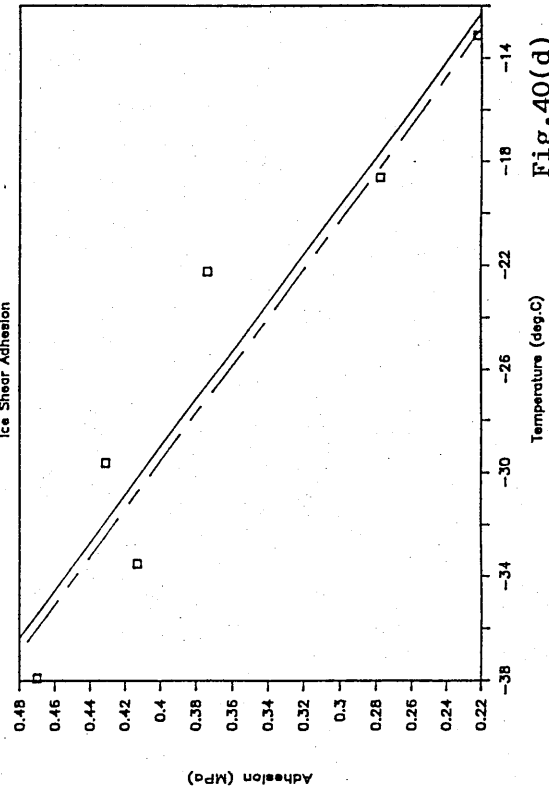


Fig. 40(d)

Ice Shear Adhesion Results Using Research Programme Test Rig

Polyacetal

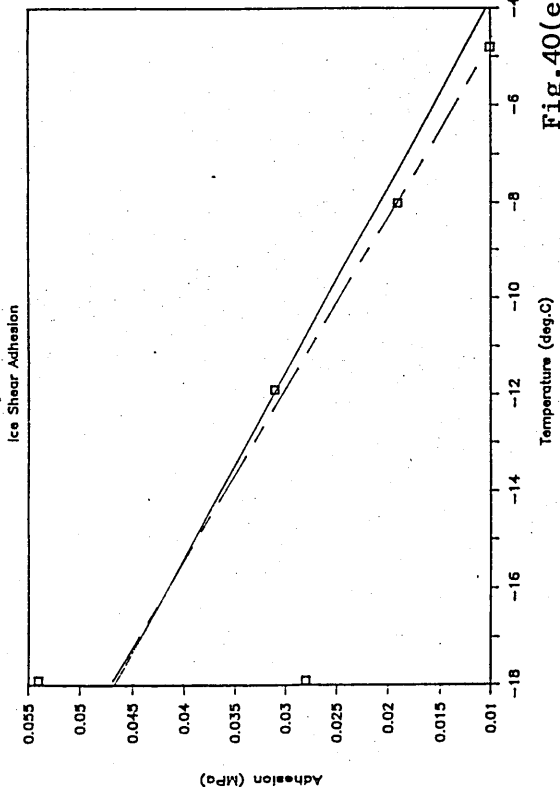


Fig.40(e)

Neoprene

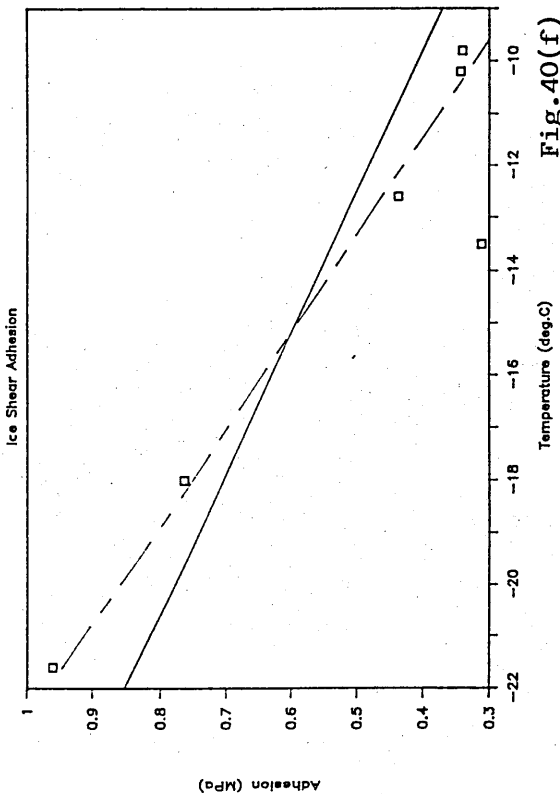


Fig.40(f)

All Substrates

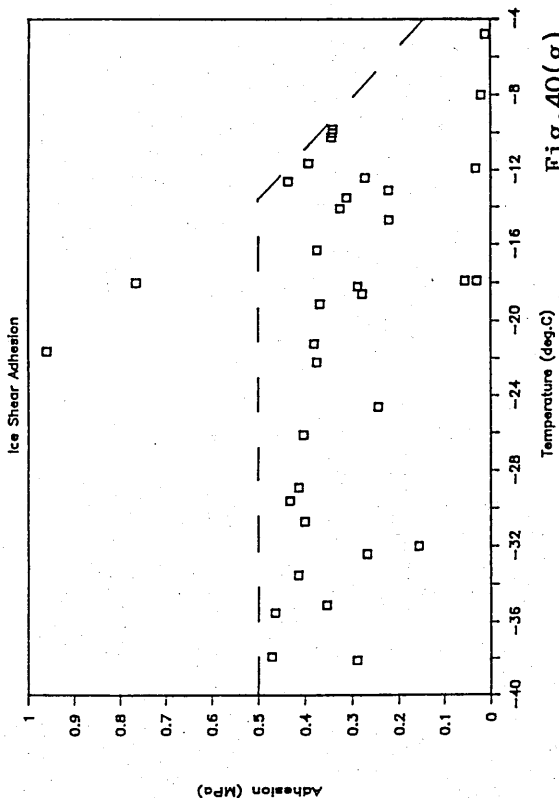


Fig.40(g)

Fit through origin

Fit through available data

Practical maximum

Ice Accretion Profiles

$$Y=kx^a$$

ICE DENSITY
(Kg.m⁻³)

Specimen ice accretion profiles
for three values of accretion
thickness and three mean
ice mass densities.

Accretion aligned with
it's nose centre on
the aerofoil line of
incidence.

Ice Accretion

~900
~700
~500

1.5°
INCIDENCE

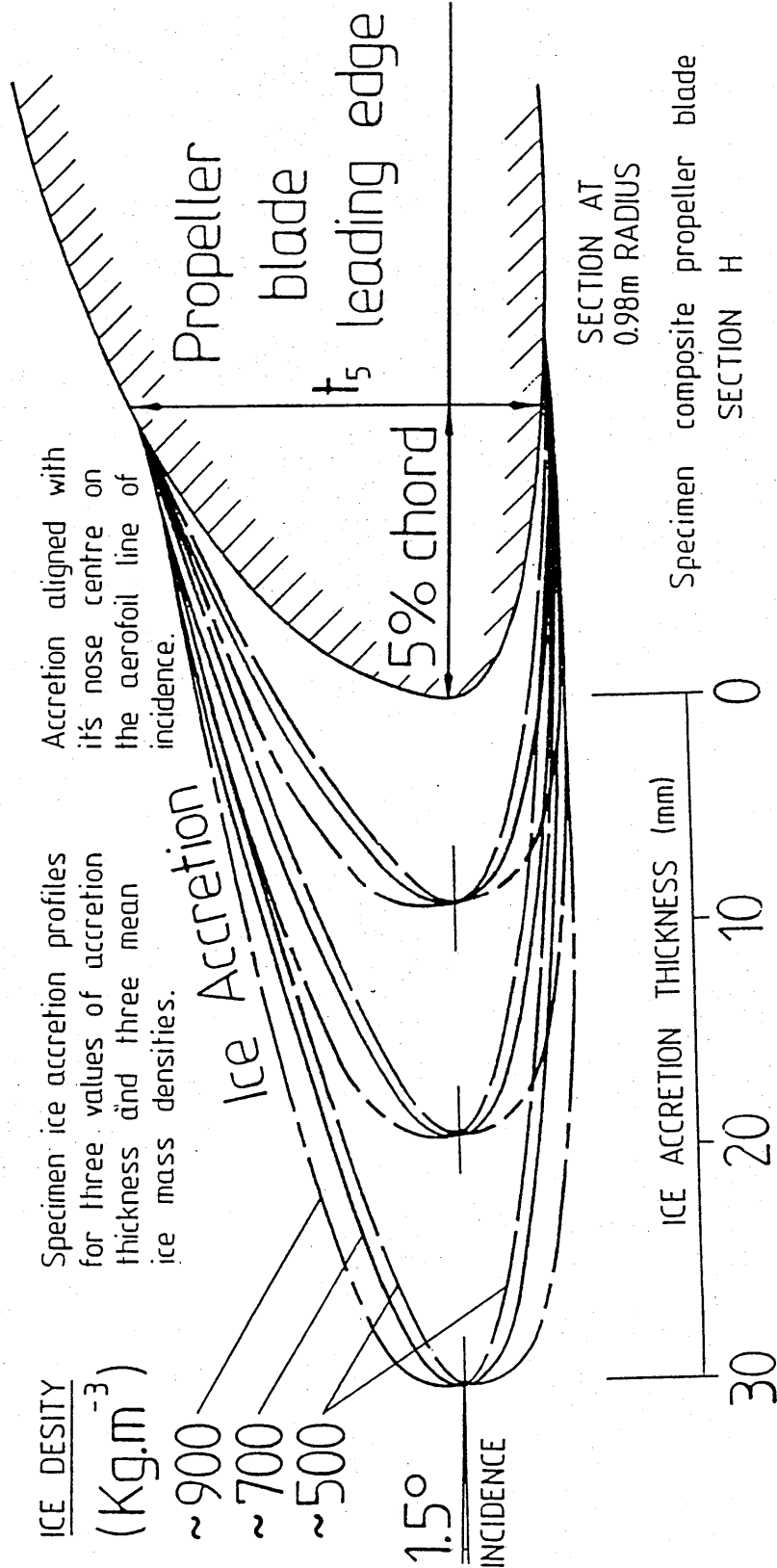
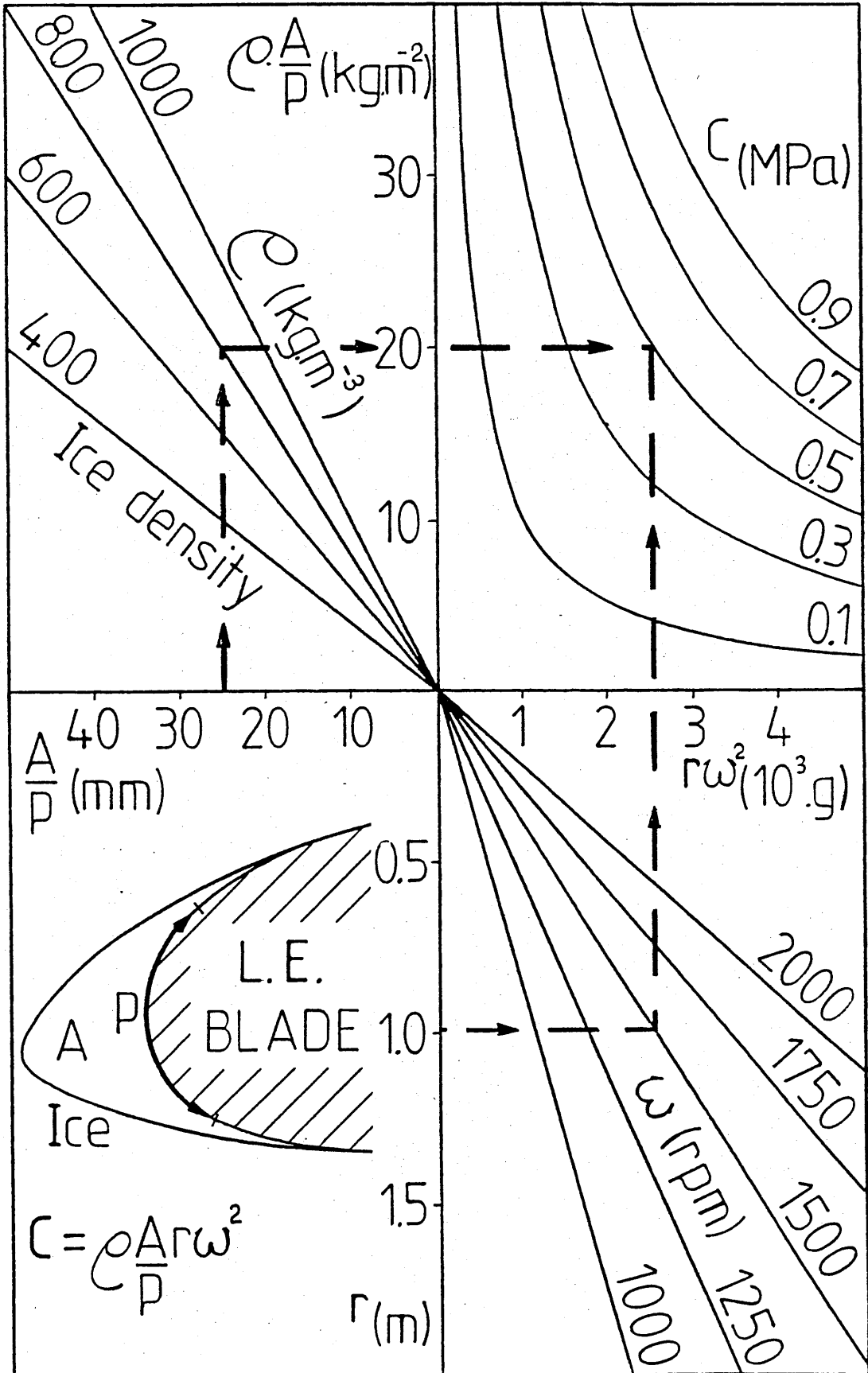
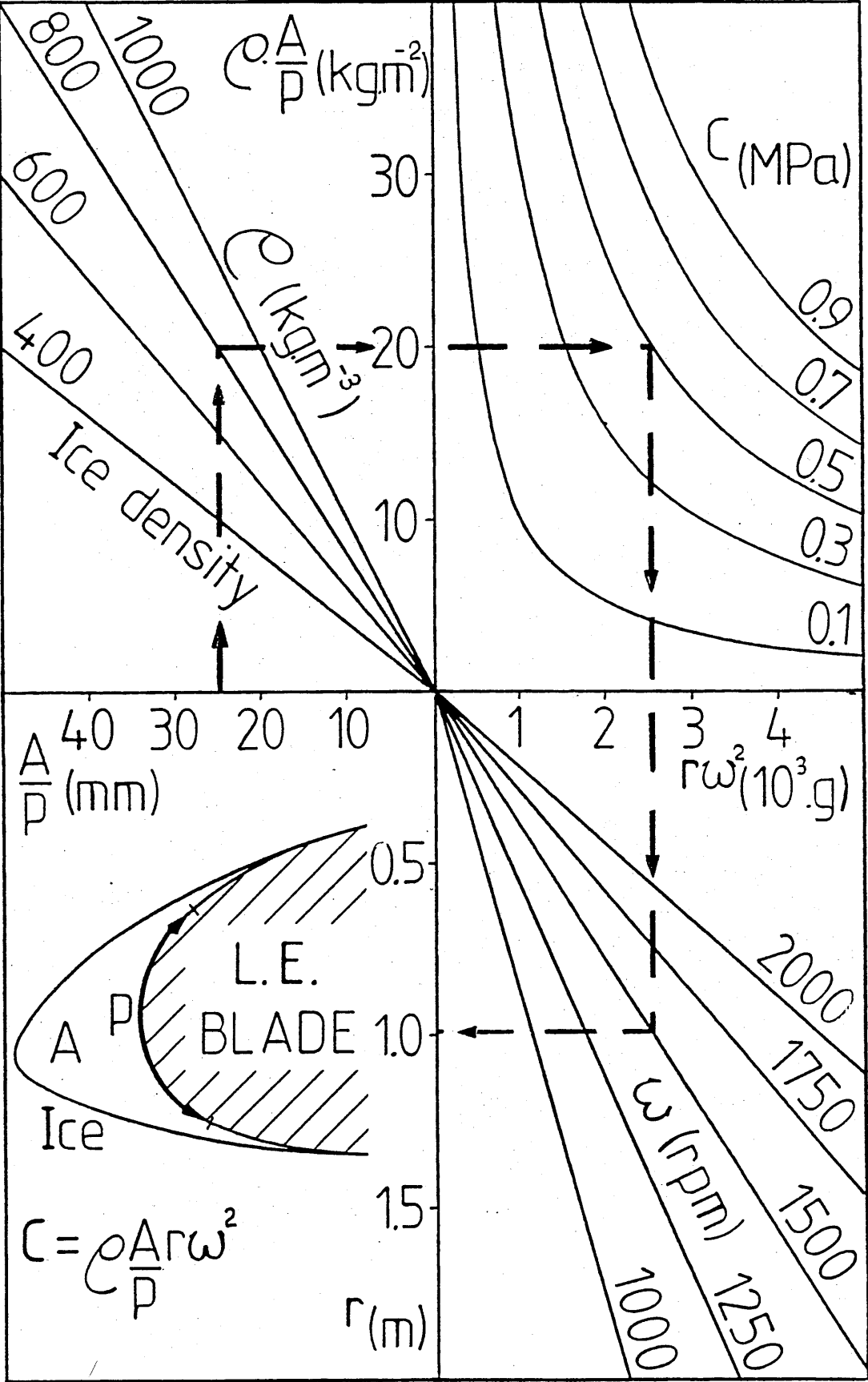


Fig.41



Ice Accretion Empirical Profile Chart

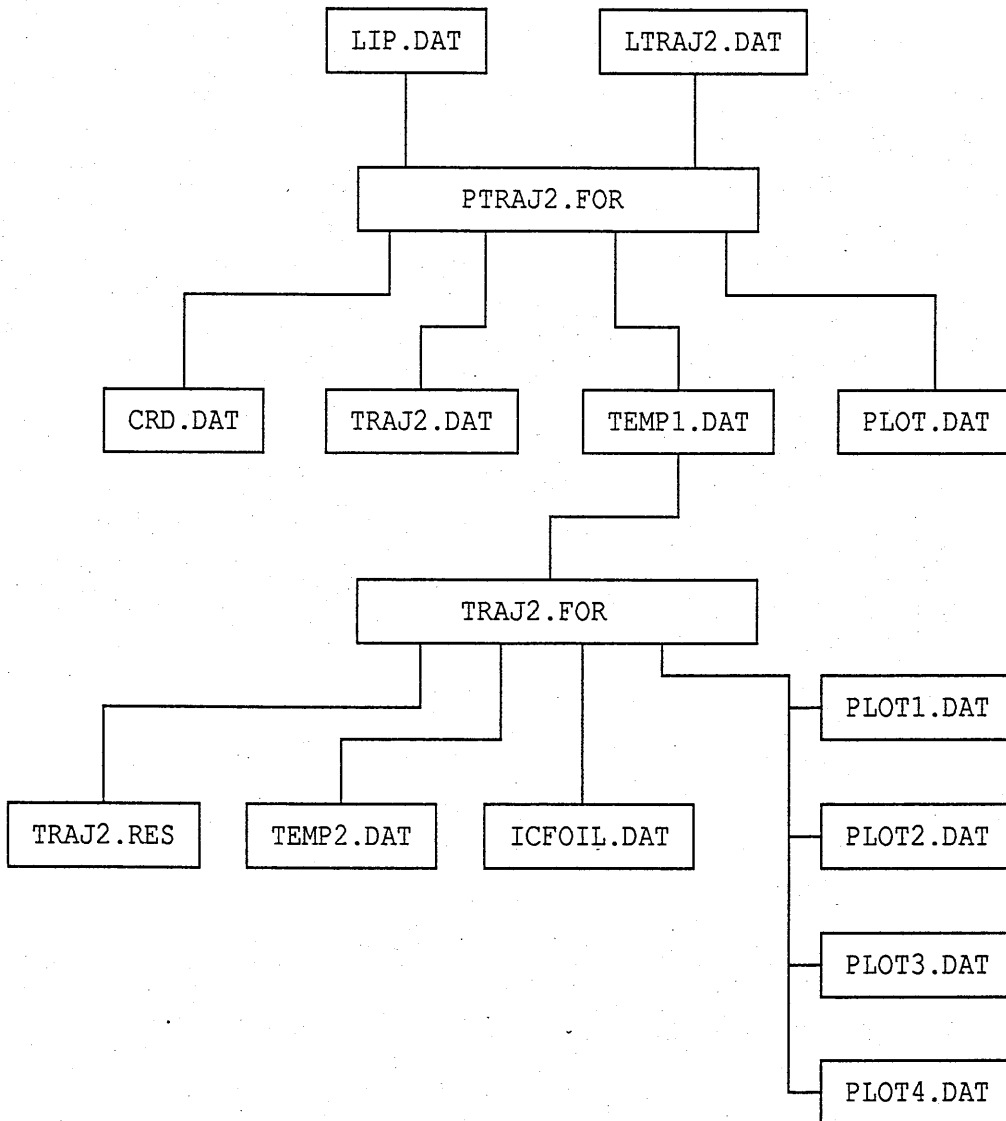
Fig.42



Ice Accretion Empirical Profile Chart

Fig.43

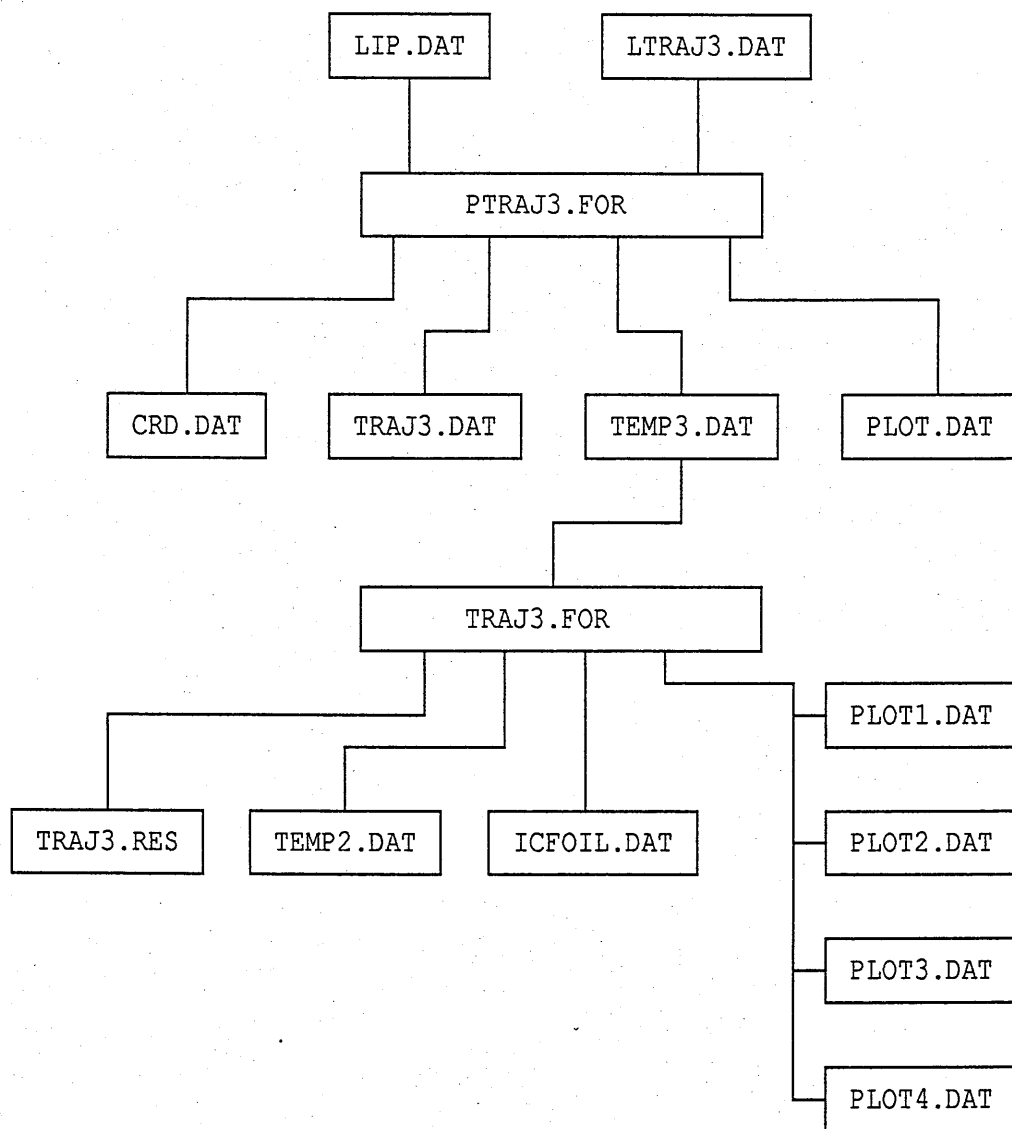
Software System Layout - PTRAJ2/TRAJ2



LIP.DAT	Lip co-ordinates
LTRAJ2.DAT	Conditions and lip parameters
PTRAJ2.FOR	Pre-processor program for intake lip applications
CRD.DAT	Simulating aerofoil co-ordinates
TRAJ2.DAT	Conditions and aerofoil parameters
PLOT.DAT	Simulating aerofoil
TEMP1.DAT	Panel strengths and non-dimensional co-ordinates
TRAJ2.FOR	Aerofoil icing prediction program
TRAJ2.RES	Complete data output
TEMP2.DAT	Trajectory non-dimensional co-ordinates
ICFOIL.DAT	Iced aerofoil co-ordinates

Fig.44(a)

Software System Layout - PTRAJ3/TRAJ3



LIP.DAT	Lip co-ordinates
LTRAJ3.DAT	Conditions and lip parameters
PTRAJ3.FOR	Pre-processor program for intake lip applications
CRD.DAT	Simulating aerofoil co-ordinates
TRAJ3.DAT	Conditions and aerofoil parameters
PLOT.DAT	Simulating aerofoil
TEMP3.DAT	Panel strengths and non-dimensional co-ordinates
TRAJ3.FOR	Aerofoil icing prediction program
TRAJ3.RES	Complete data output
TEMP2.DAT	Trajectory non-dimensional co-ordinates
ICFOIL.DAT	Iced aerofoil co-ordinates

Fig.44(b)

Fig.45(a) FLOW CHART - PTRAJ2.FOR

(i)

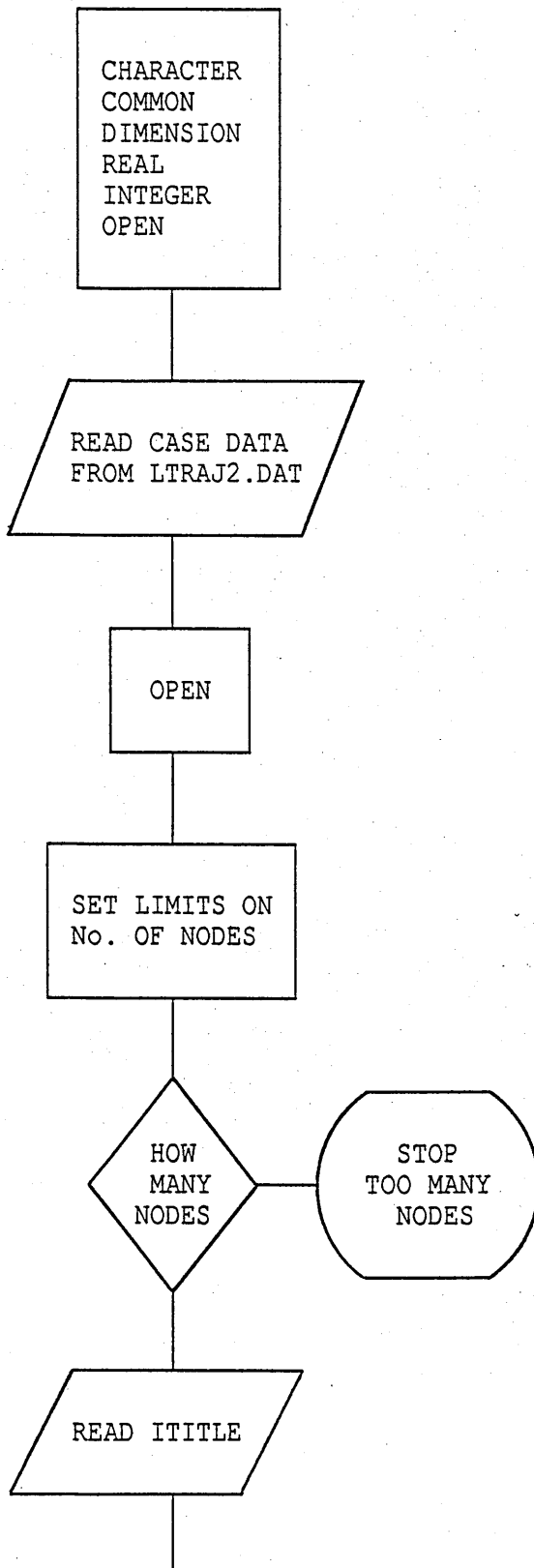
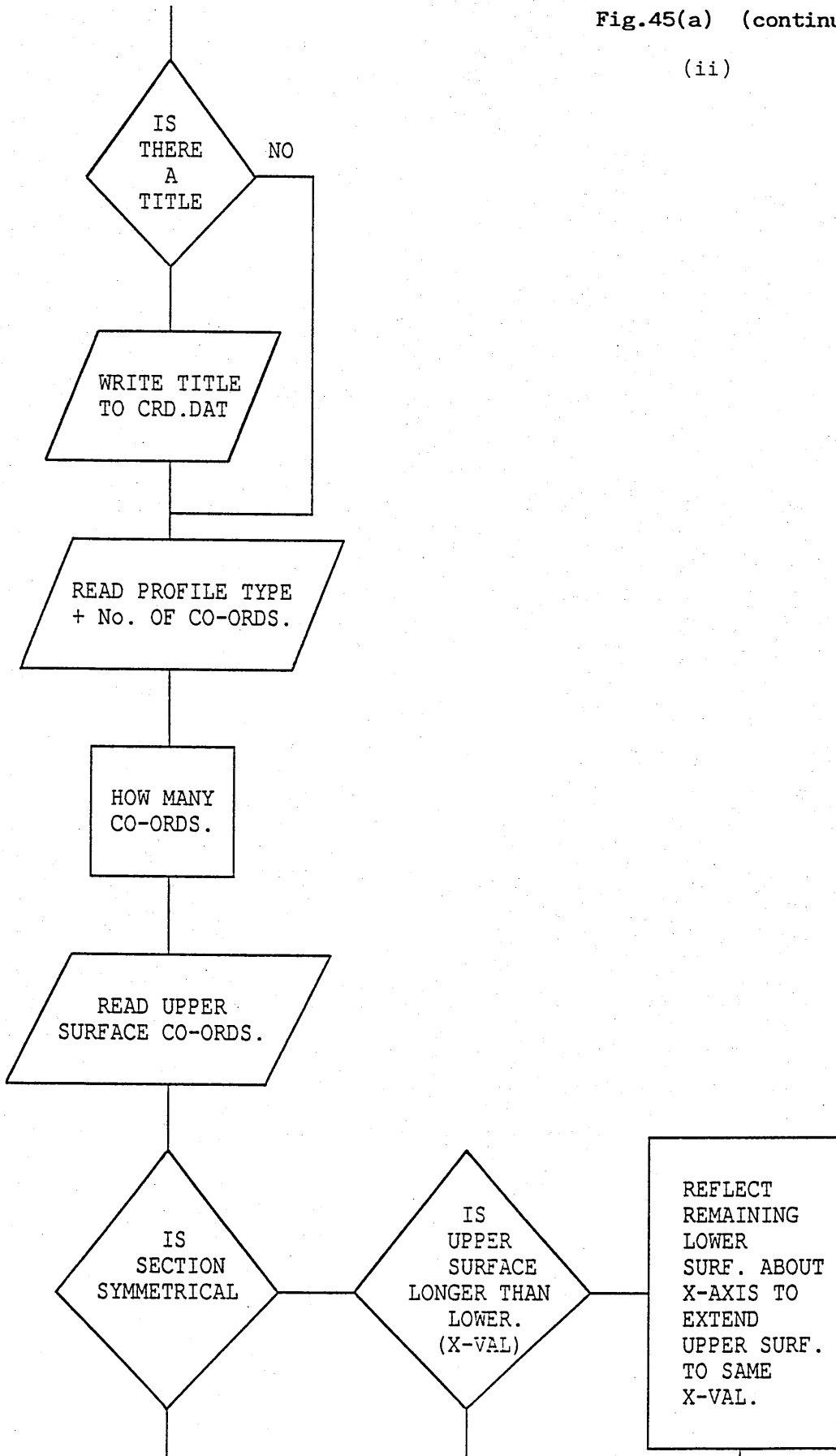


Fig.45(a) (continued)

(ii)



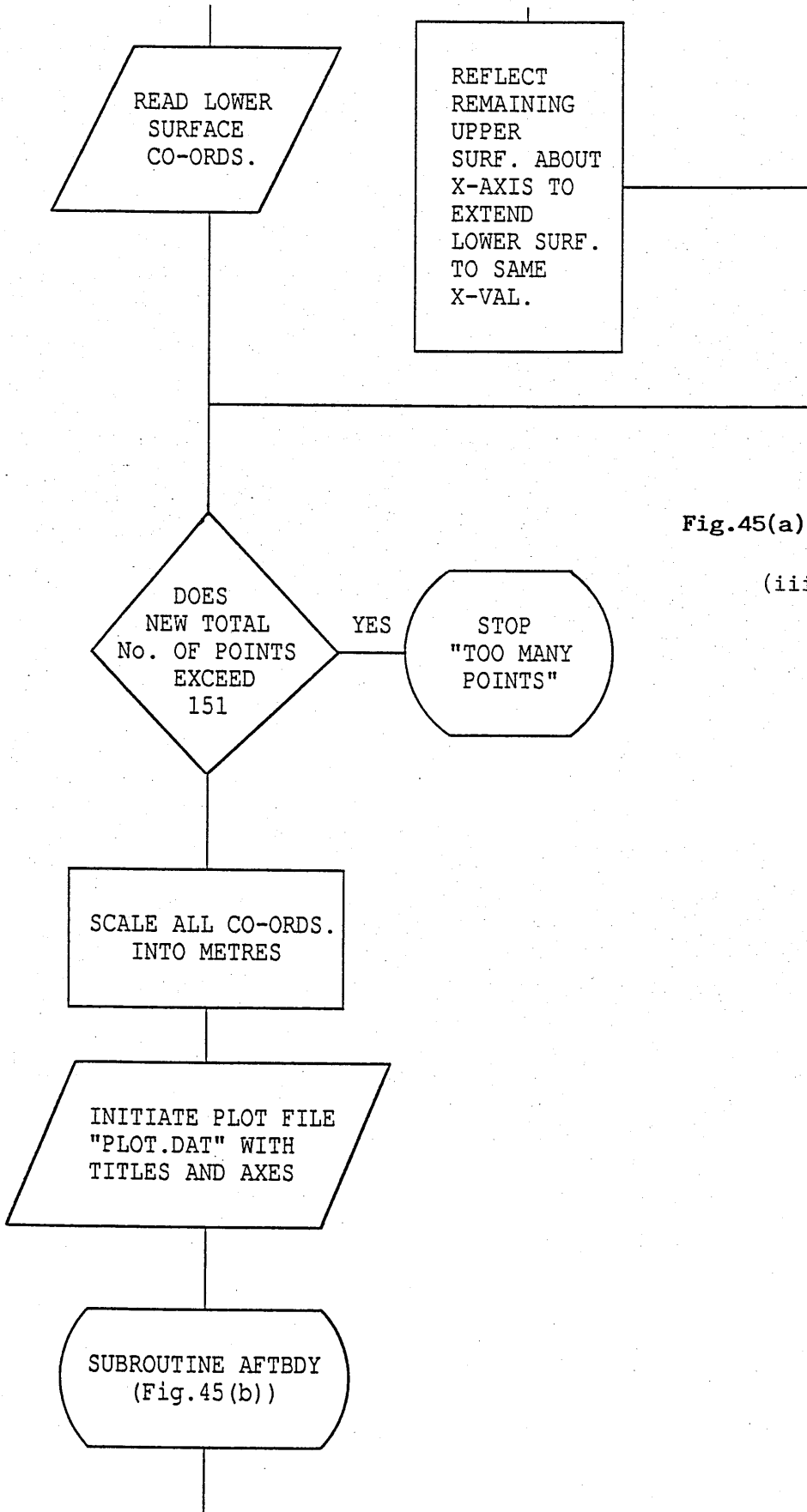


Fig.45(a) (continued)

(iii)

Fig.45(a) (continued)

(iv)

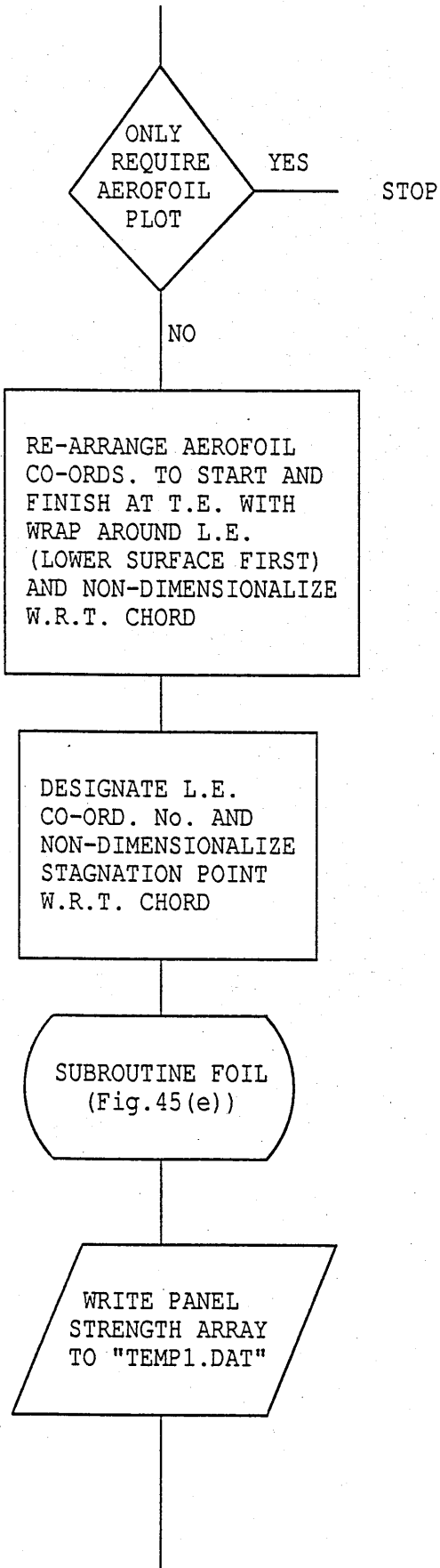


Fig.45(a) (continued)

(v)

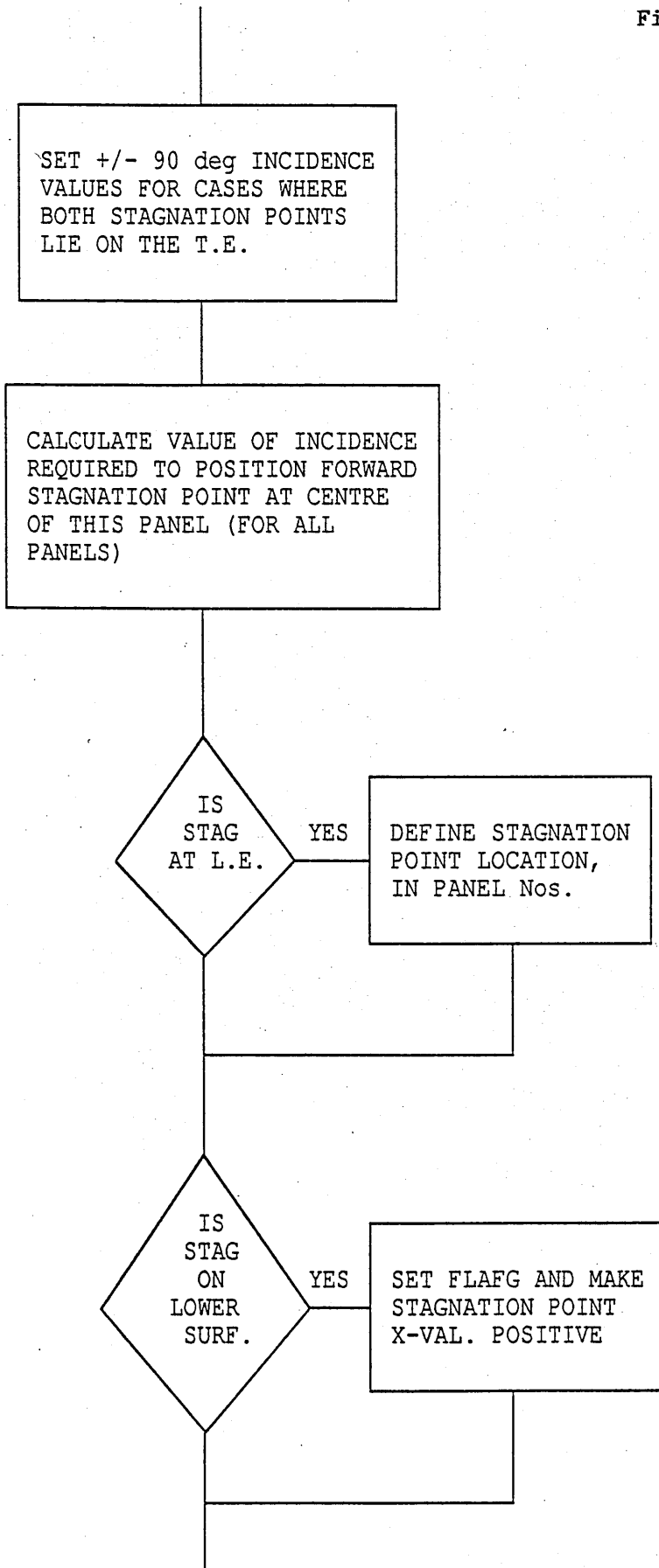


Fig.45(a) (continued)

(vi)

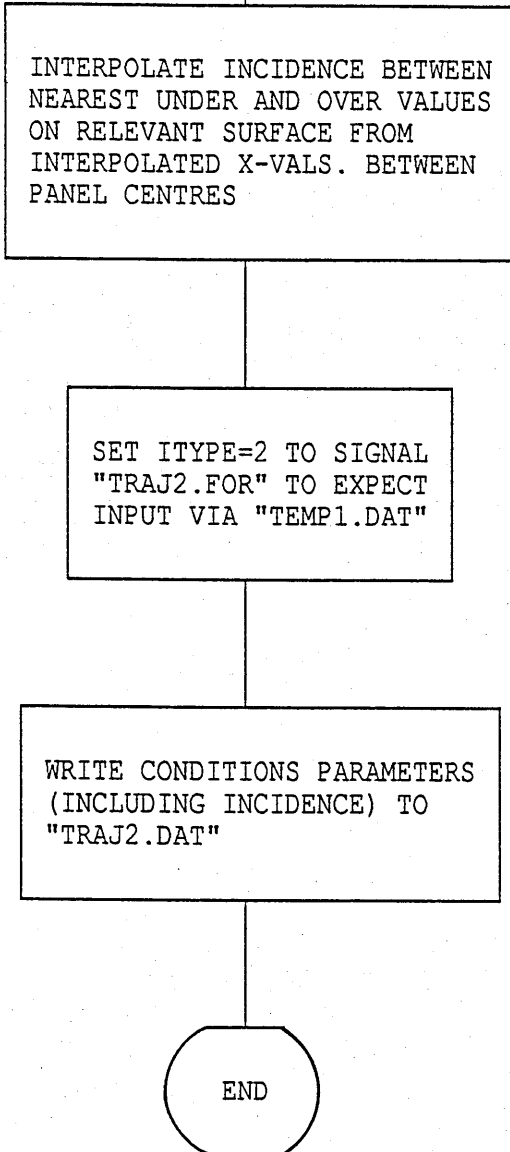


Fig.45(b) SUBROUTINE AFTBDY

(i)

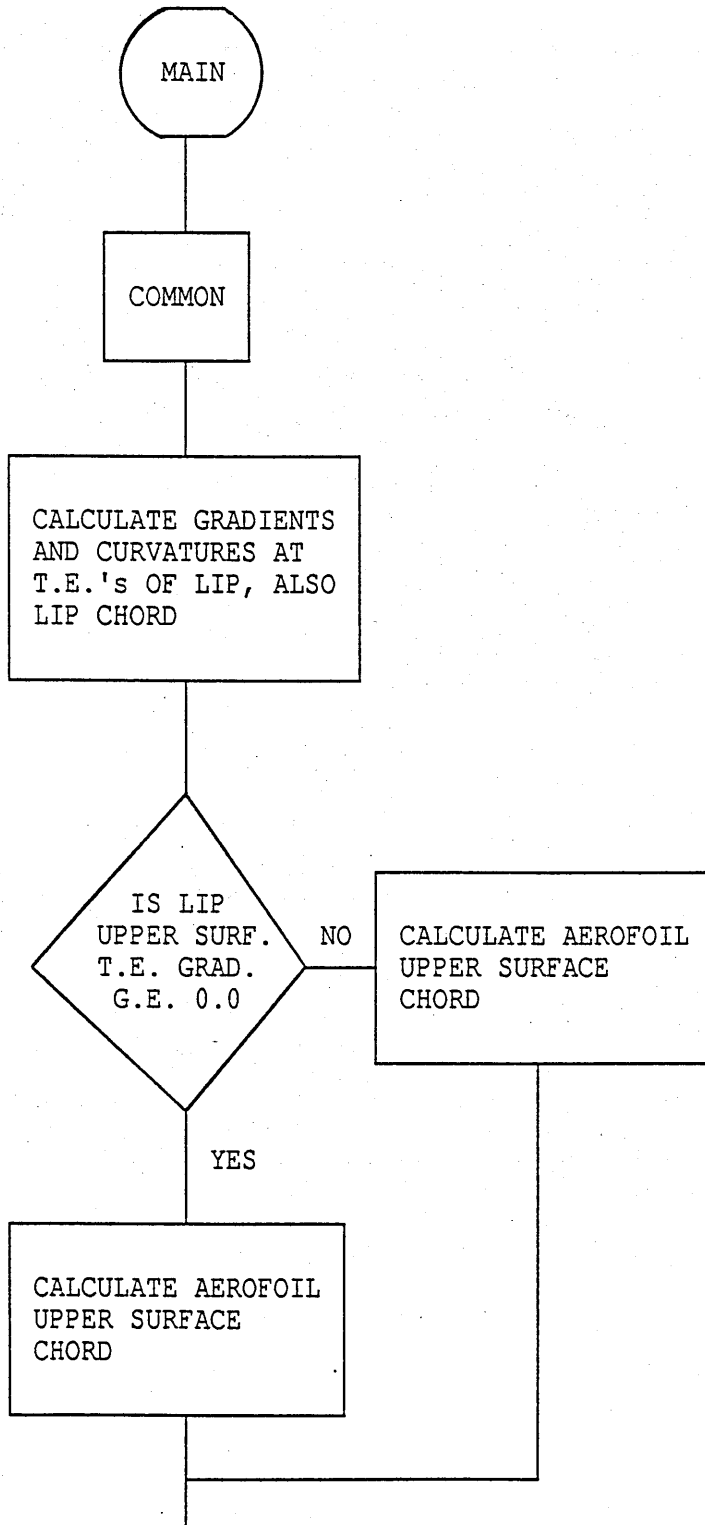


Fig.45(b) (continued)

(ii)

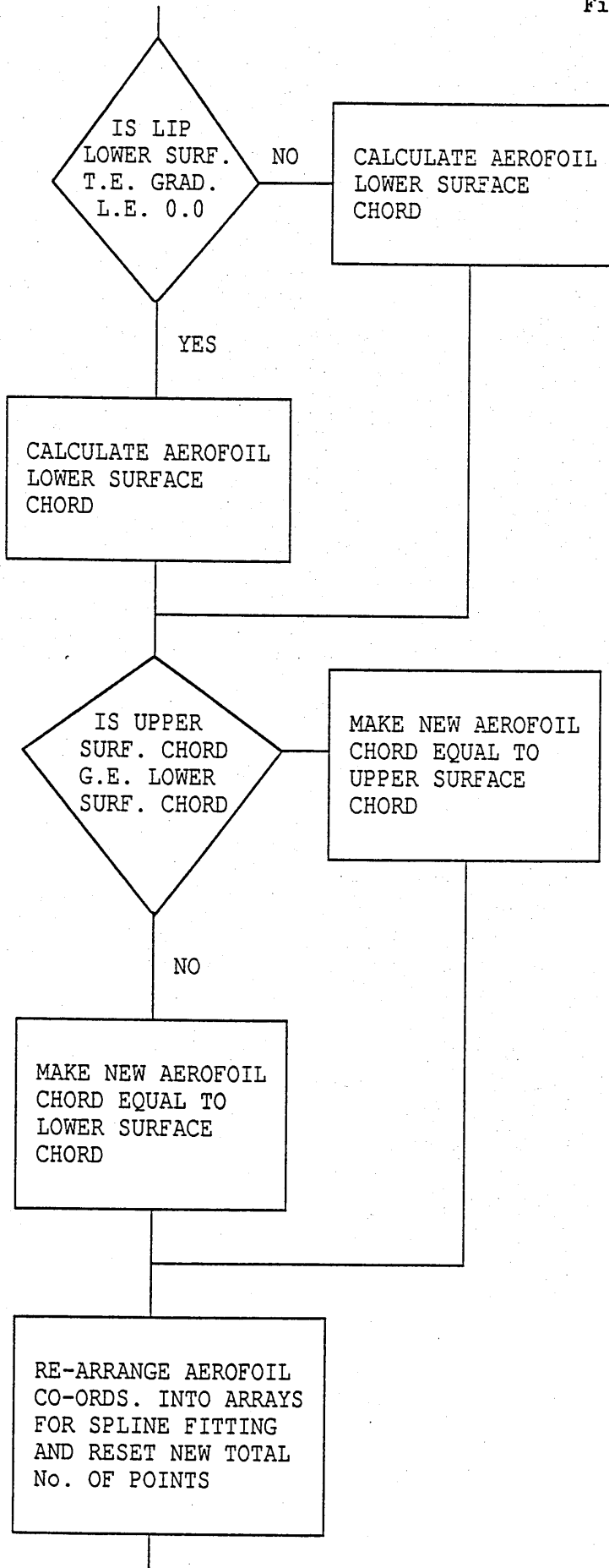


Fig.45(b) (continued)

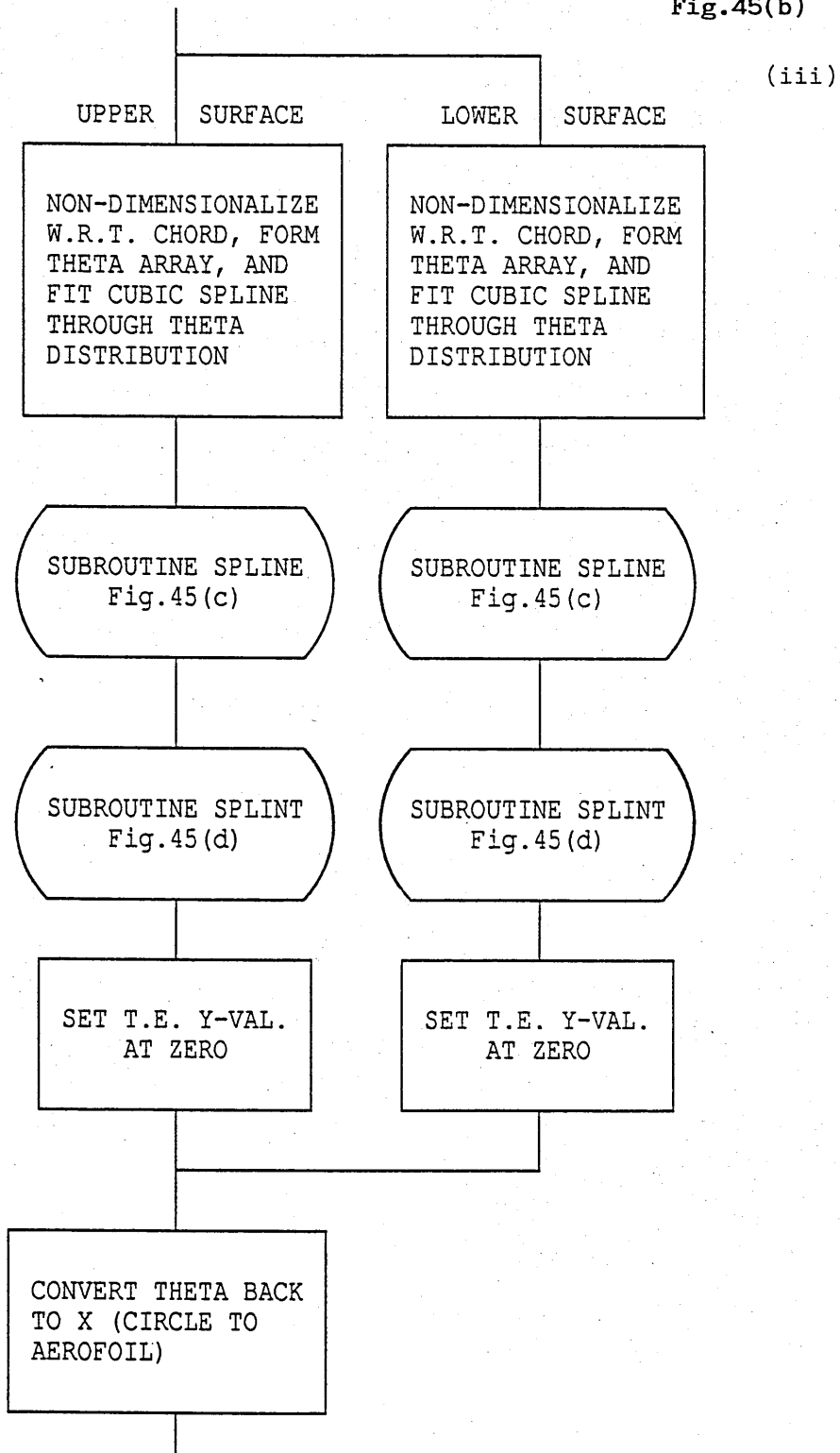


Fig.45(b) (continued)

(iv)

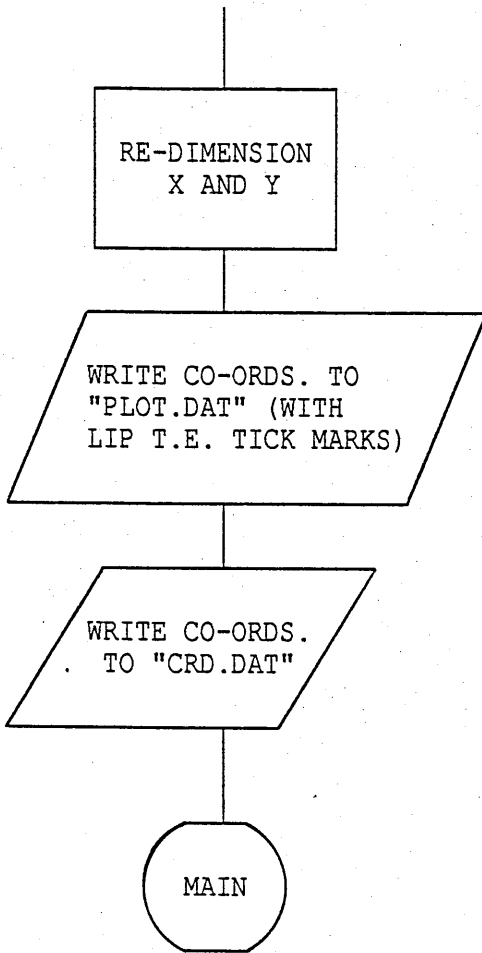


Fig.45(c) SUBROUTINE SPLINE

Ref. "Numerical Recipes", page 88

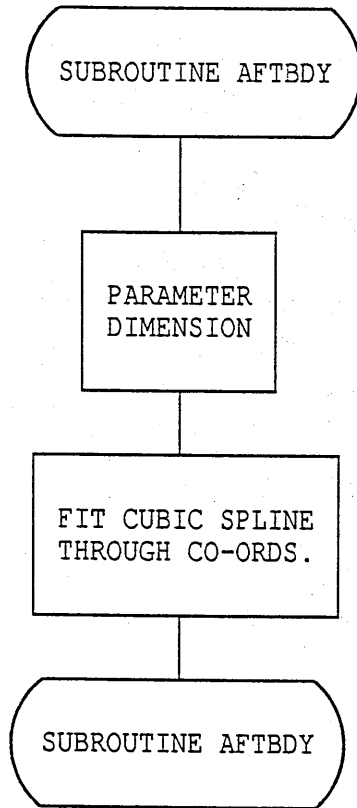


Fig.45(d) SUBROUTINE SPLINT

Ref. S. P. Fiddes. Bristol University

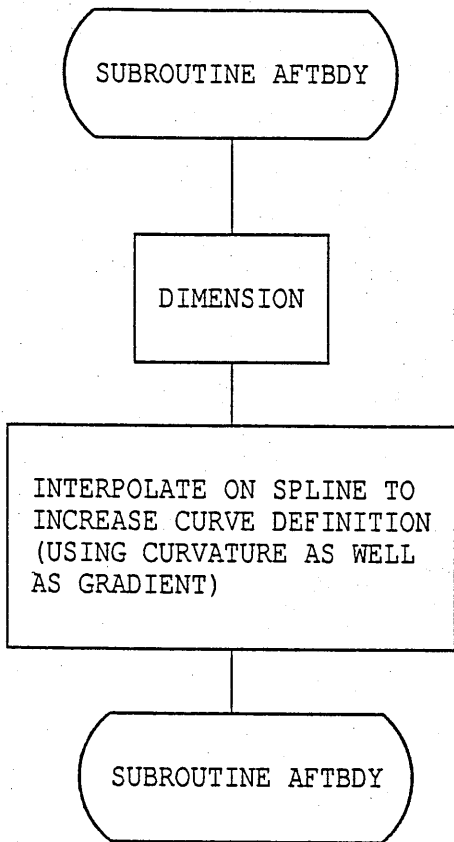


Fig.45(e) SUBROUTINE FOIL

(i)

Ref. RAE Program

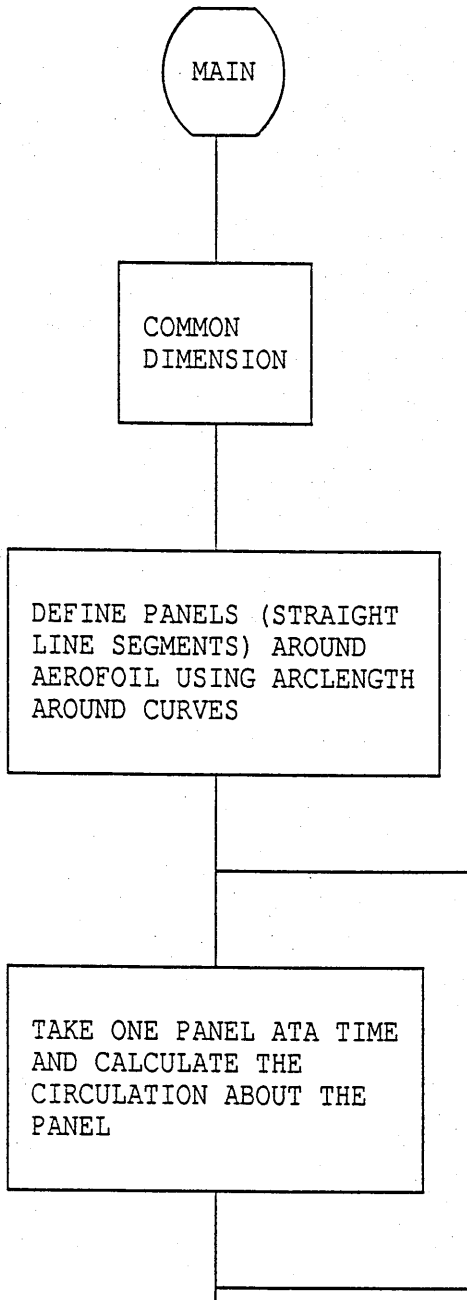
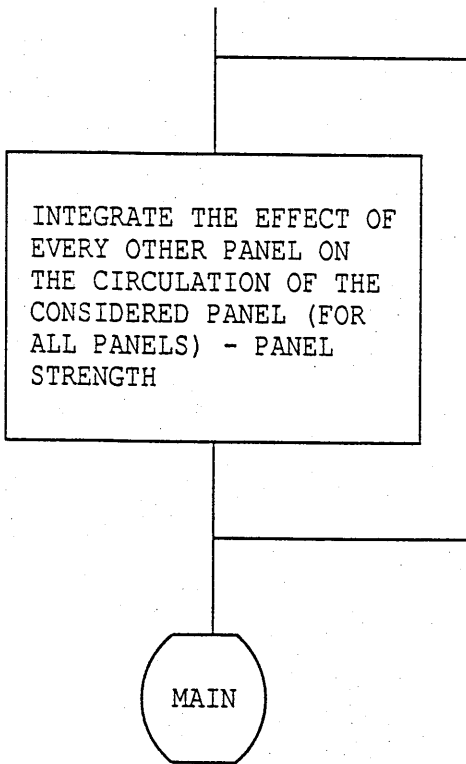
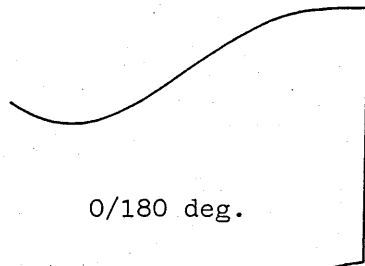


Fig.45(e) (continued)

(ii)

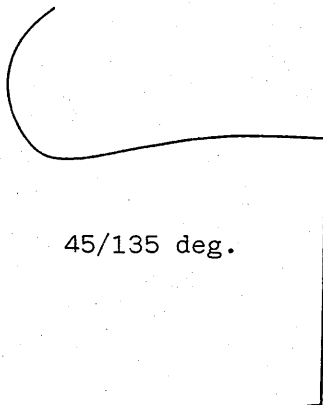


Sample Engine Air Intake Mouth Profiles



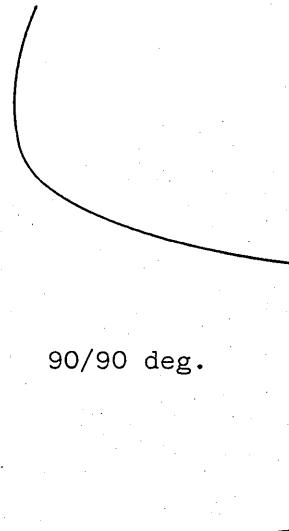
0/180 deg.

Fig.46(a)



45/135 deg.

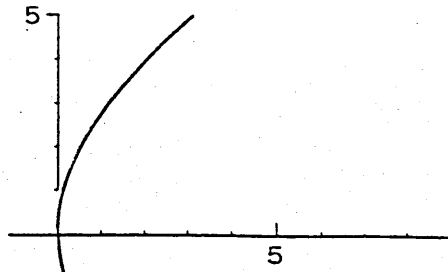
Fig.46(b)



90/90 deg.

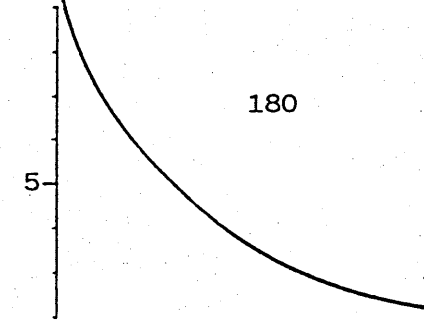
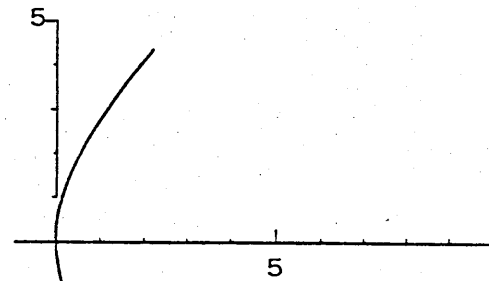
Fig.46(c)

Sample Intake Lip Profiles Used in Software Validation



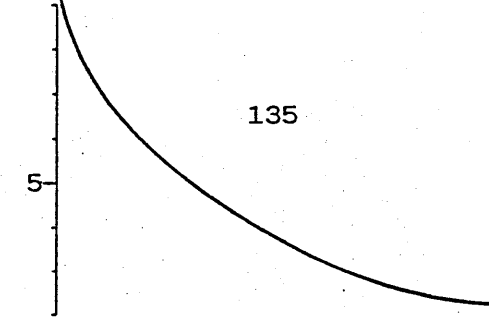
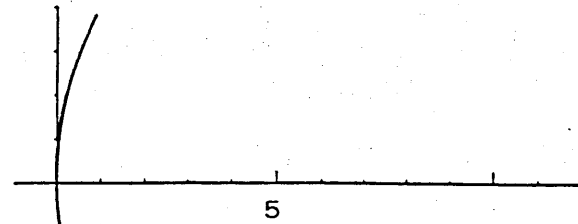
180

Fig.49



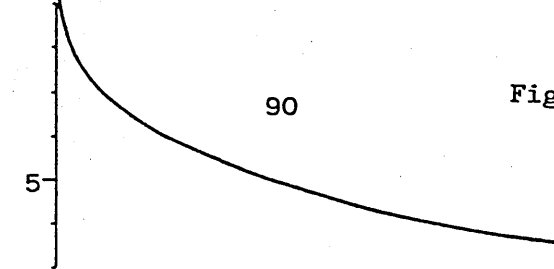
135

Fig.48



90

Fig.47



Static View of Sample Inlet with Wool Tufts

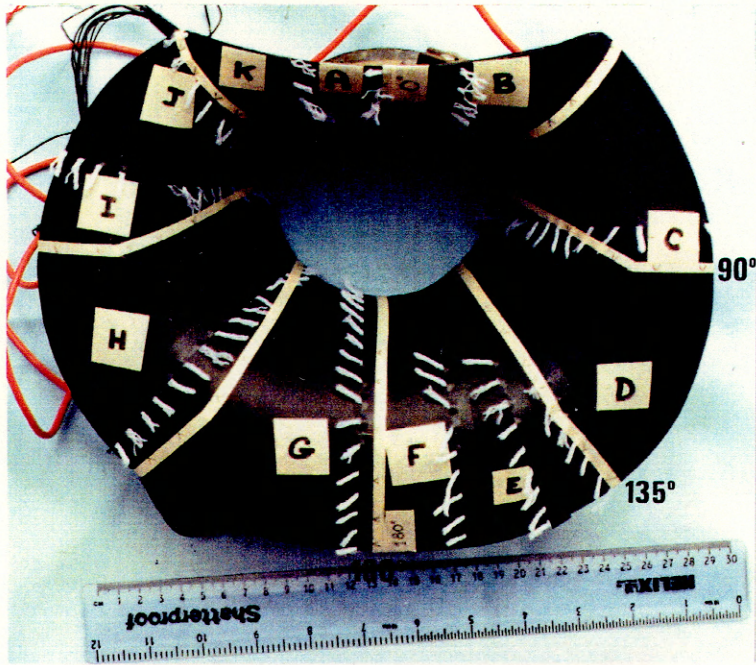


Fig.50

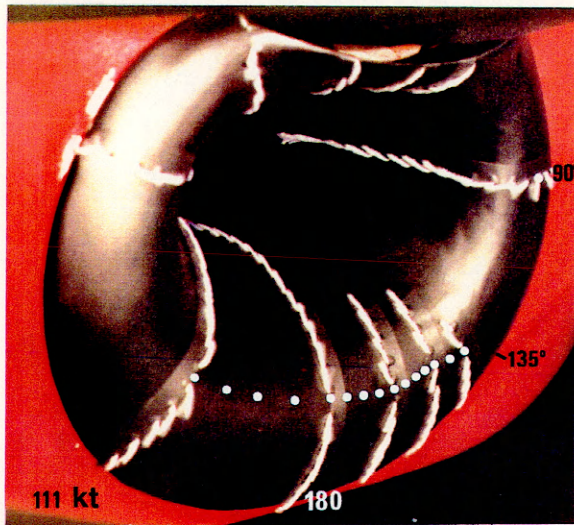


Fig.51

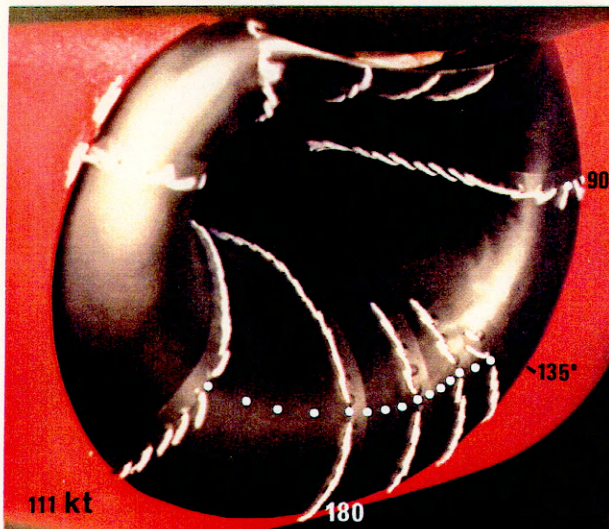


Fig.52

Wool Tuft Test Photographs

Wool Tuft Test Photographs

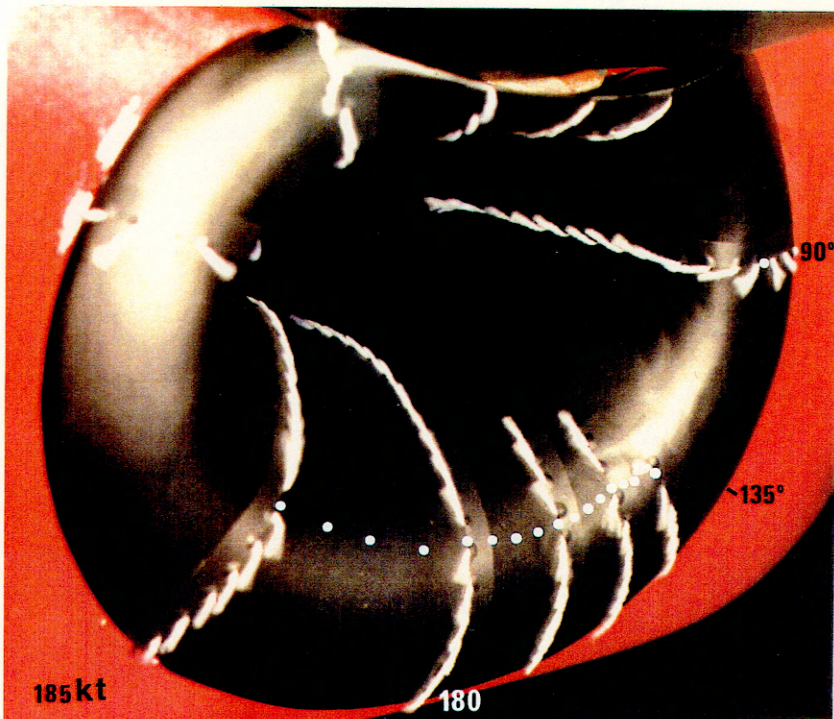


Fig.53

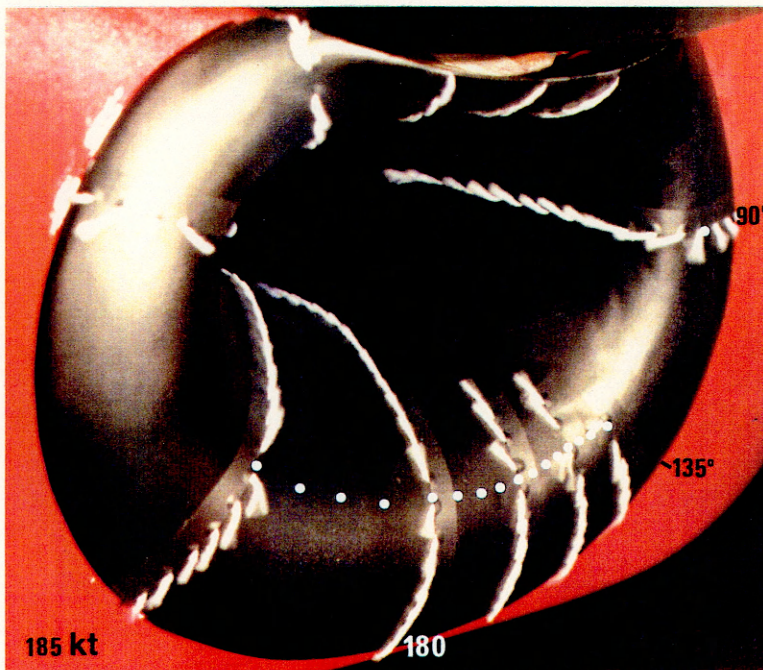


Fig.54

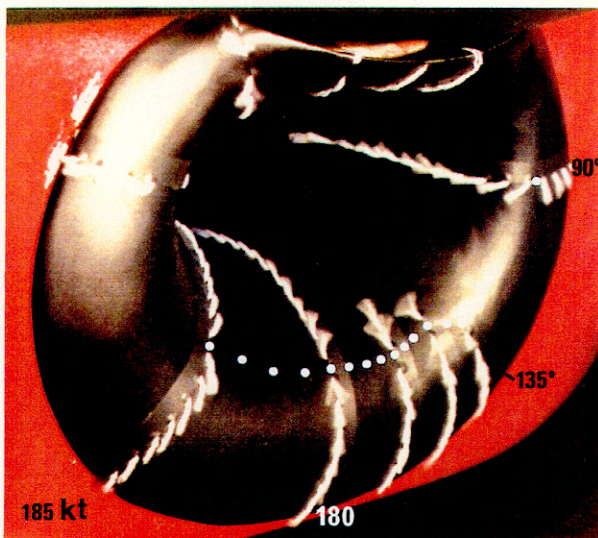


Fig. 55

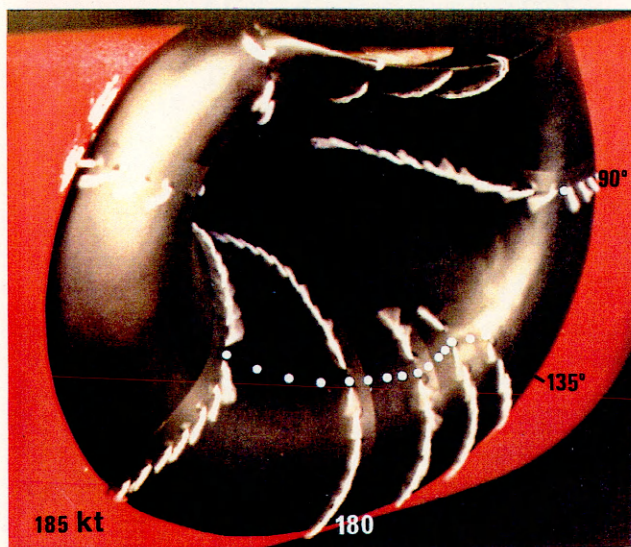


Fig. 56

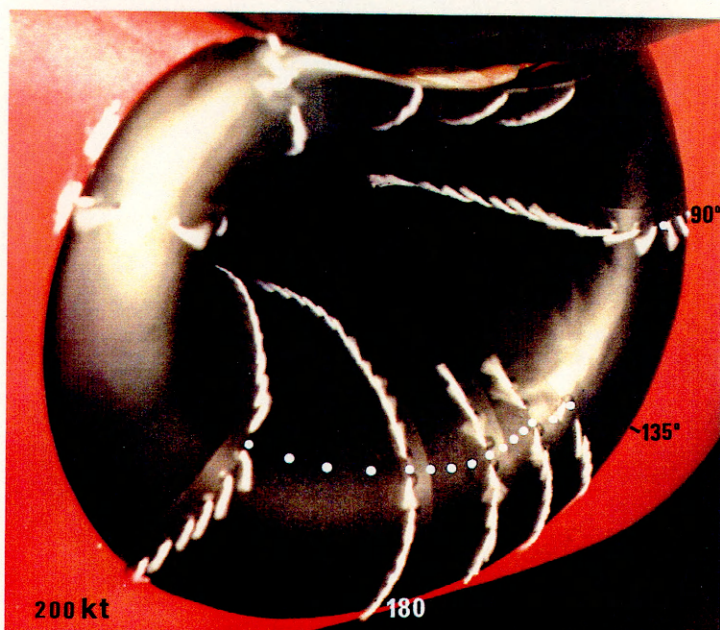


Fig. 57

Wool Tuft Test Photograph

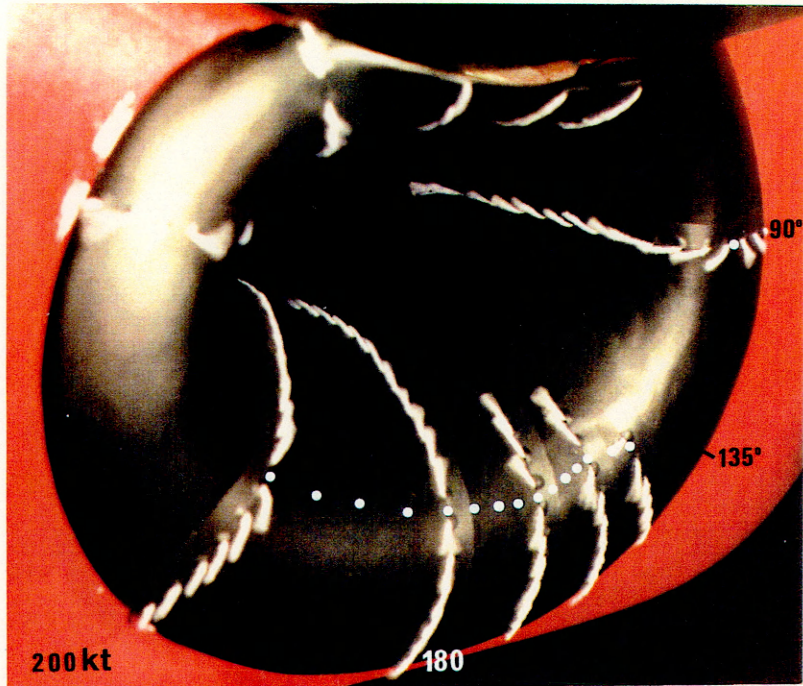


Fig.58

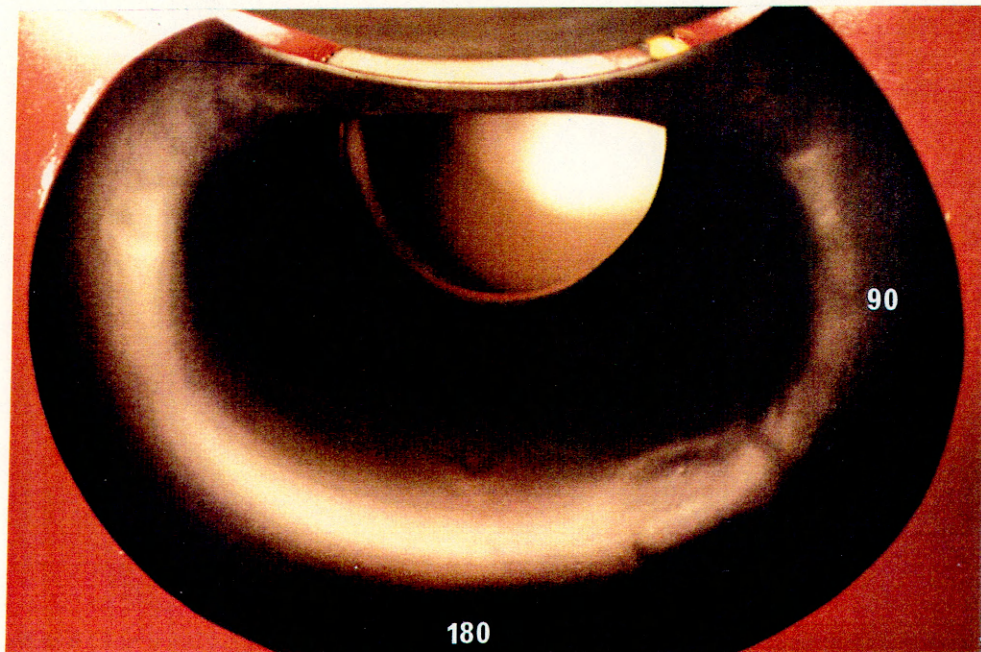


Fig.59

Sample Inlet Showing Thermal Sensor Location

Tunnel Icing Test Photographs

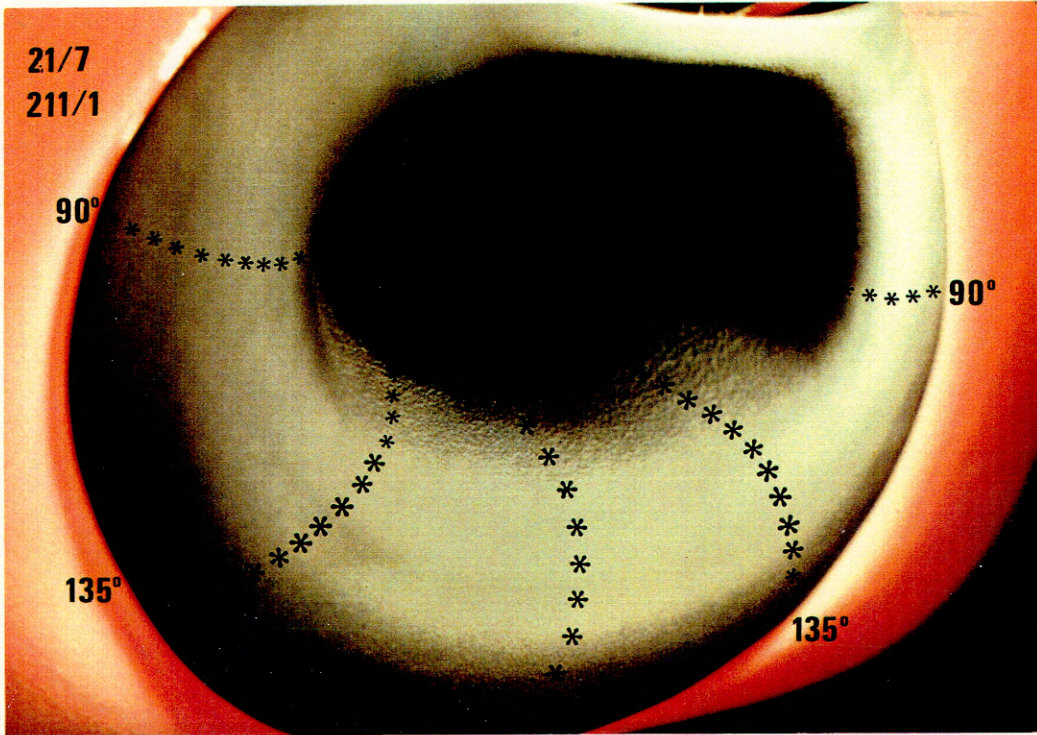


Fig.60

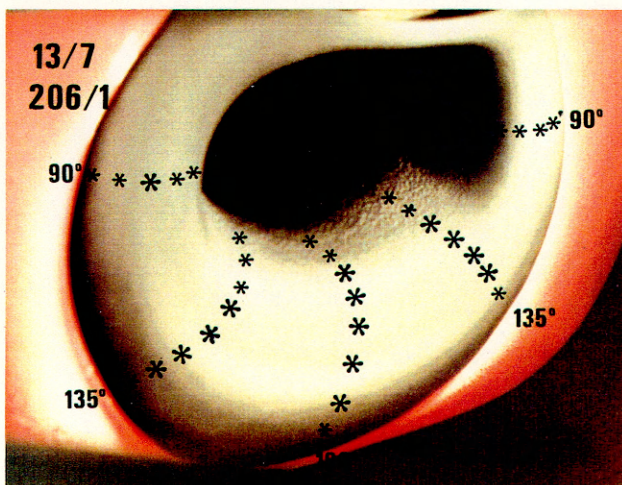


Fig.61

Tunnel Icing Test Photographs

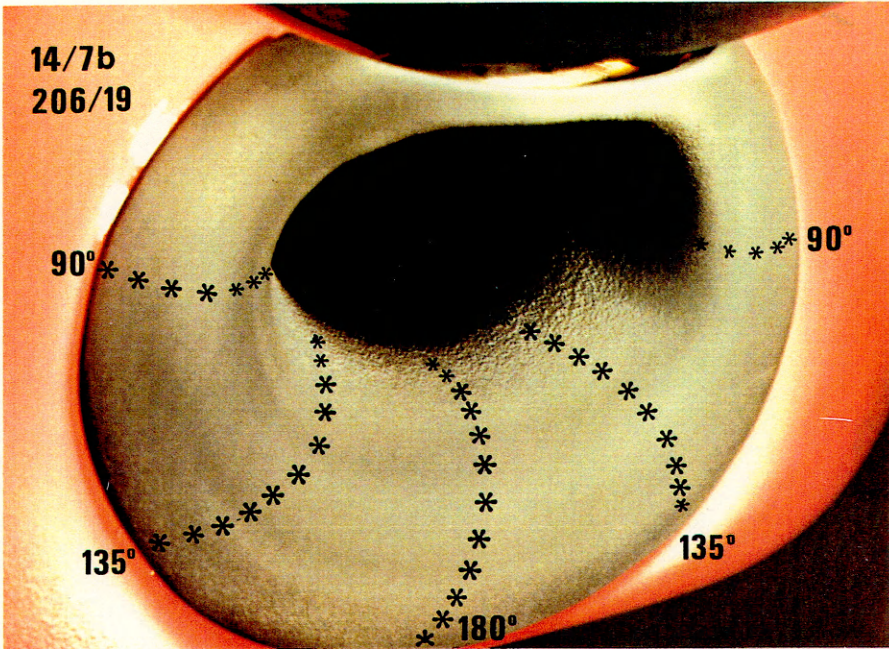


Fig.62

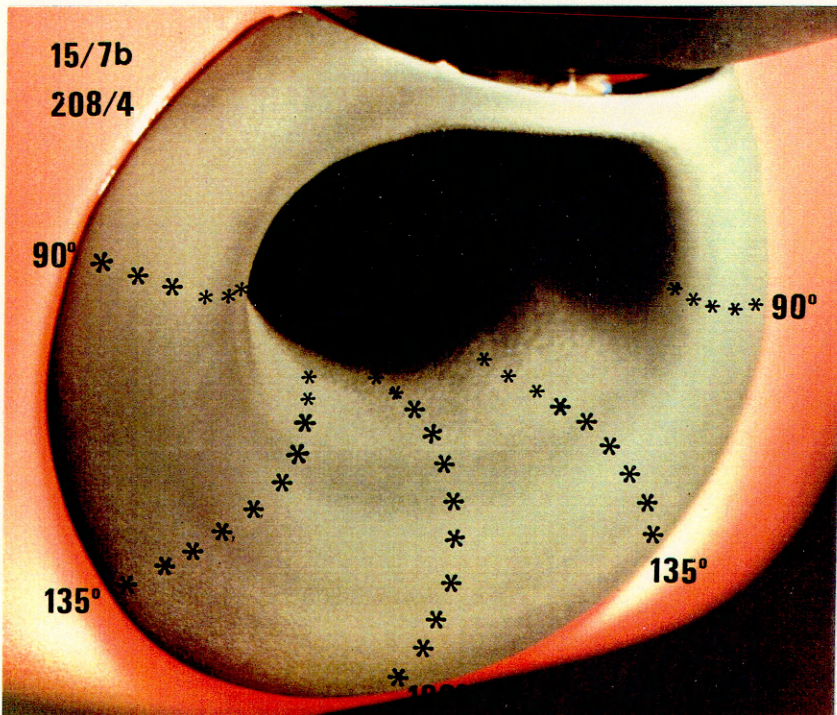
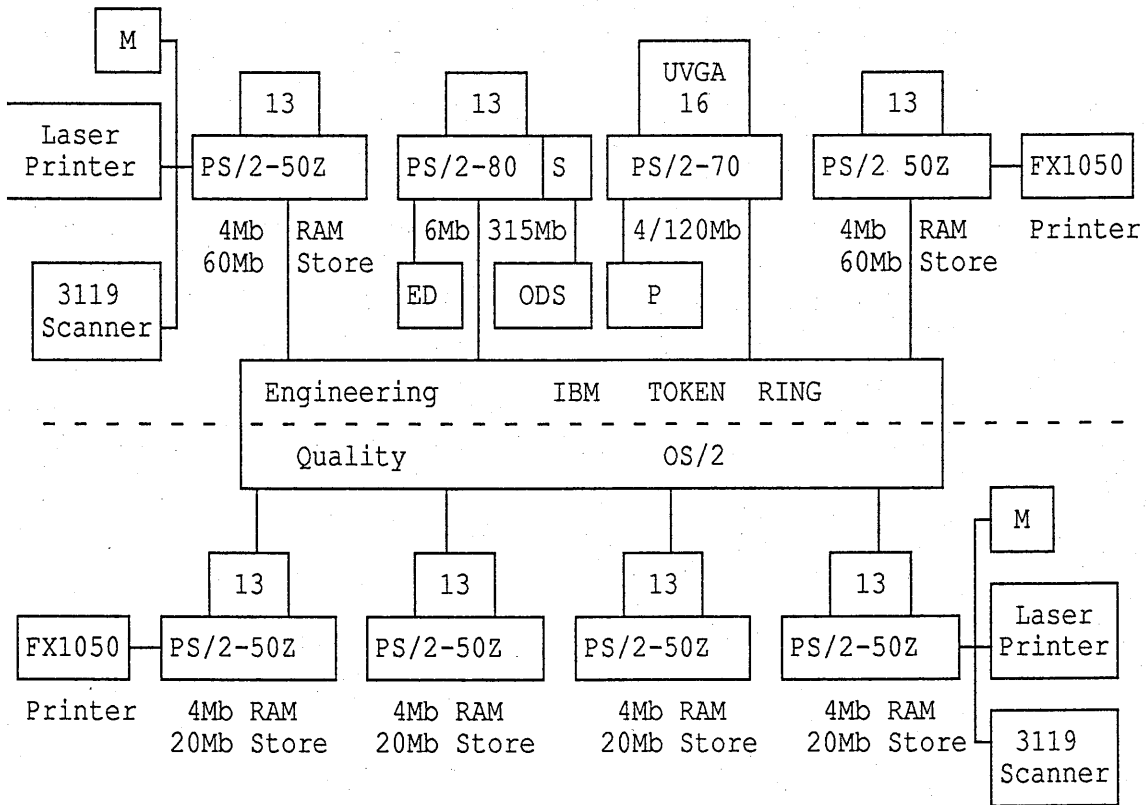


Fig.63



M	Mouse (digitizer)
Laser Printer	IBM personal pageprinter 4216-020
3119 Scanner	IBM 3119 Scanner
13	13 inch VGA colour IBM 8513 display
16	16 inch VGA colour IBM 8514 display
UVGA	UVGA screen adaptor card
RAM	System RAM memory
Store	System Store memory
FX1050	Epson FX1050 printer
S	120Mb Tape Streamer
ED	5.25 inch External Disk drive
ODS	Optical Disk Storage system
P	Hewlett Packard HP7475A Plotter

Fig.64

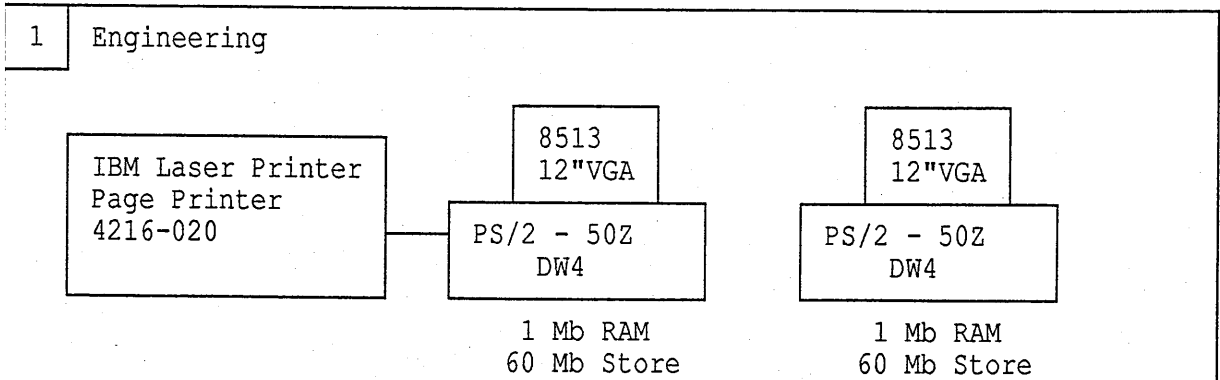


Fig.64(a)

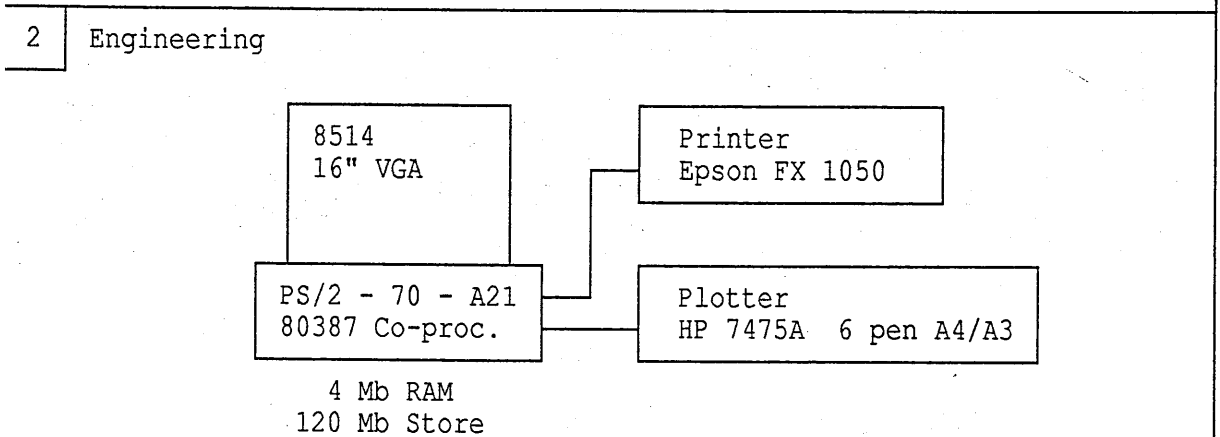


Fig.64(b)

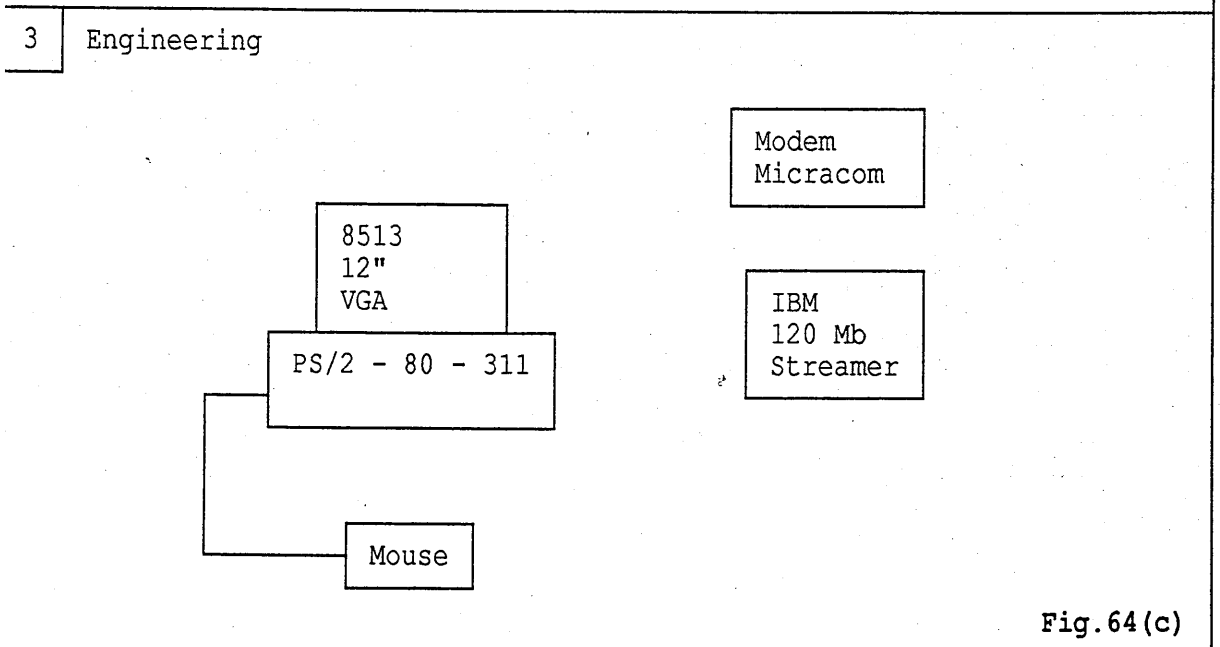
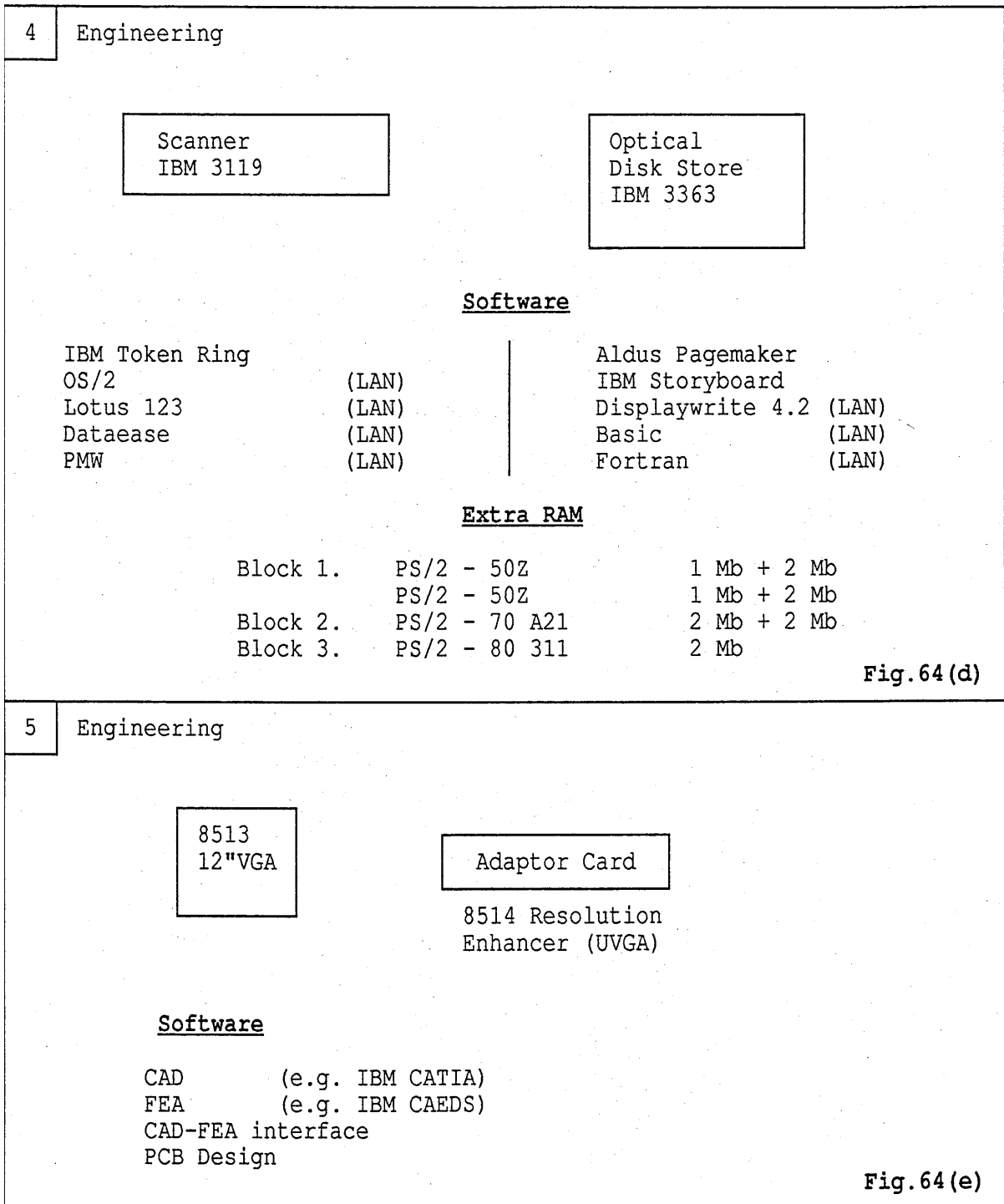
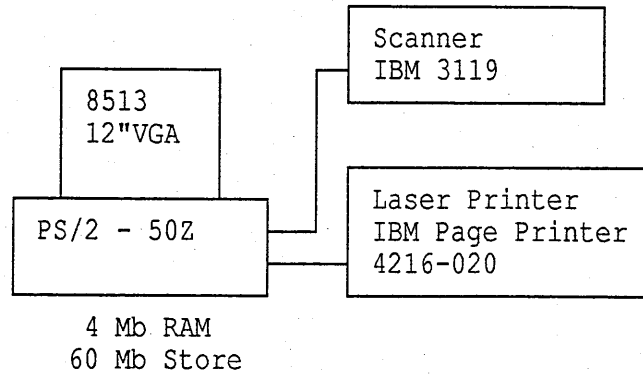


Fig.64(c)



Computer Network - Purchase Blocks

6 Quality



Software
Aldus Pagemaker
OS/2

Fig.64(f)

7 Quality

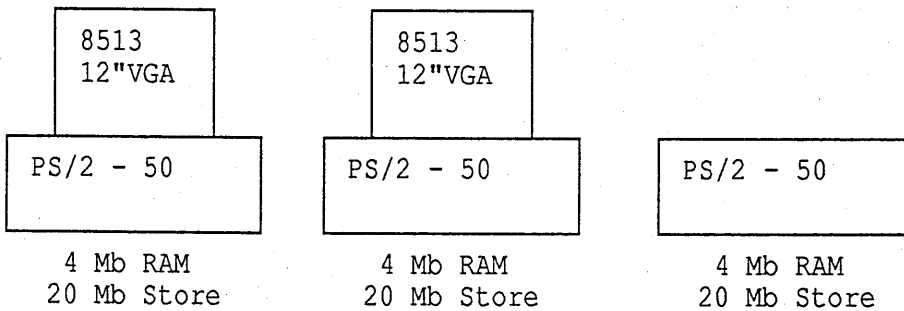


Fig.64(g)

Computer Network - Purchase Blocks

Empirical Ice Accretion Profile

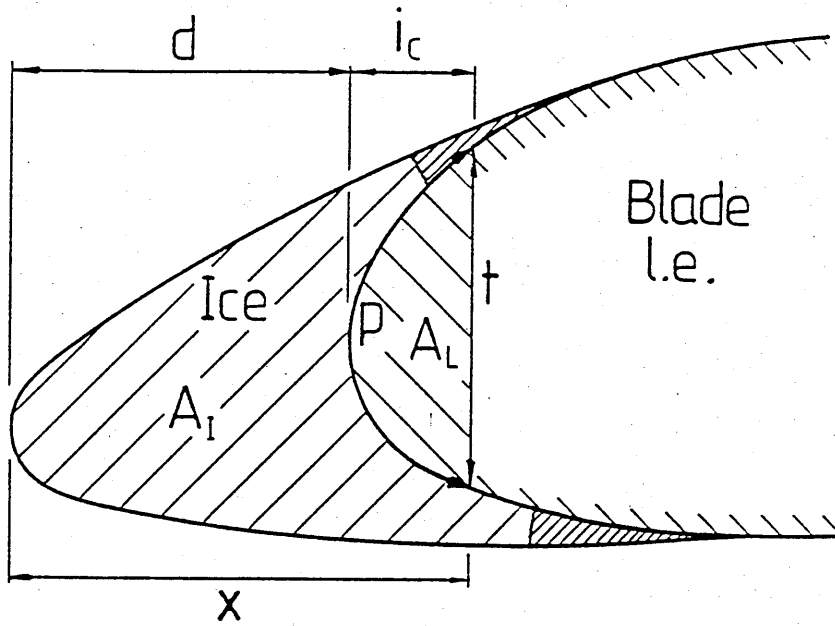


Fig.65(a)

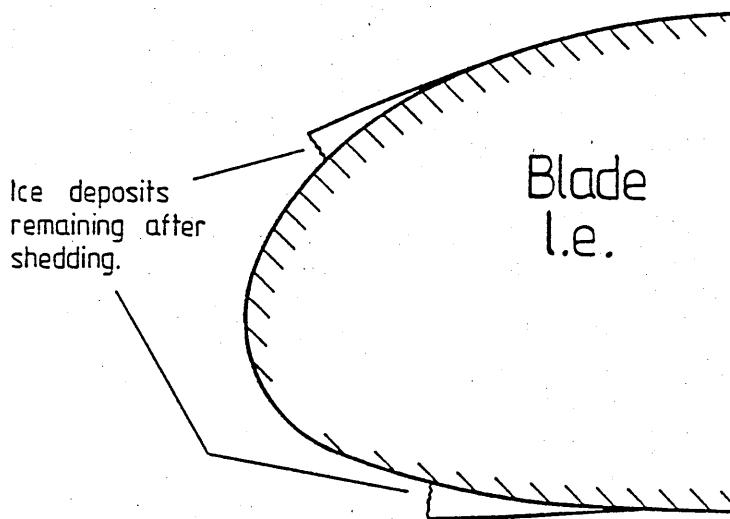


Fig.65(b)

Specimen Composite Propeller Blade

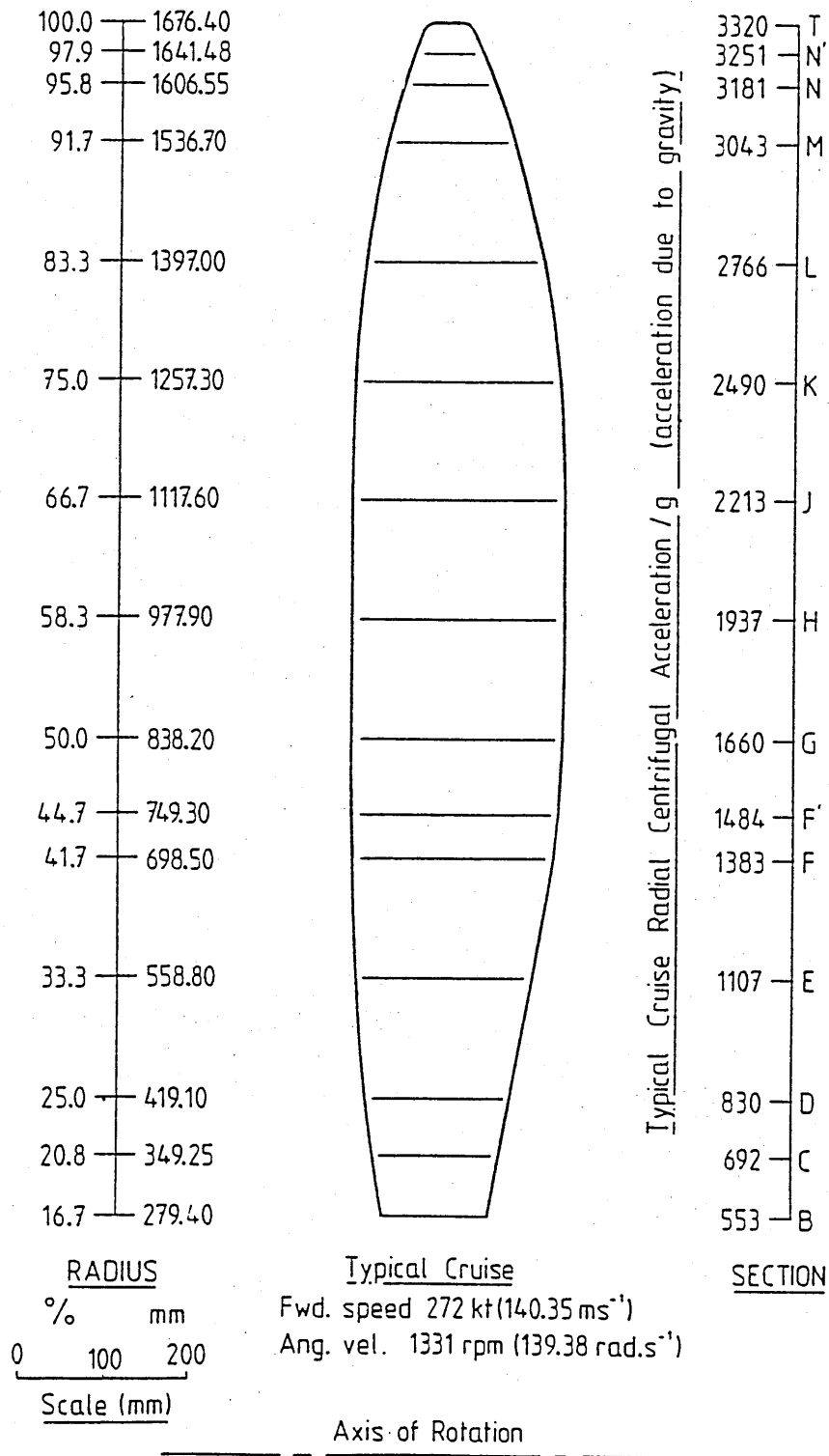
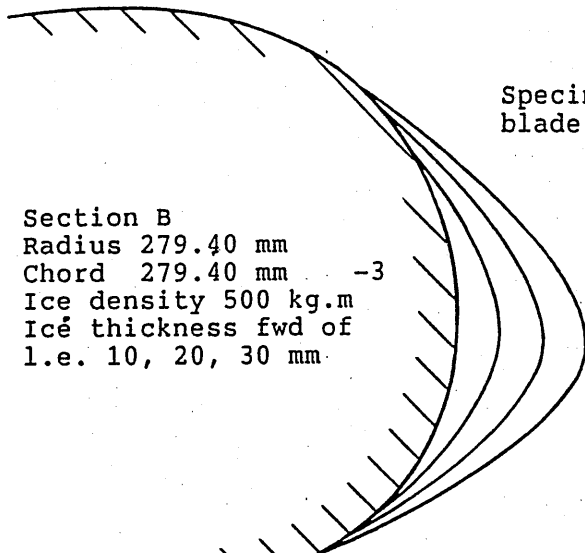


Fig.66

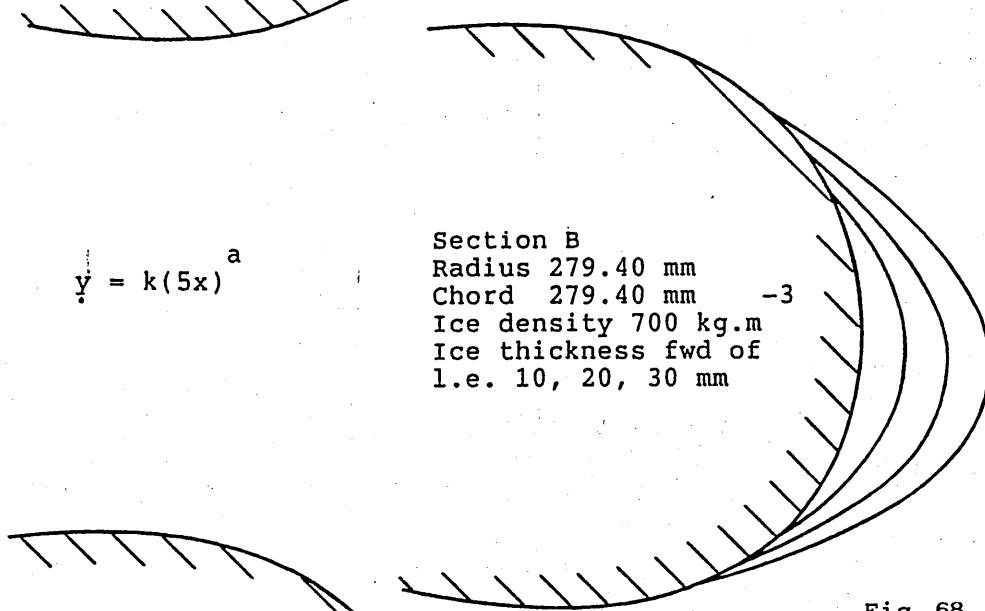
Specimen Ice Accretion Profiles



Specimen composite propeller
blade leading edge profiles

Section B
Radius 279.40 mm
Chord 279.40 mm -3
Ice density 500 kg.m
Ice thickness fwd of
l.e. 10, 20, 30 mm

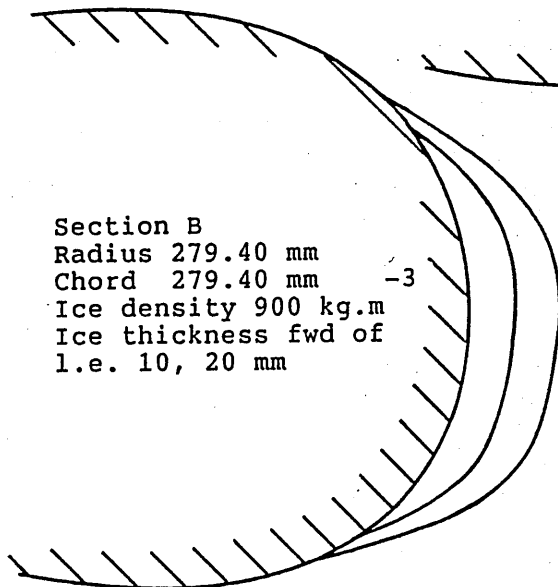
Fig. 67



$$\dot{y} = k(5x)^a$$

Section B
Radius 279.40 mm
Chord 279.40 mm -3
Ice density 700 kg.m
Ice thickness fwd of
l.e. 10, 20, 30 mm

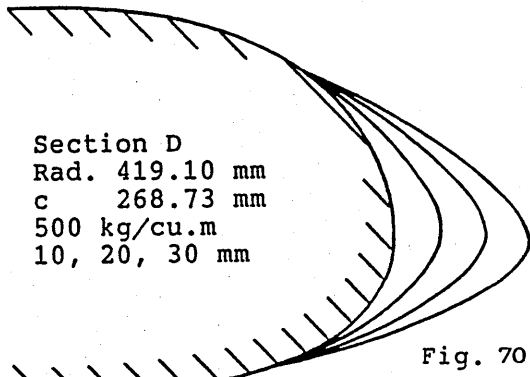
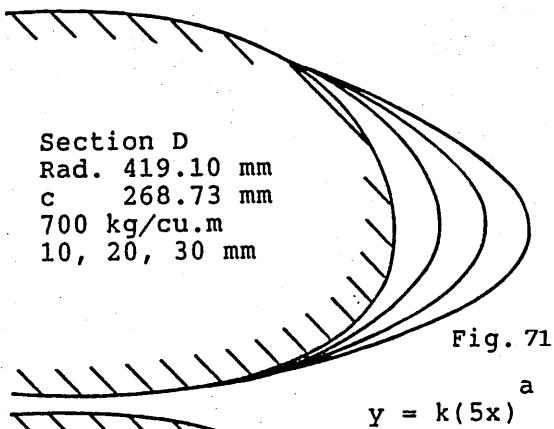
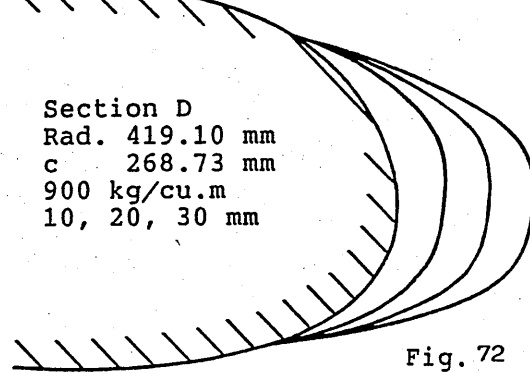
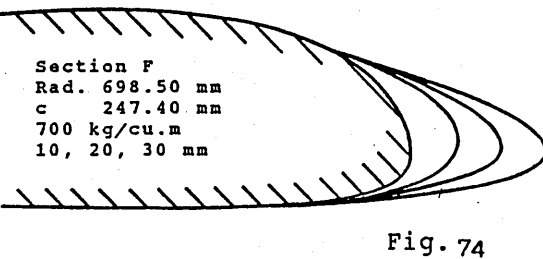
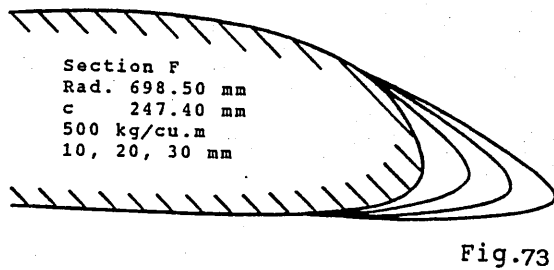
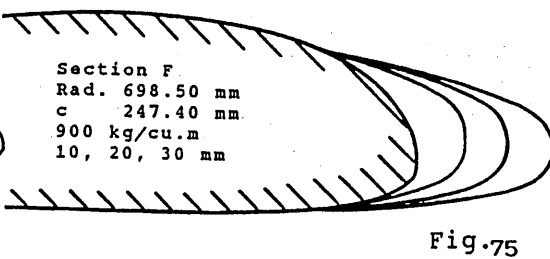
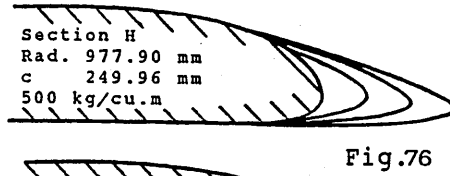
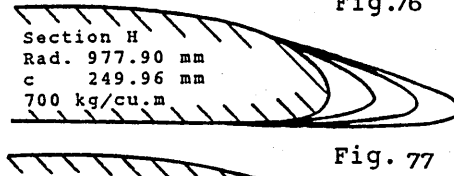
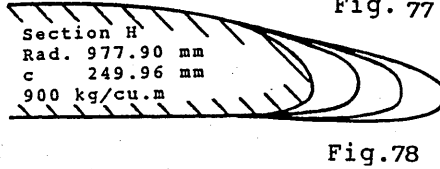
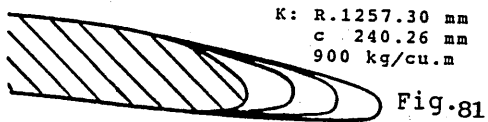
Fig. 68

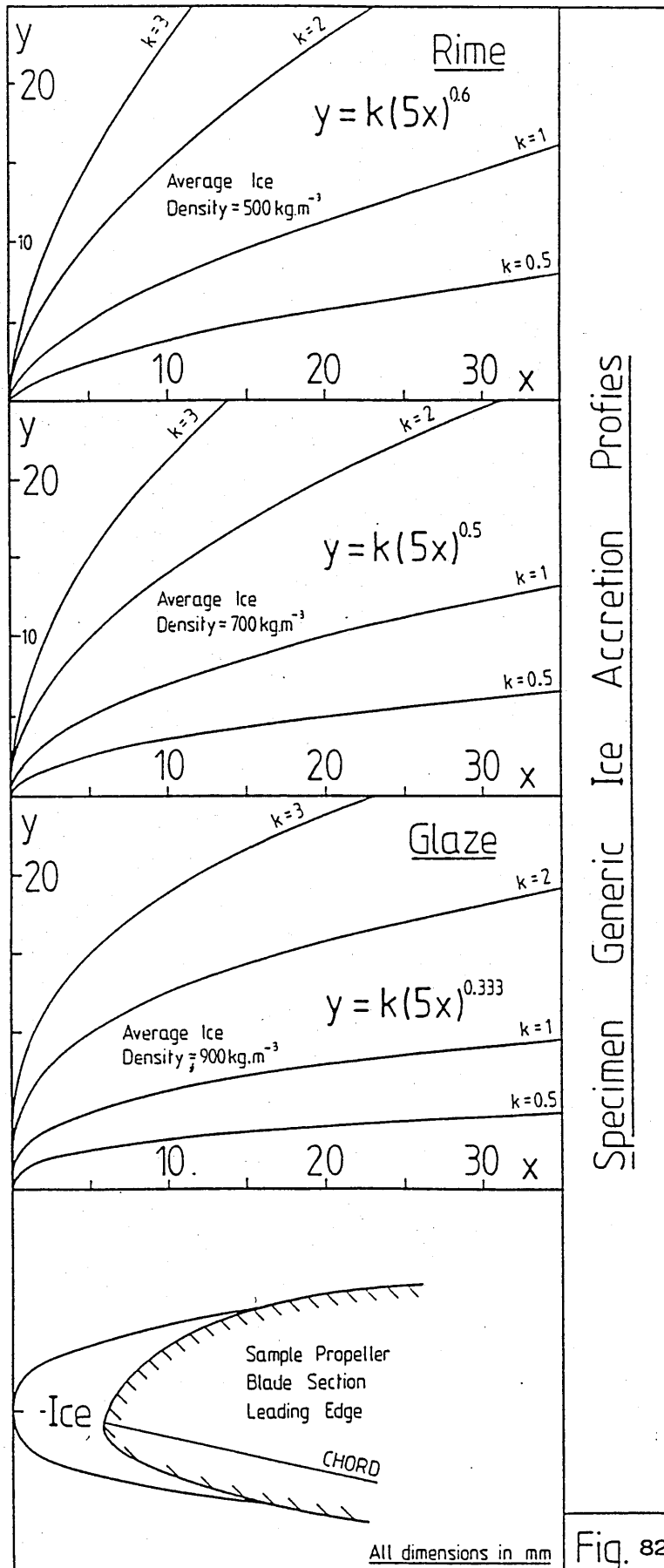


Section B
Radius 279.40 mm
Chord 279.40 mm -3
Ice density 900 kg.m
Ice thickness fwd of
l.e. 10, 20 mm

Fig. 69

Specimen Ice Accretion Profiles





Specimen Generic Ice Accretion Profiles

Fig. 82

Specimen Composite Blade Leading Edge Geometry

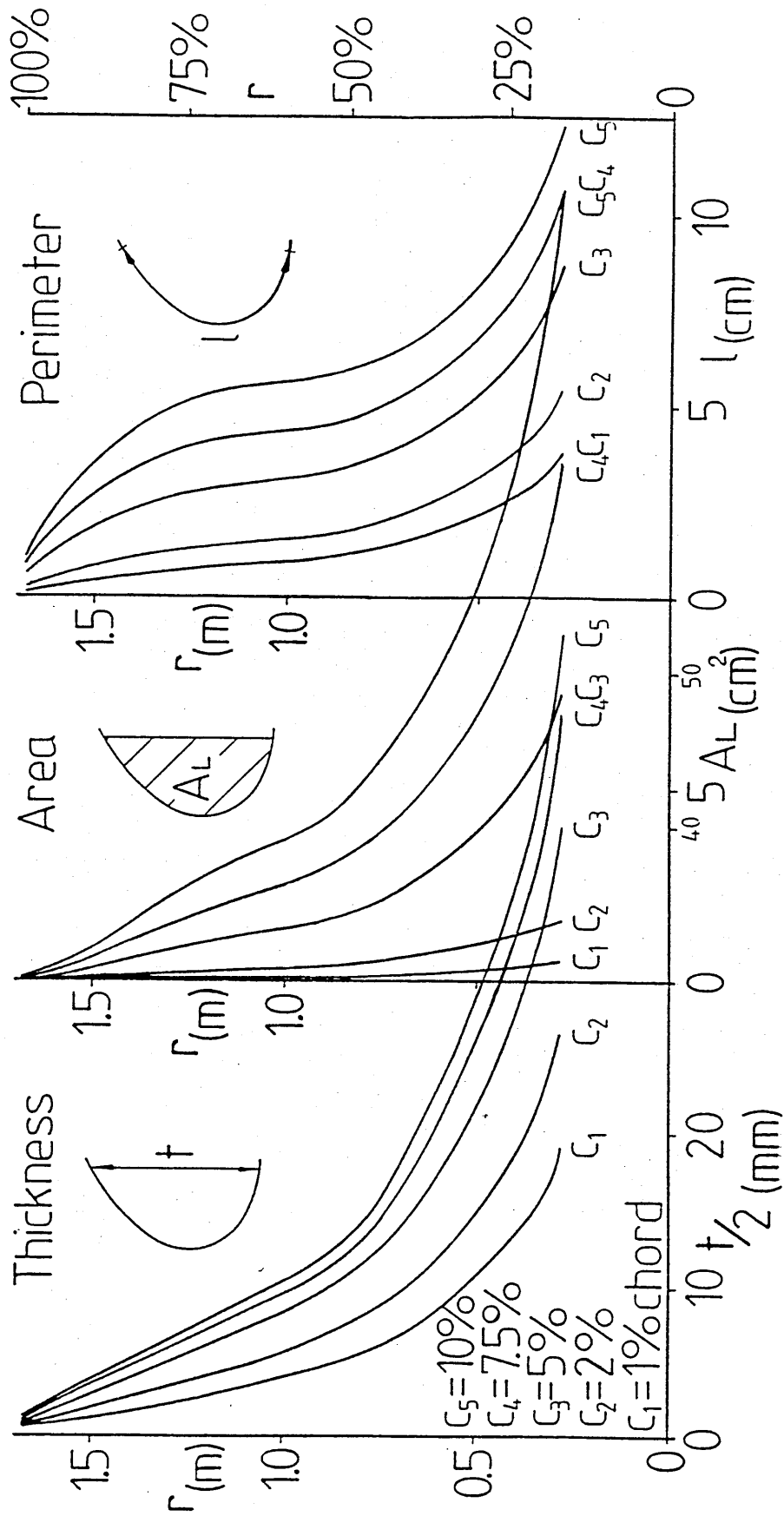


Fig.83

CASE 1: Metal Propeller Blade Composition

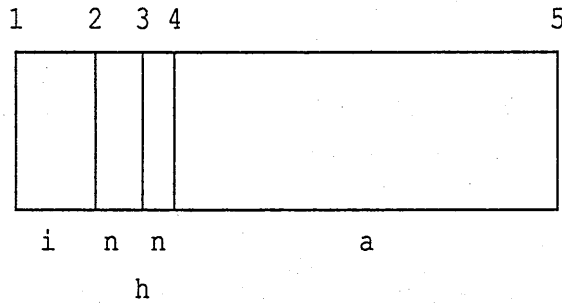


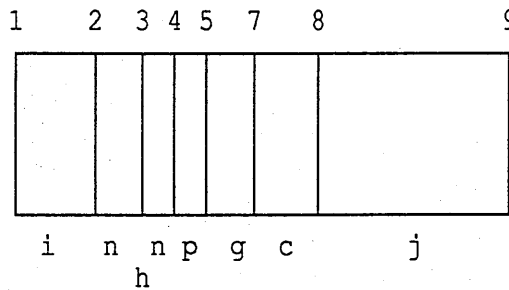
Fig.84

i = ice n = neoprene h = heater a = aluminium

Stations

1. Ice/air interface.
2. Ice/neoprene interface.
3. Electric heater matrix.
4. Neoprene/aluminium alloy interface.
5. Aluminium alloy/air interface.

Case 2: Composite Propeller Blade Composition



type (a)
(no polyurethane cuff)

Fig.85

mtp = mid thickness plane

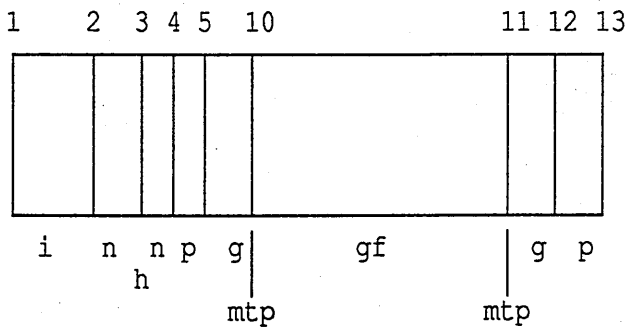


Fig.85(a)

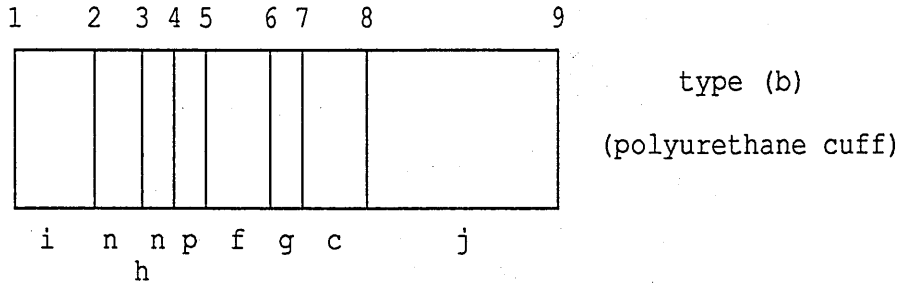


Fig.86

i = ice n = neoprene h = heater p = polyurethane paint
 f = foam cuff g = glass/resin c = carbon/resin
 j = foam core

(Fig.85) shows the construction of the sample composite blade as it exists between radii 750 mm and 890 mm. In this area the blade does not possess the polyurethane foam cuff as is the case inboard of 750 mm. The cuff is fitted to the blade between the glass fibre and spray polyurethane layers as in (Fig.86). The composite blade is fitted with a standard neoprene de-icing boot similar to that used on the metal blade.

Stations

1. Ice/air interface.
2. Ice/neoprene interface.
3. Electric heater matrix.
4. Neoprene/polyurethane interface.
5. (a). Polyurethane/glass fibre-epoxy resin interface.
 (b). Polyurethane/polyurethane foam cuff interface.
6. Polyurethane foam cuff/glass fibre-epoxy resin interface.
7. Glass fibre-epoxy resin/carbon fibre-epoxy resin interface.
8. Carbon fibre-epoxy resin/polyurethane foam core interface.
9. Polyurethane foam core centre.

gf = glass fibres cf = carbon fibres

g/r = glass fibre matrix resin

c/r = carbon fibre matrix resin

Typical Composite Propeller Blade Composition

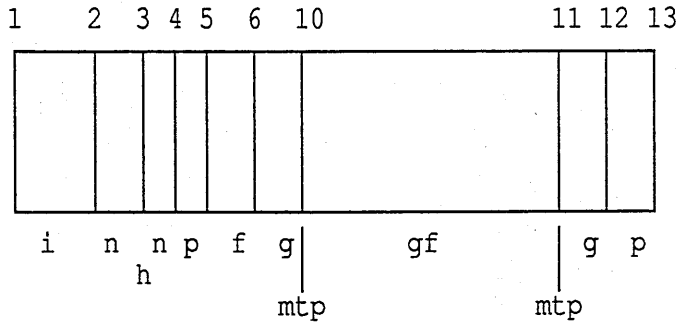


Fig.86(a)

mtp = mid thickness plane

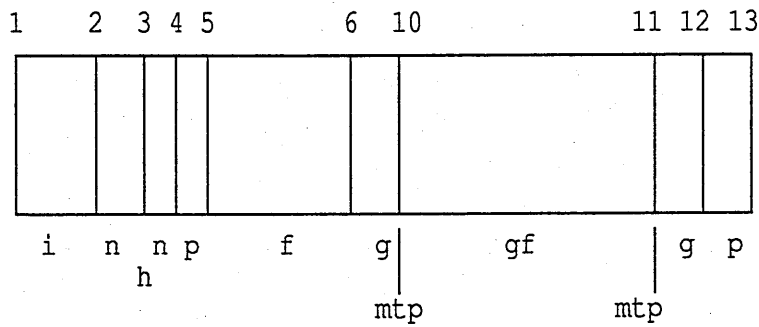


Fig.86(b(i))

mtp = mid thickness plane

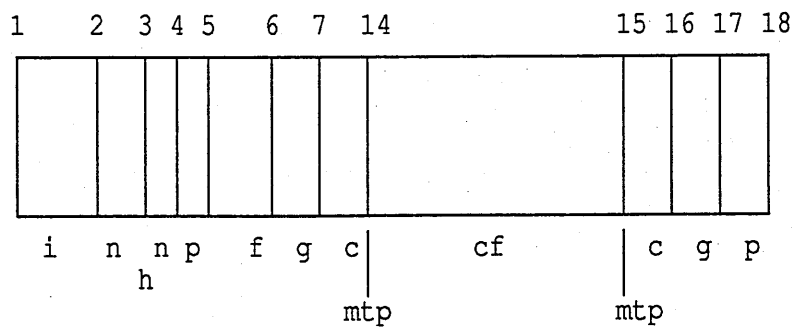


Fig.86(b(ii))

mtp = mid thickness plane

Typical Composite propeller Blade Composition

Typical Composite Propeller Blade Sections

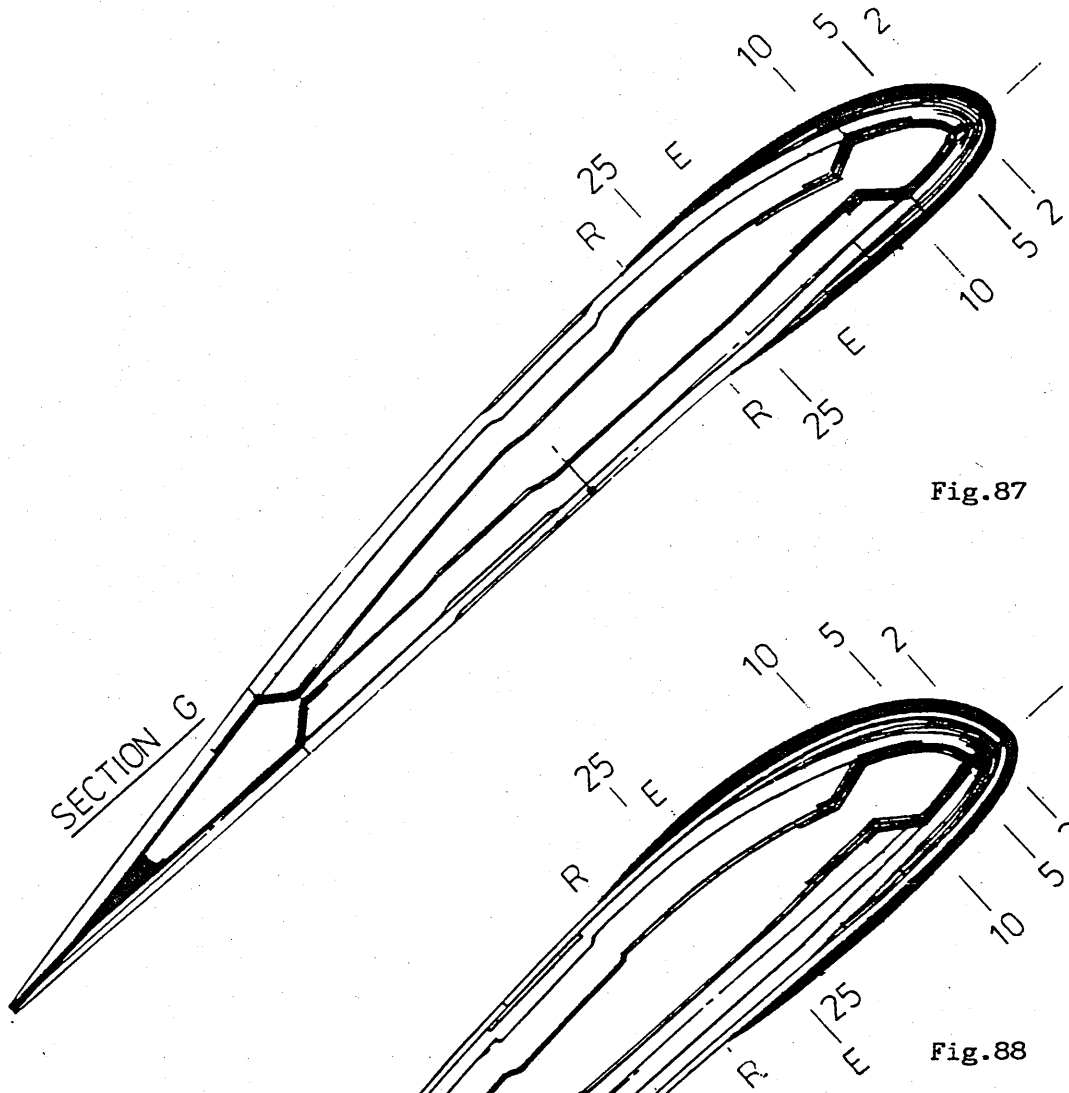
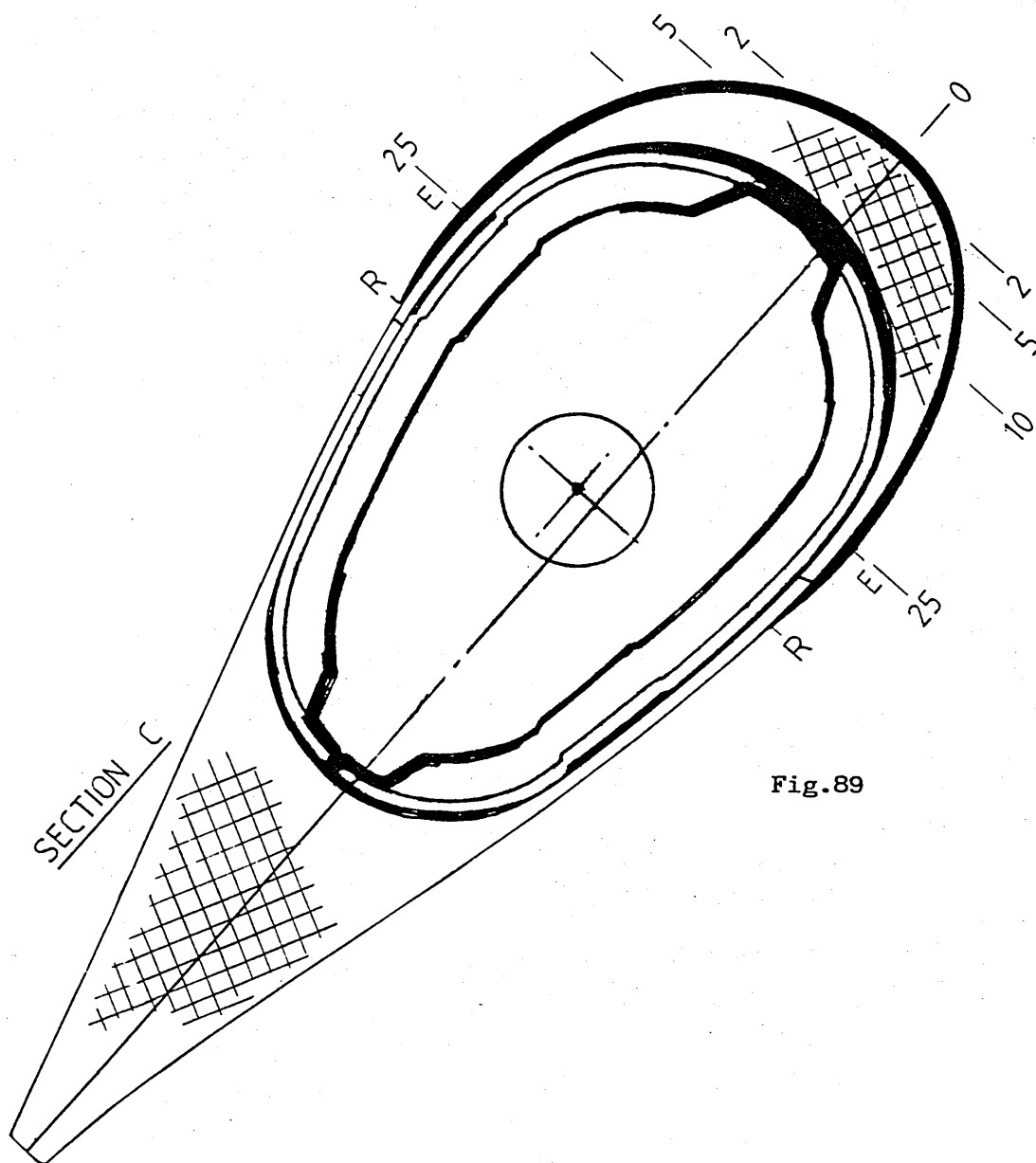


Fig.87

Fig.88

R t/e rubber
E t/e element
2 2% chord

Typical Composite Propeller Blade Section



Theoretical Heat Transfer Coefficient for Flat Plate

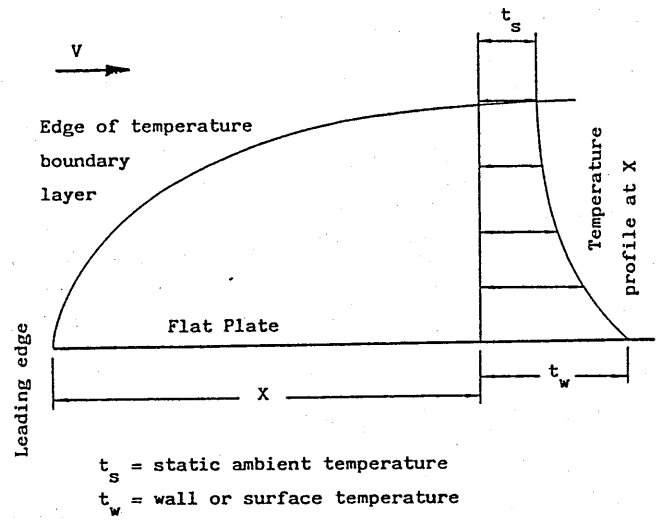


Fig.90

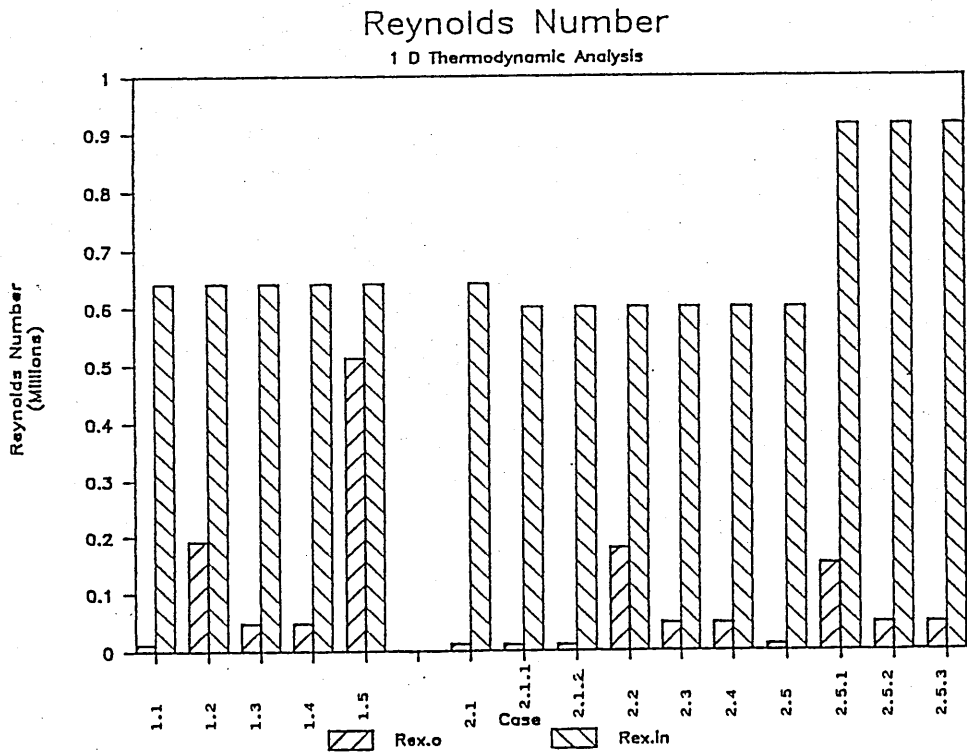


Fig.91

One-Dimensional Thermodynamic Analysis Results

Heat Transfer Coefficient
1D Thermodynamic Analysis

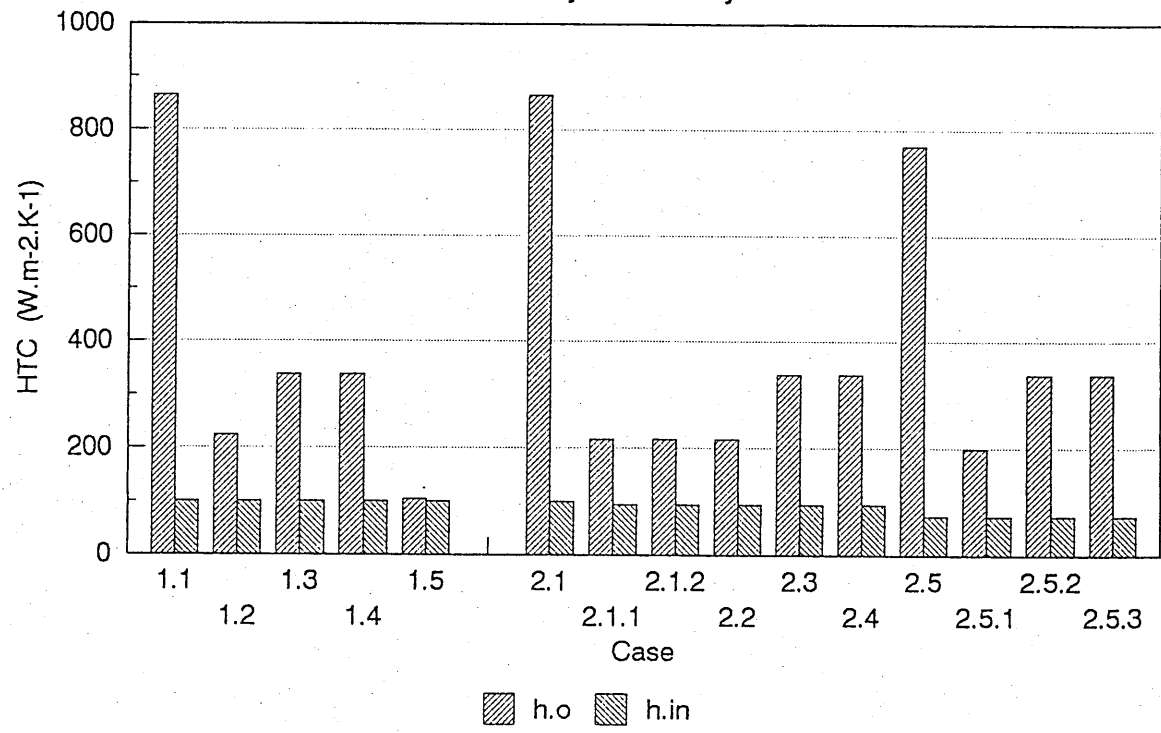


Fig.92

Overall Thermal Conductivity
1D Thermodynamic Analysis

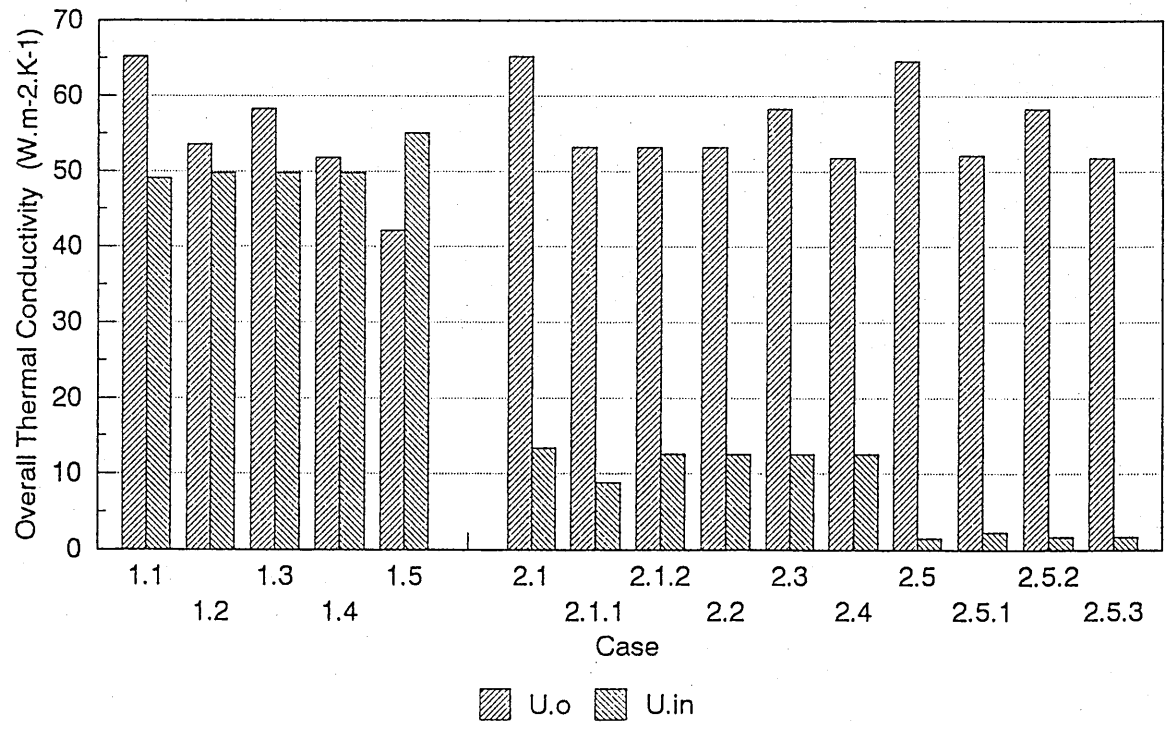


Fig.93

Heat Output Ratio

1D Thermodynamic Analysis

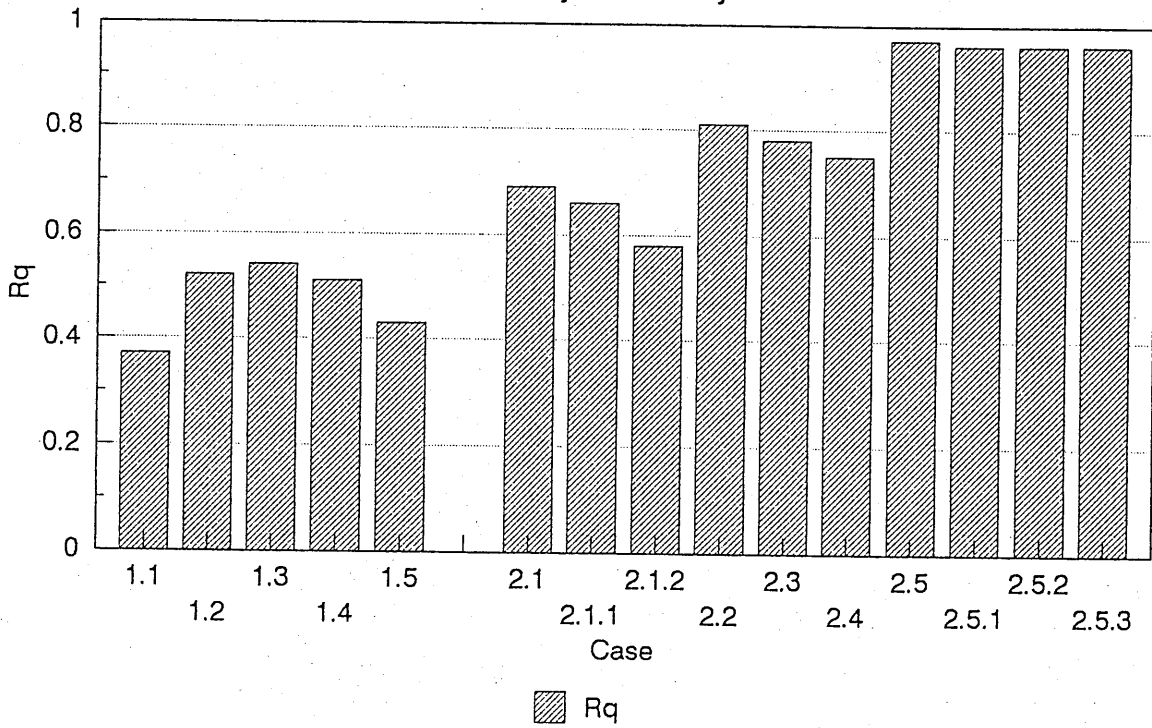


Fig.94

Heat Transfer Rate

1D Thermodynamic Analysis

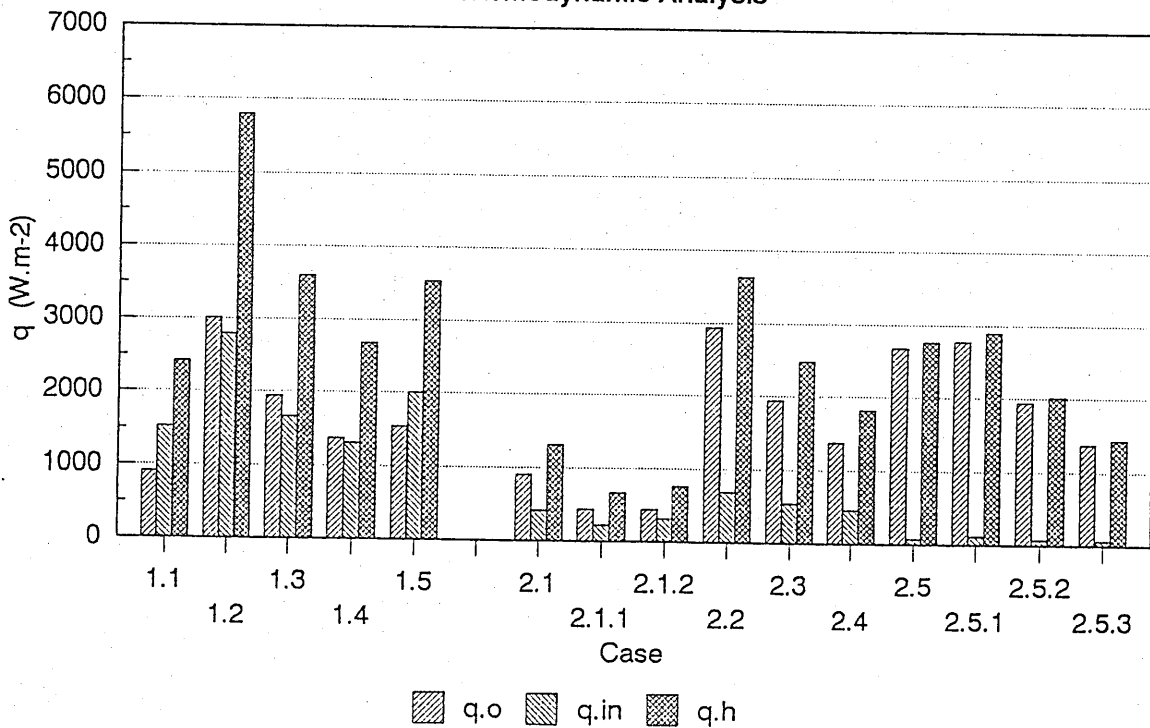


Fig.95

Heater Temperature 1D Thermodynamic Analysis

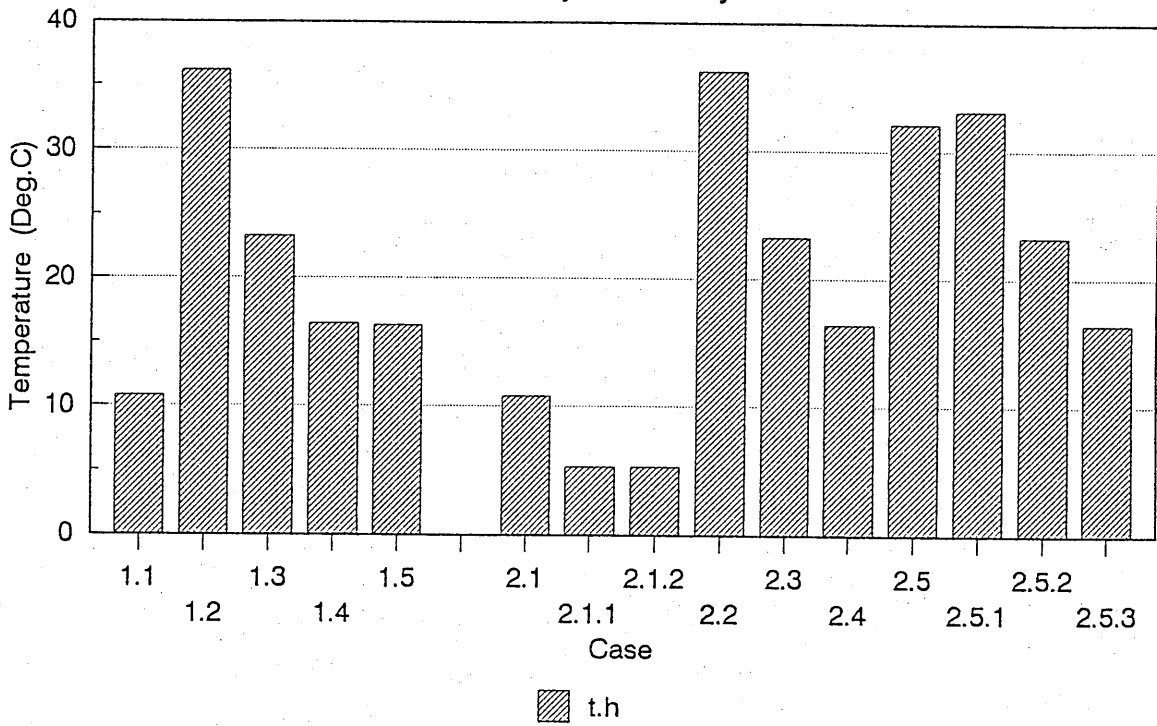


Fig.96

Temperature : Ice/Air Interface (fwd) 1D Thermodynamic Analysis

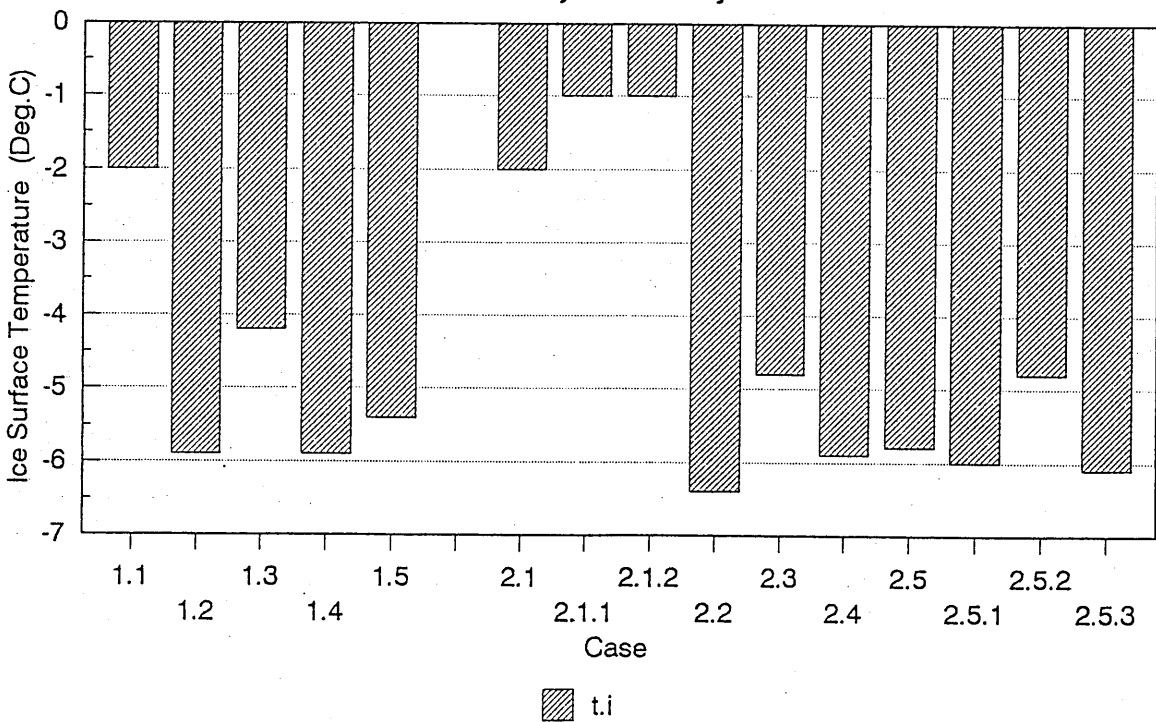


Fig.97

De-Icer/Blade Interface Temperature 1D Thermodynamic Analysis

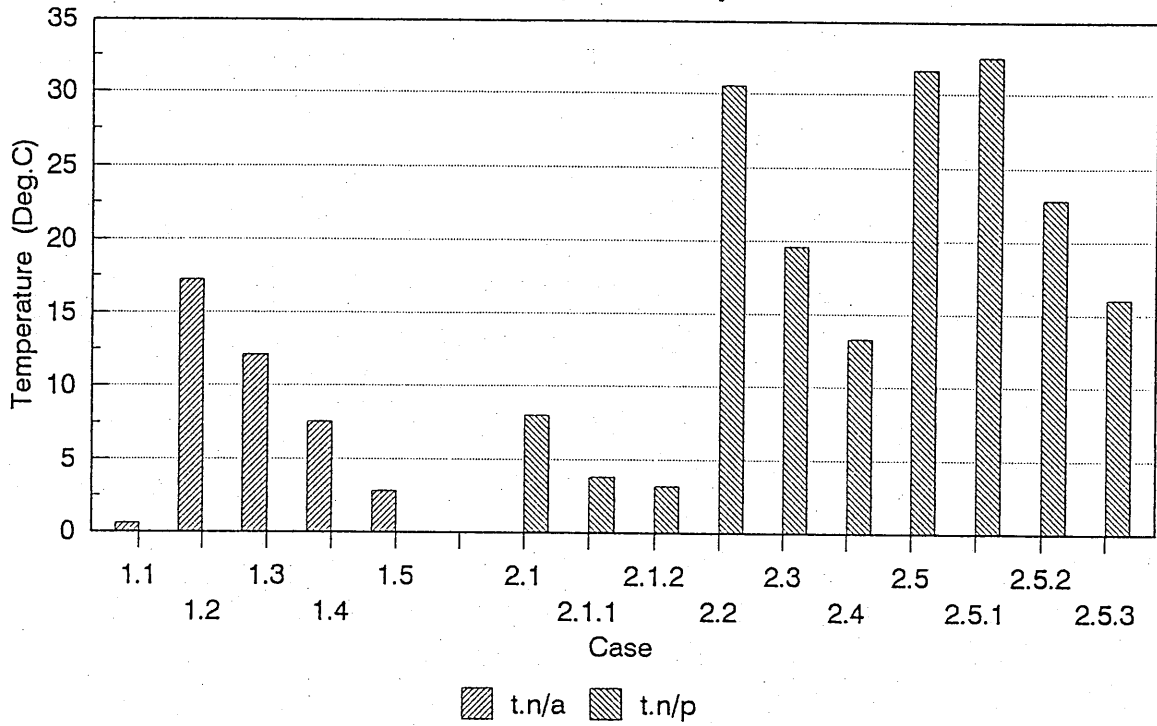


Fig.98

Aft Heat Exit Surface Temperature 1D Thermodynamic Analysis

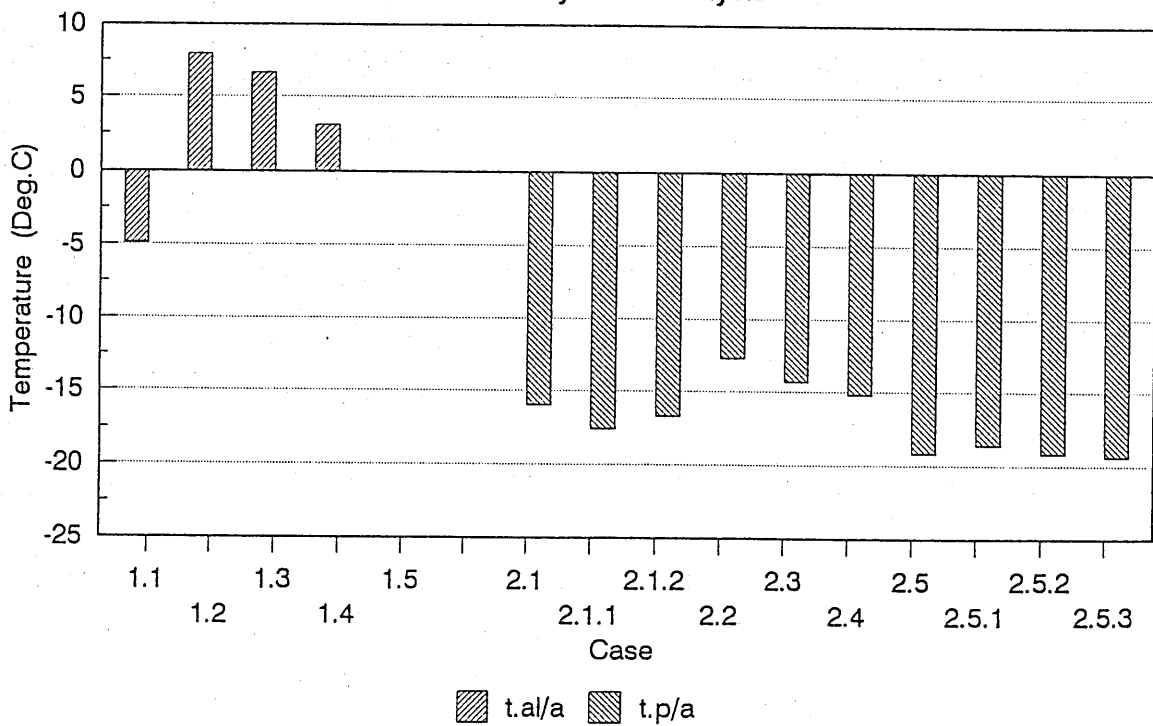
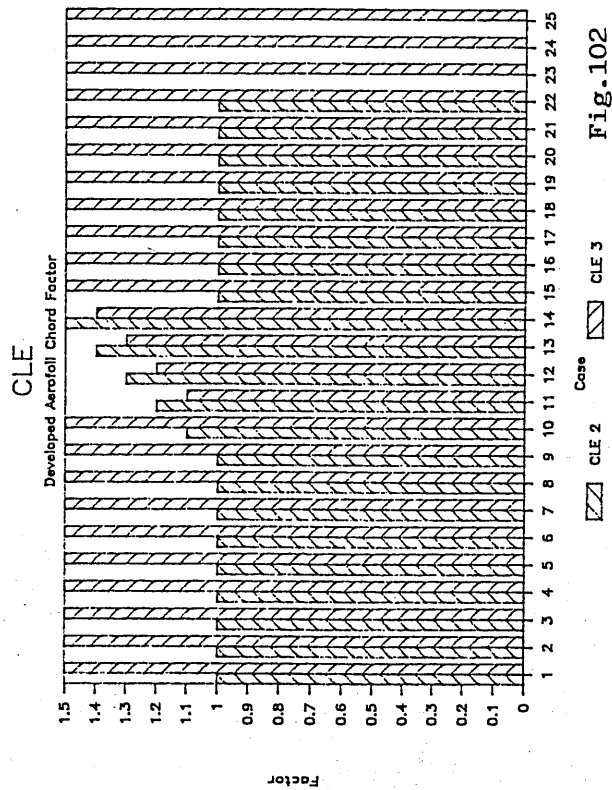
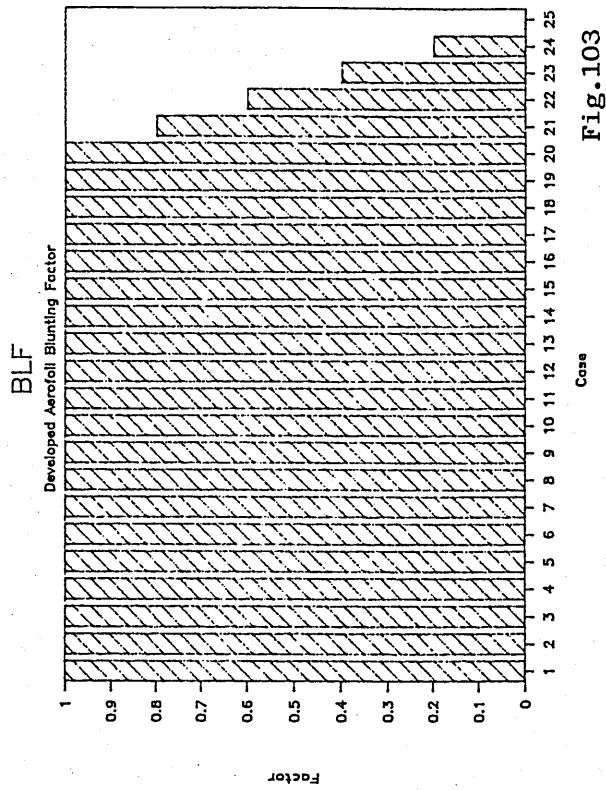
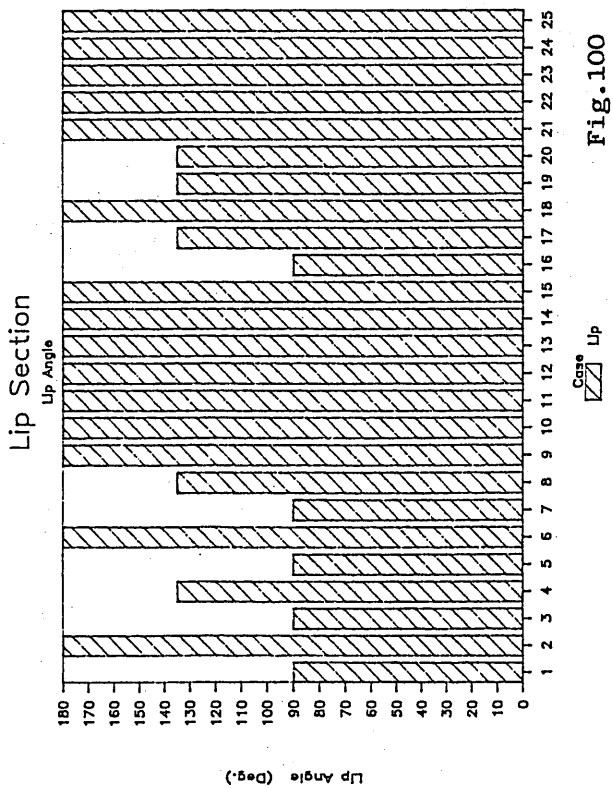
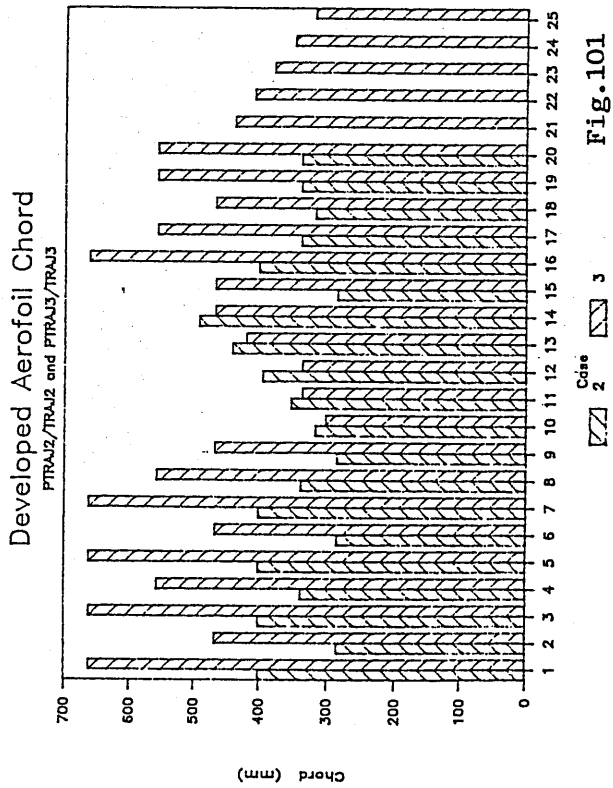
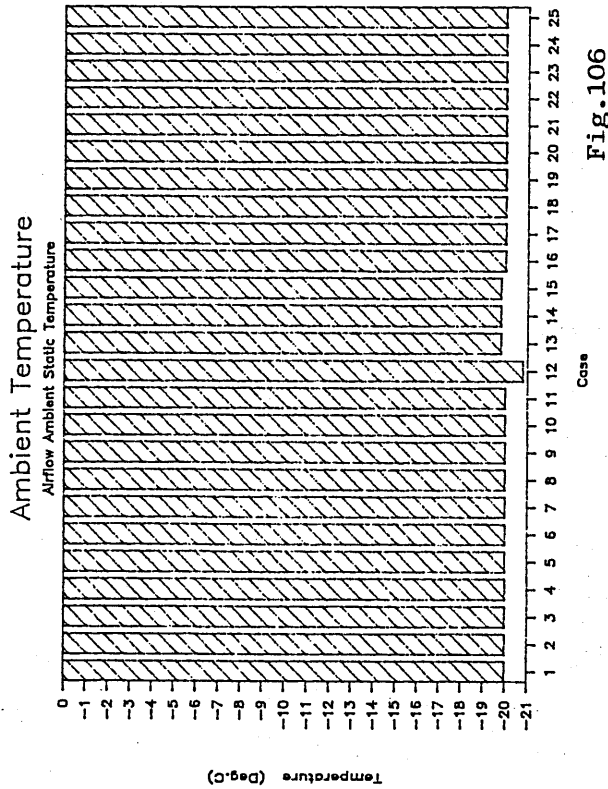
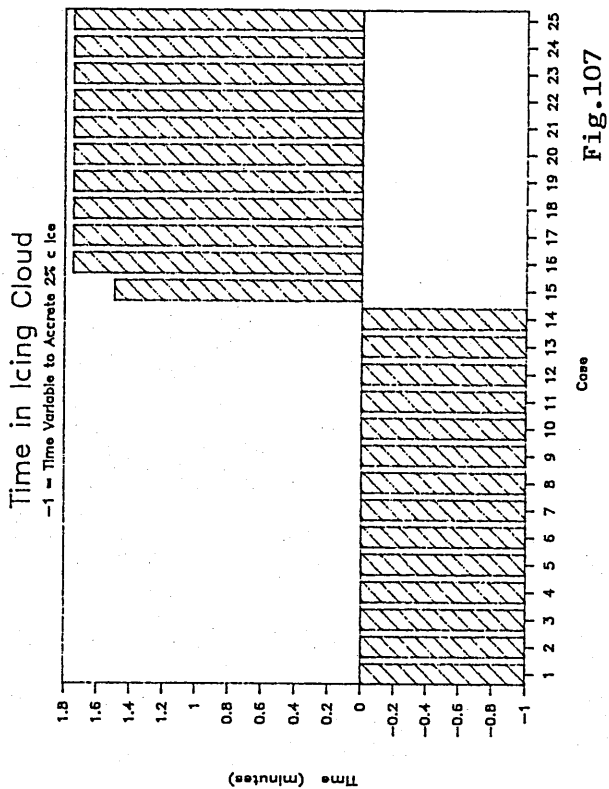


Fig.99

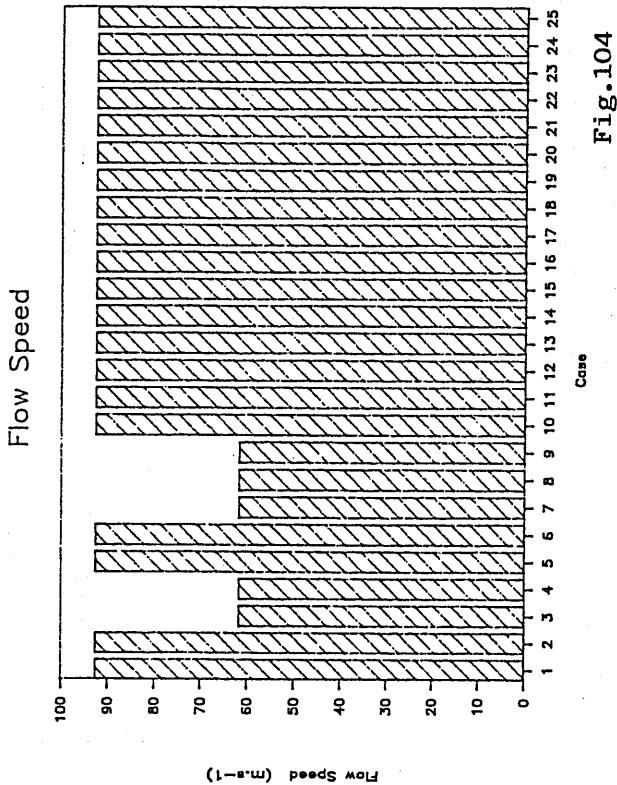
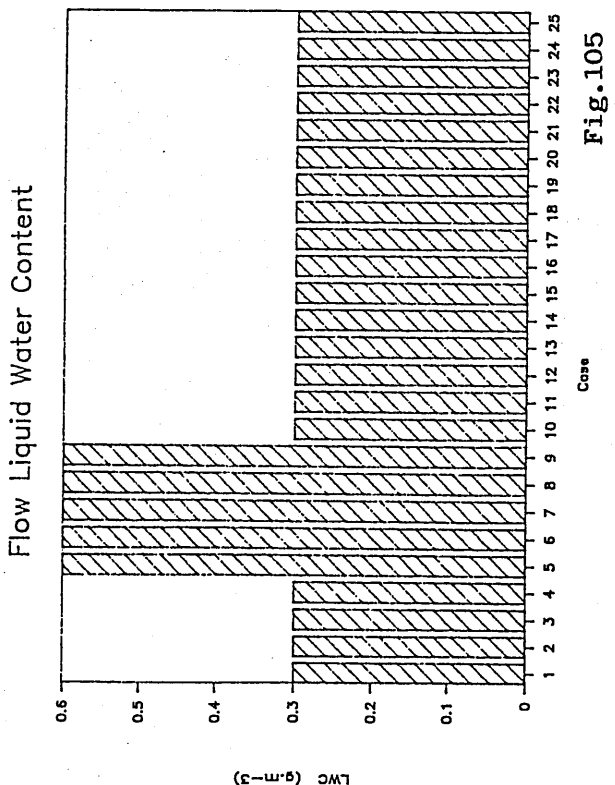


Two-Dimensional Ice Accretion Prediction Results





Two-Dimensional Ice Accretion Prediction Results



Ice Catch — Upper Surface

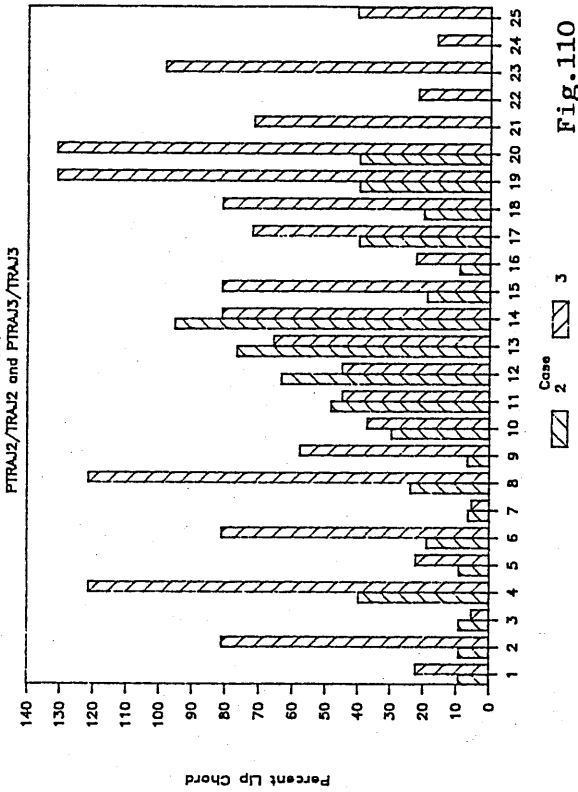


Fig.110

Ice Catch — Upper Surface

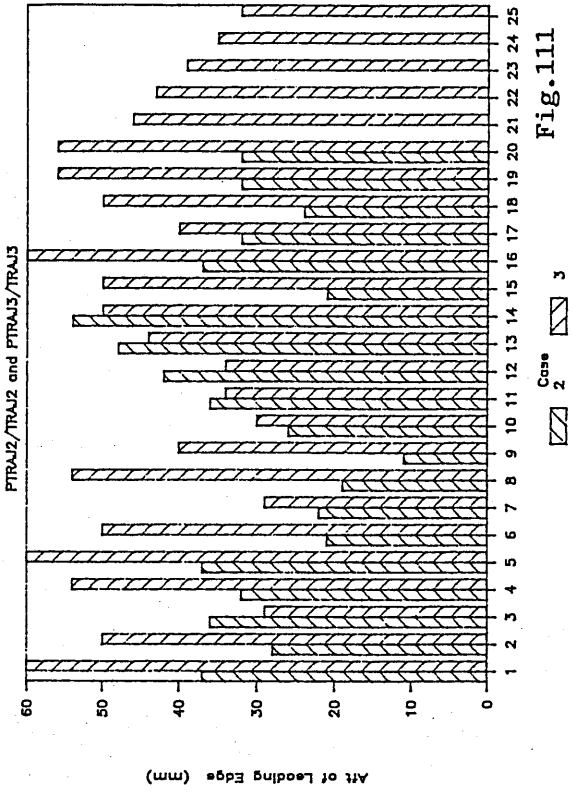


Fig.111

Two-Dimensional Ice Accretion Prediction Results

Catch — Upper Surface

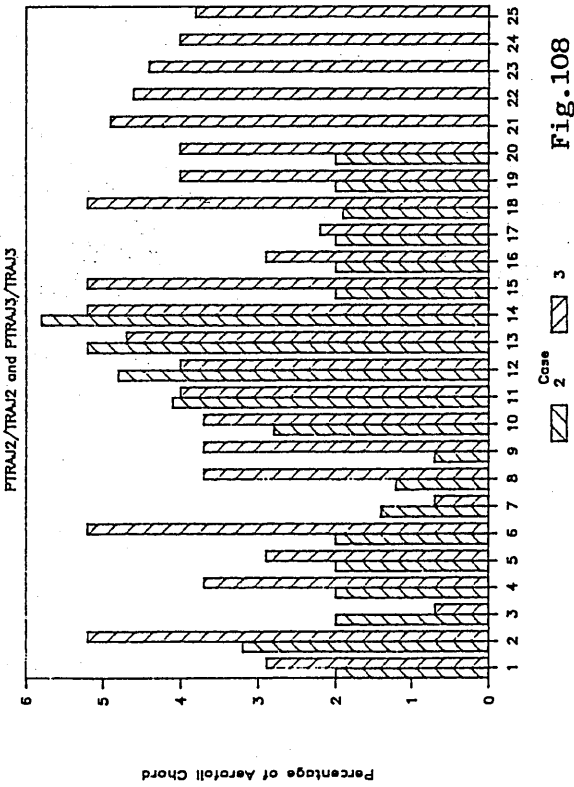


Fig.108

Ice Catch — Upper Surface

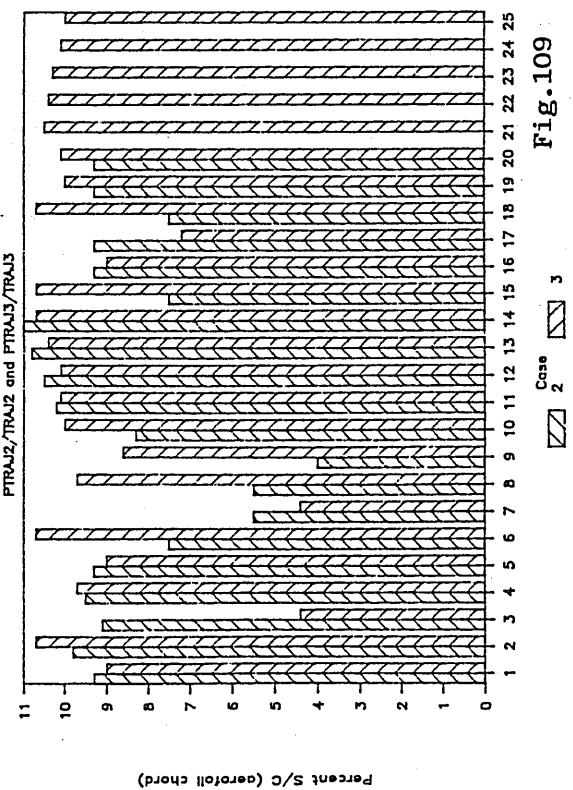


Fig.109

Ice Catch — Lower Surface

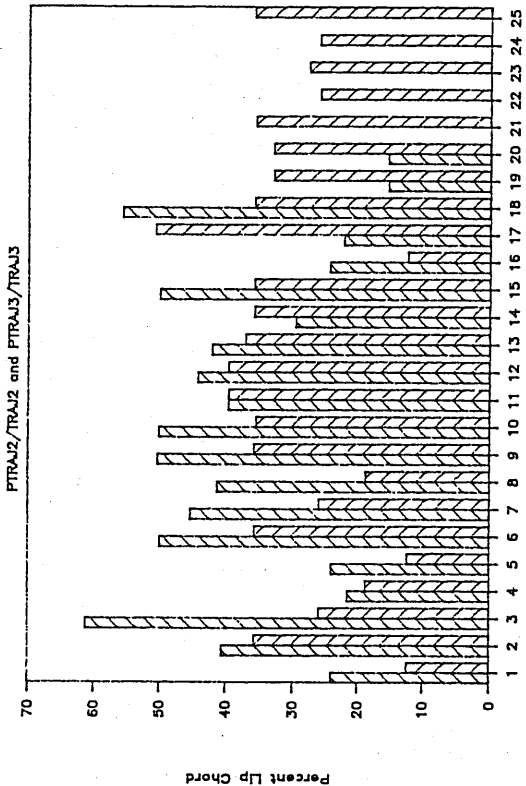


Fig.114

Ice Catch — Lower Surface

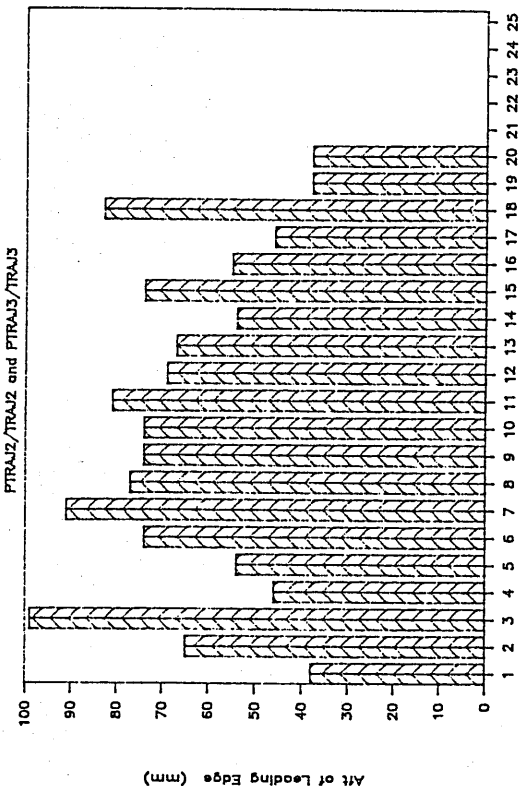


Fig.115

Two-Dimensional Ice Accretion Prediction Results

Catch — Lower Surface

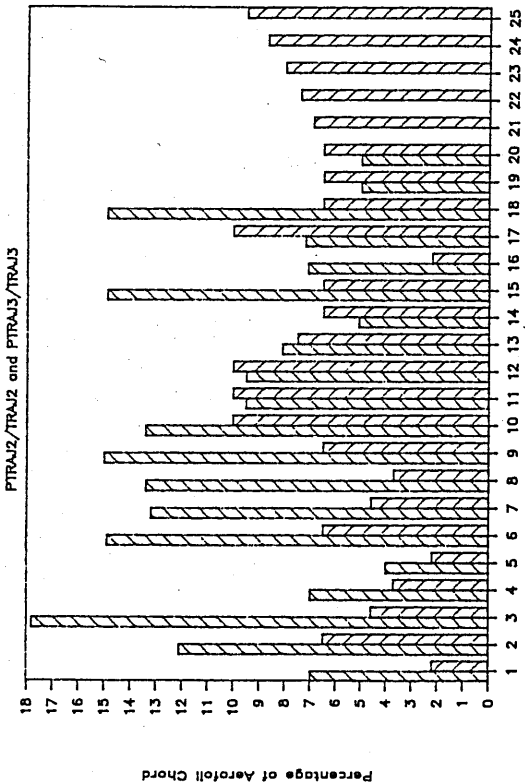


Fig.112

Ice Catch — Lower Surface

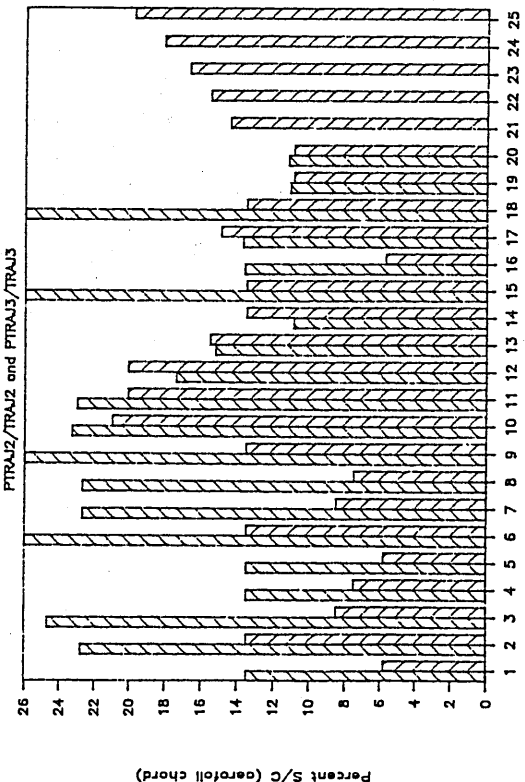


Fig.113

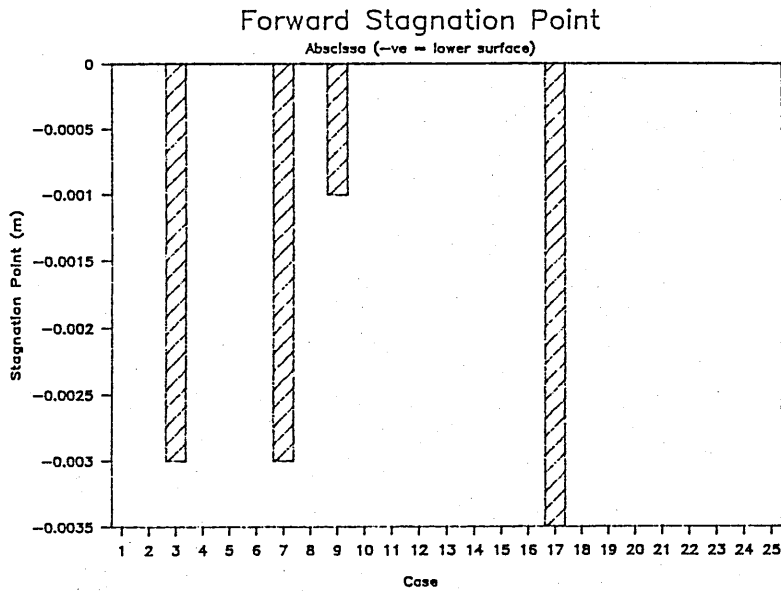


Fig.116

Two-Dimensional Ice Accretion Prediction Results

Fig.117

Sample aerofoil section ('sharp' trailing edge)
Preprocessor program PTRAJ2
Chord = 0.6 m

Fig.118

Sample aerofoil section ('sharp' trailing edge)
Preprocessor program PTRAJ2
Main ice prediction program TRAJ2
Chord = 0.6 m
Ambient flow velocity = 226.4 ms⁻¹
Ambient temperature = -20.0°C
Ambient air pressure = 37.58 kPa
Flow liquid water content = 0.3 gm⁻³
Water droplet diameter = 20 µm
Time in icing cloud = 2.0 minutes

Fig.119

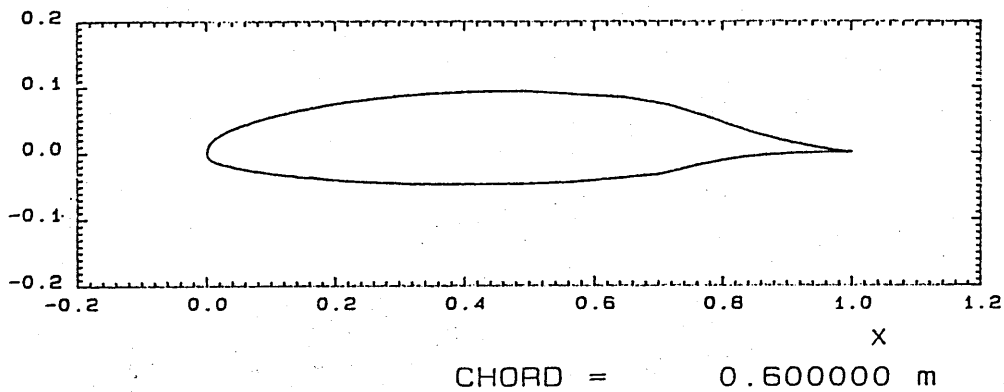
Simulated aerofoil section using original lip (32%) and blunt t.e.
Preprocessor program PTRAJ3
Main ice prediction program TRAJ3
CLE/BLF = 1.0/1.0
Lip chord = 0.194 m
Developed aerofoil chord = 0.607 m
Ambient flow velocity = 226.4 ms⁻¹
Ambient temperature = -20.0°C
Ambient air pressure = 37.58 kPa
Flow liquid water content = 0.3 gm⁻³
Water droplet diameter = 20 µm
Time in icing cloud = 2.0 minutes

Fig.119	Forward stagnation point abscissa (mm)	Surface
(a)	0.23	upper
(b)	0.20	lower
(c)	0.10	lower
(d)	0.00	upper
(e)	0.10	upper
(f)	0.20	upper
(g)	0.21	upper
(h)	0.22	upper
(i)	0.24	upper
(j)	0.25	upper
(k)	0.30	upper

Fig.120

Simulated aerofoil section ('blunt' trailing edge)
Preprocessor program PTRAJ3
Chord = 0.607 m
CLE/BLF = 1.0/1.0

Two-Dimensional Ice Accretion Prediction Validation



Actual Aerofoil

Fig.117

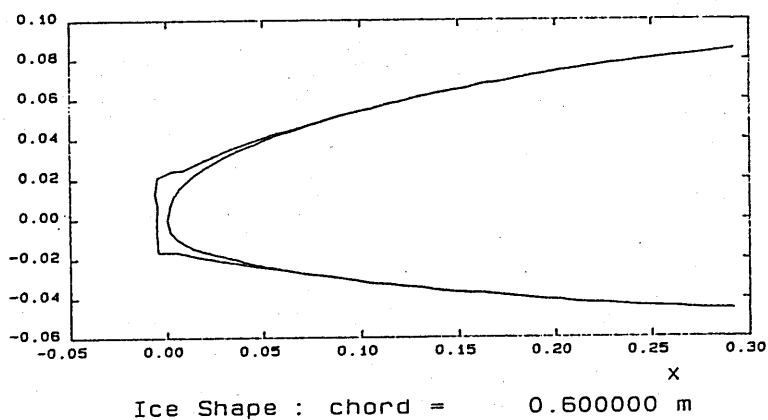


Fig.118

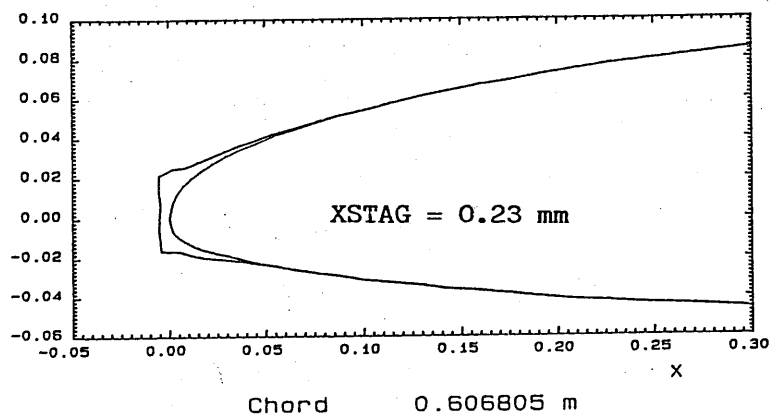


Fig.119(a)

Two-Dimensional Ice Accretion Prediction Validation

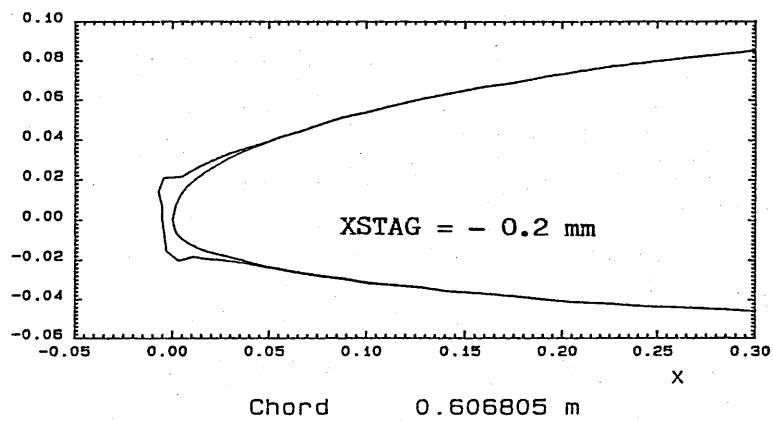


Fig.119(b)

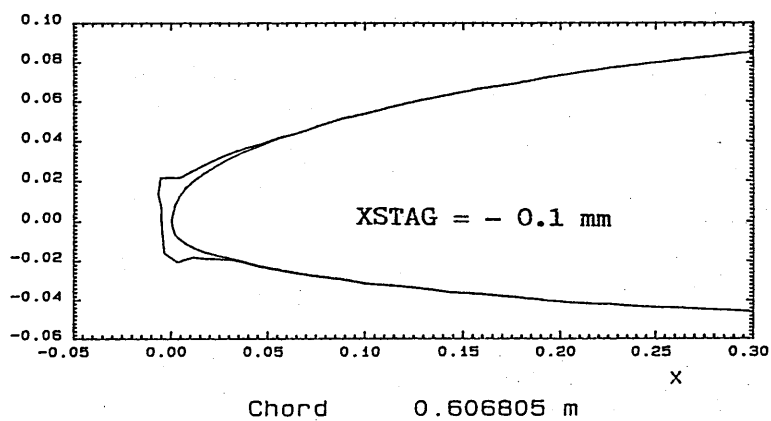


Fig.119(c)

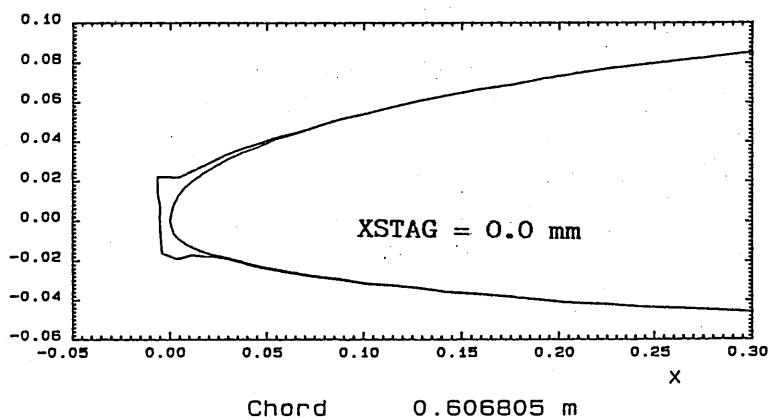


Fig.119(d)

Two-Dimensional Ice Accretion Prediction Validation

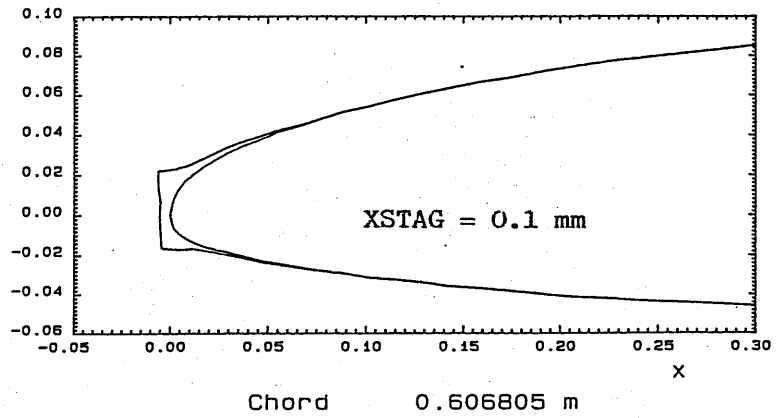


Fig.119(e)

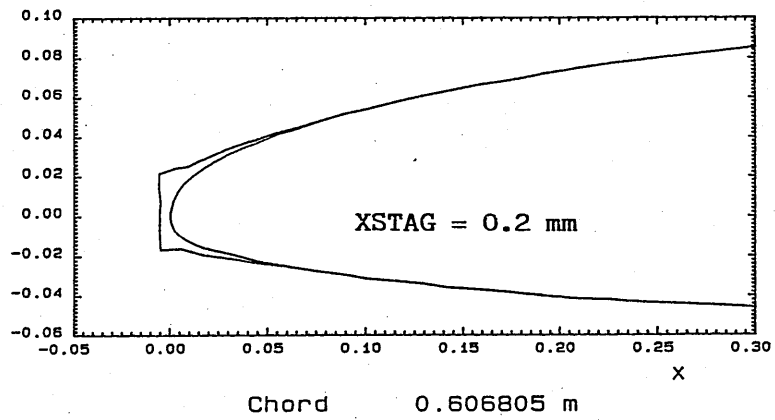


Fig.119(f)

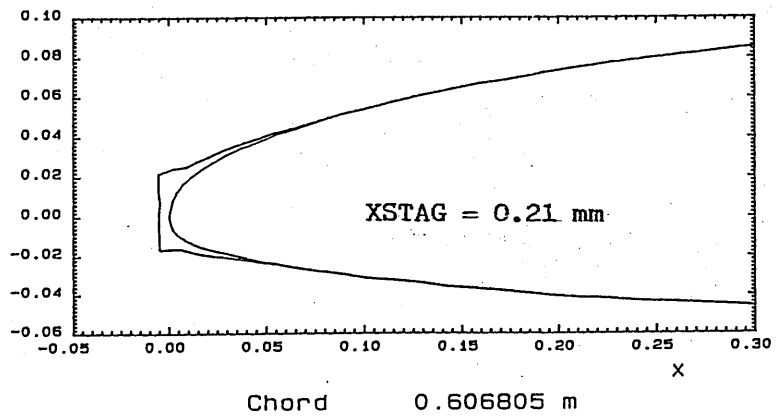


Fig.119(g)

Two-Dimensional Ice Accretion Prediction Validation

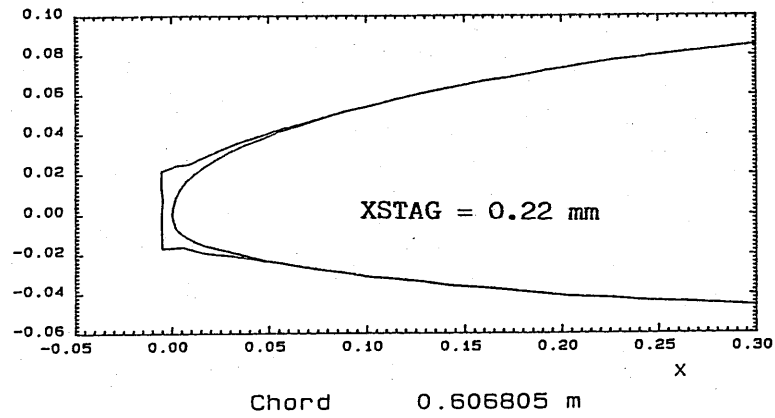


Fig.119(h)

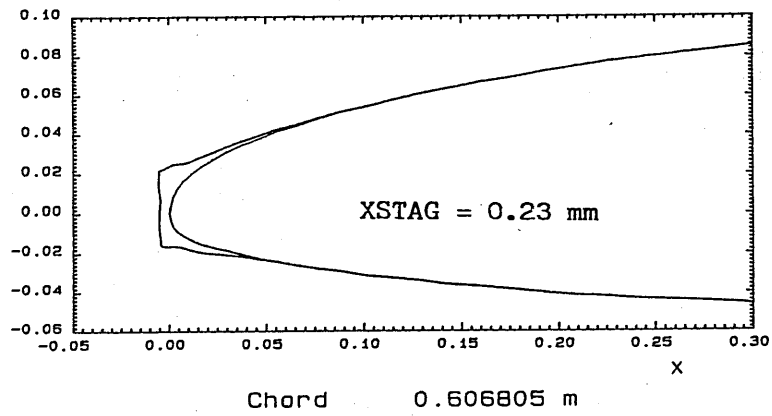


Fig.119(a)

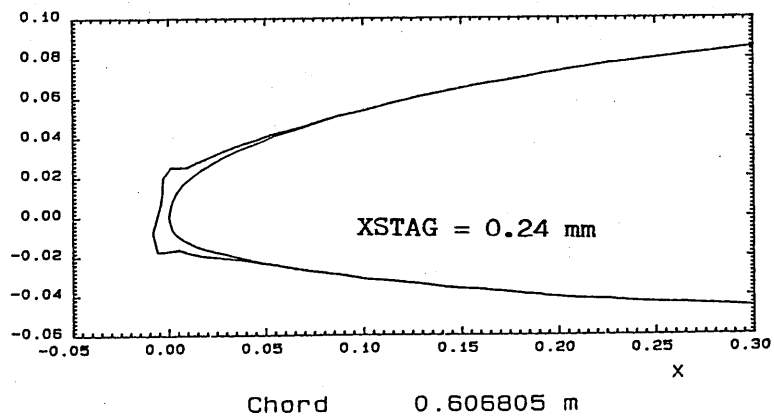


Fig.119(i)

Two-Dimensional Ice Accretion Prediction Validation

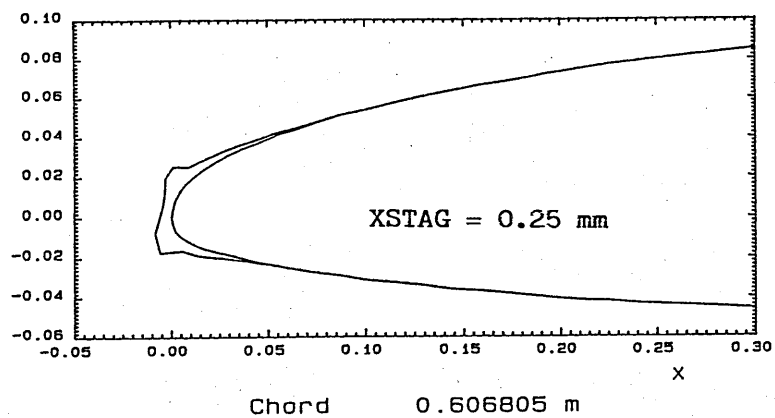


Fig.119(j)

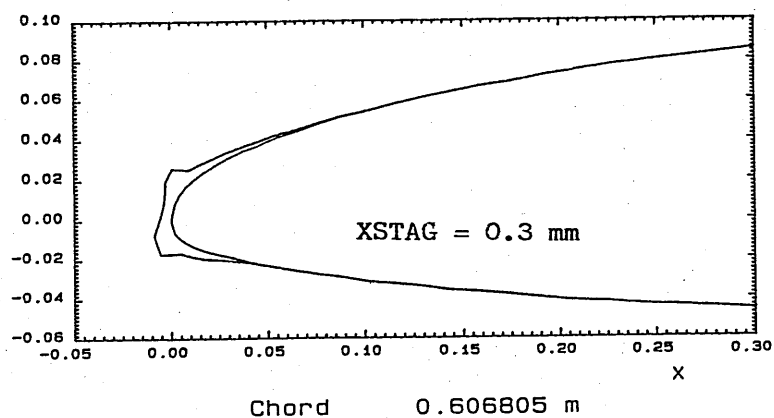


Fig.119(k)

Simulating Aerofoil

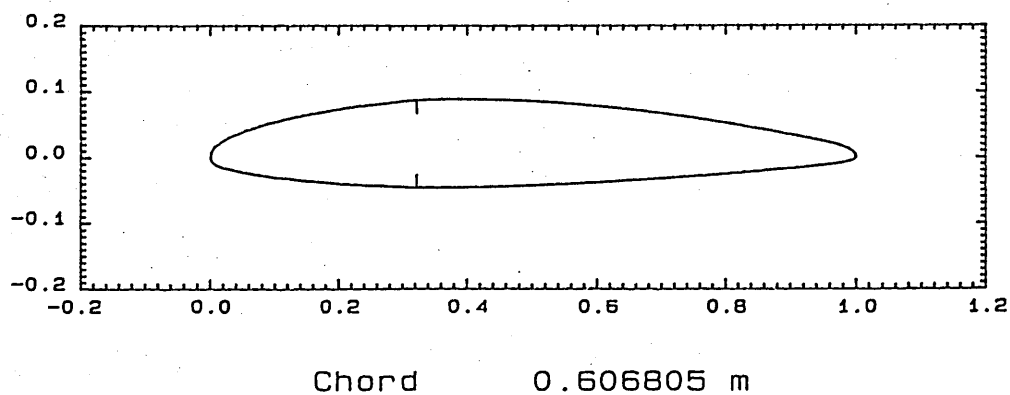


Fig.120

Test Rig Survey

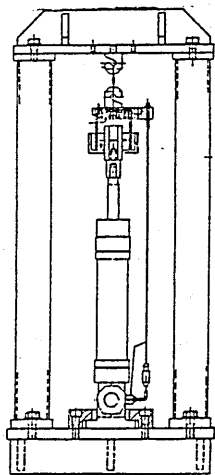
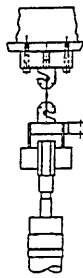
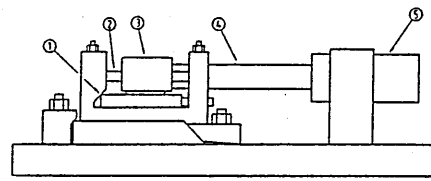


Fig.R1



1. Test plate, 2. Guide rods, 3. Substrate, 4. Plunger, 5. Hydraulic jack.

Fig.R2

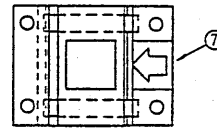
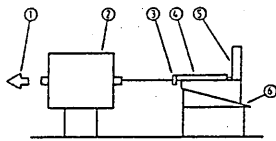


Fig.R4

1. Mechanical pulling force via worm gear, 2. Baldwin load cell, 3. Offset hook, 4. Ice in slider, 5. Statham strain gauge, 6. Inclined plane substrate/ice interface height adjustment.

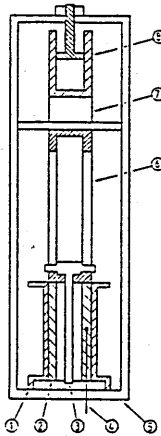


Fig.R5

1. Outer cylinder, 2. Inner cylinder, 3. Heater, 4. Thermocouple, 5. Rigid frame, 6. Guide slots, 7. Load cell, 8. Hydraulic jack.

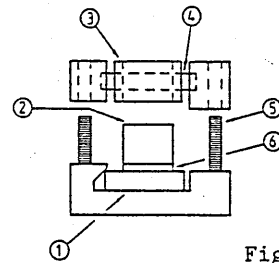
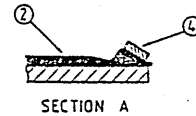


Fig.R3

1. Test plate, 2. Ice, 3. Slider, 4. Guide rods, 5. Locating bolt, 6. Substrate.



SECTION A

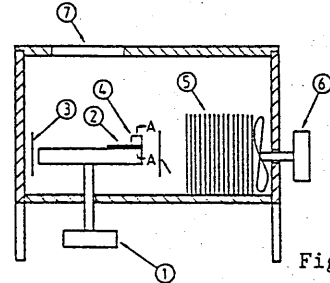
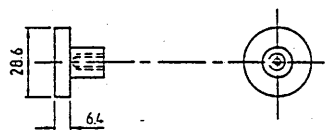


Fig.R7

1. High speed electric motor, 2. Substrate, 3. Shield, 4. Ice, 5. Refrigeration unit, 6. Fan, 7. Observation window.



DIMENSIONS IN MM

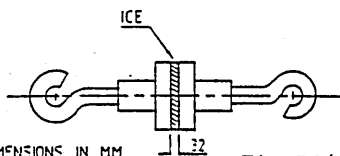
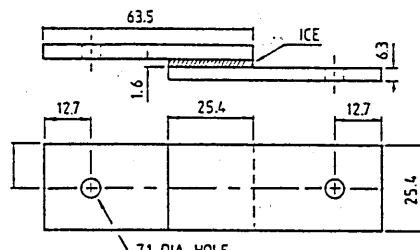


Fig.R8(a)



DIMENSIONS IN MM

Fig.R8(b)

Ice Adhesion Test Rig Design Study Options

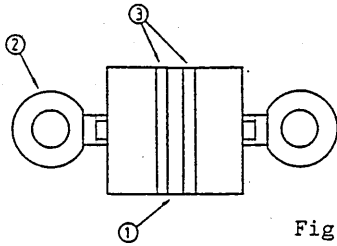


Fig.R9

1. Ice, 2. Hook, 3. Substrate.

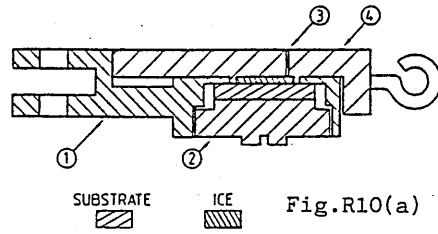


Fig.R10(a)

1. Test piece holder, 2. Test piece/substrate mounting, 3. Thermocouple, 4. Slider.

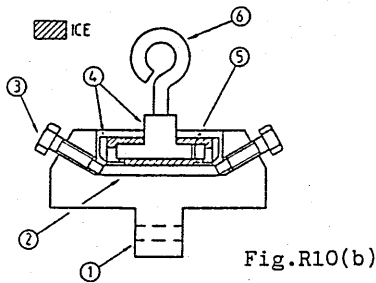


Fig.R10(b)

1. Retaining hook, 2. Substrate, 3. Substrate retaining bolts, 4. Mold, 5. Thermocouple, 6. Pulling hook.

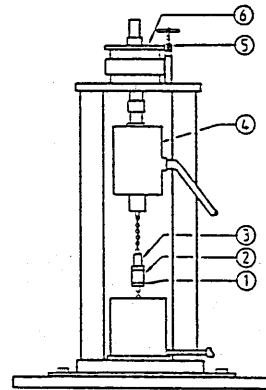


Fig.R11

1. Substrate, 2. Ice, 3. Substrate, 4. Baldwin load cell, 5. Worm gear, 6. gear wheel.

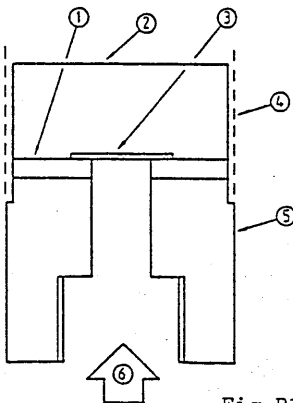


Fig.R12

1. Substrate, 2. Ice, 3. PTFE disc, 4. Molding cylinder, 5. Brass block.

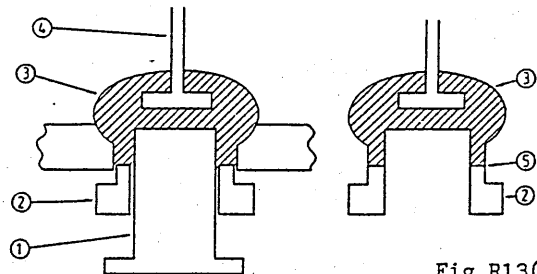


Fig.R13(a)

1. Removable tube, 2. Substrate, 3. Ice, 4. Torque rod, 5. Annular interface.

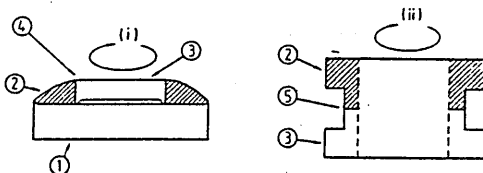


Fig.R13(b)

1. Substrate, 2. Ice, 3. Cylindrical interface, 4. Annular interface.

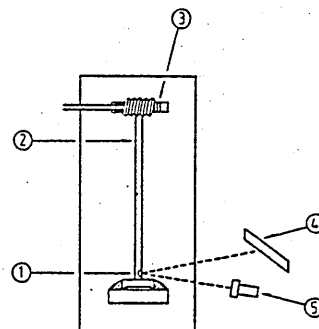
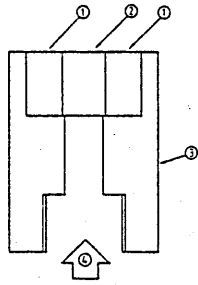


Fig.R13(c)

1. Mirror, 2. Torque rod, 3. Worm gear, 4. Scale, 5. Lamp.

Ice Adhesion Test Rig Design Study Options



1. Ice, 2. Bullet,
3. Block.

Fig.R14

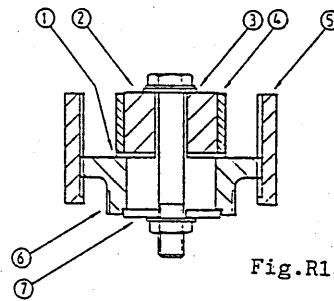


Fig.R15(a)

1. Seal, 2. Bullet, 3. Seal,
4. Substrate, 5. Barrel,
6. Breech adapter,
7. Thick washer.

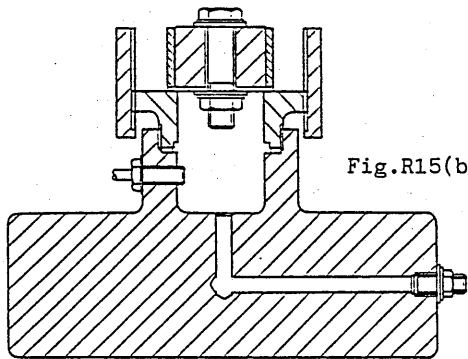


Fig.R15(b)

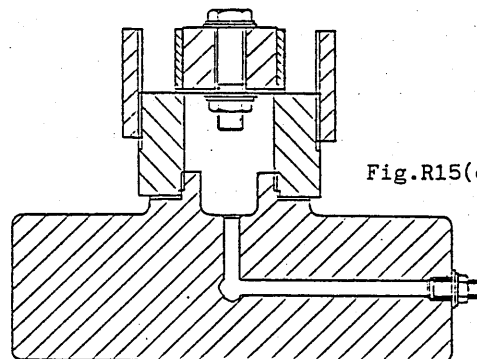
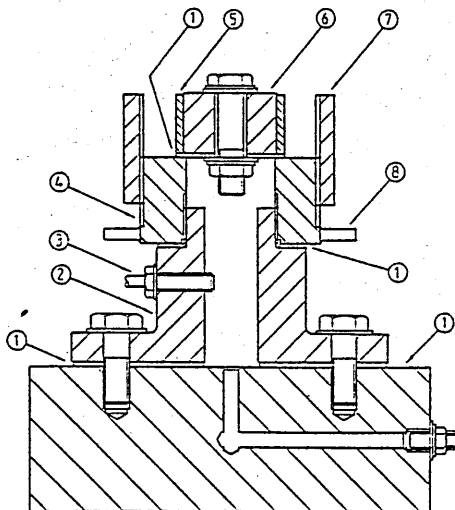
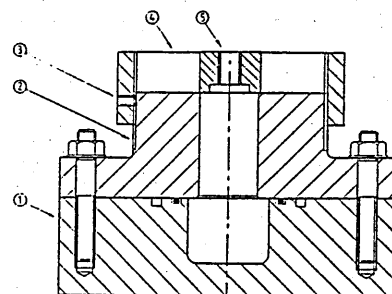


Fig.R15(c)



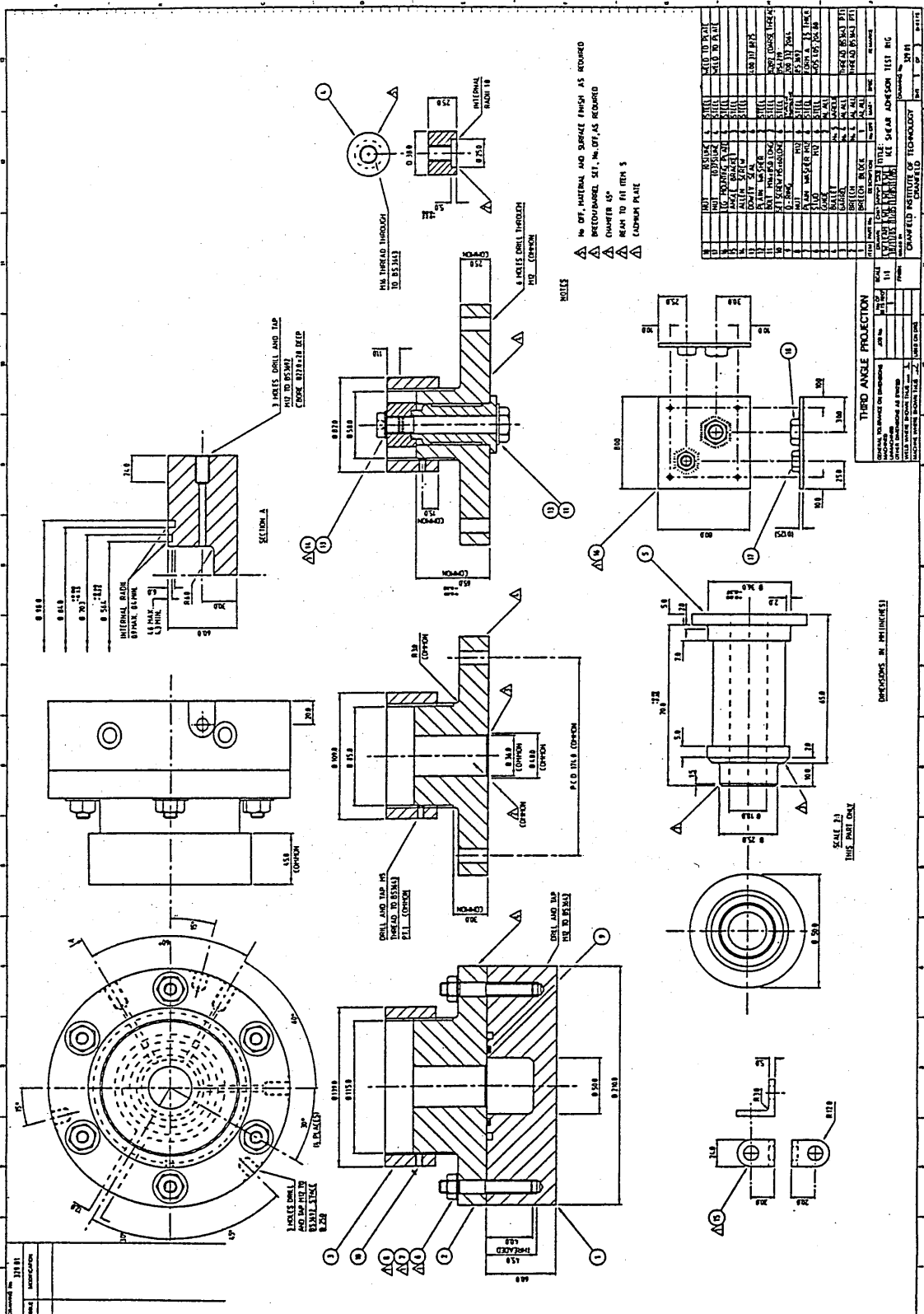
1. Seal, 2. Breech,
3. Thermocouple,
4. Breech adapter,
5. Substrate,
6. Bullet, 7. Barrel,
8. Tightening lug.

Fig.R15(d)



1. Breech block, 2. Breech,
3. Barrel, 4. Ice, 5. Bullet.

Fig.R16



Ice Shear Adhesion Test Rig Engineering Drawing

Test Rig Operation

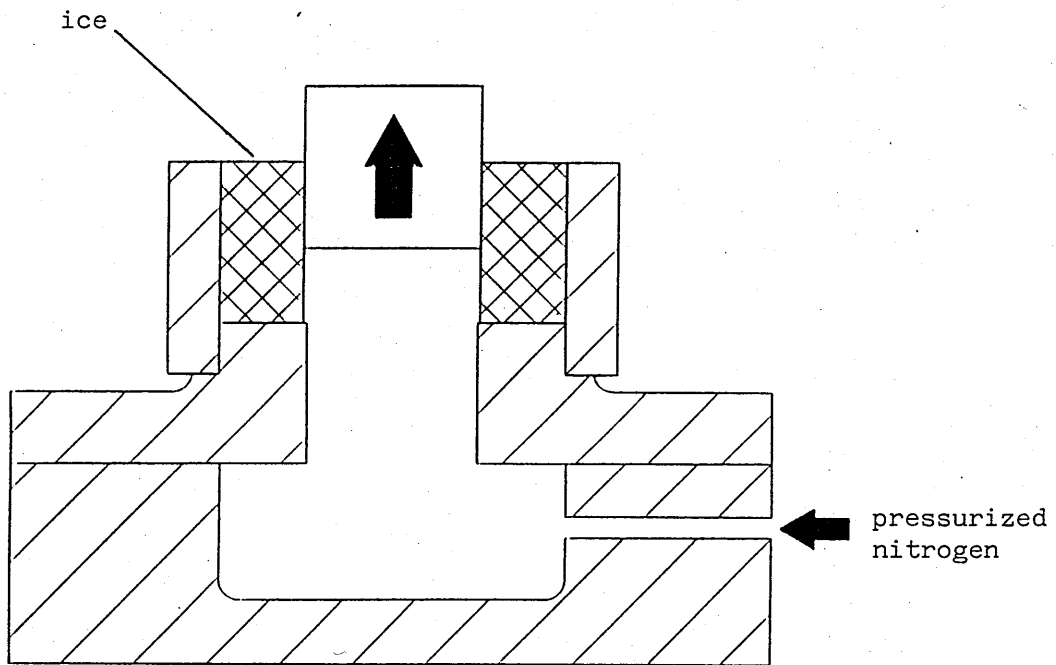
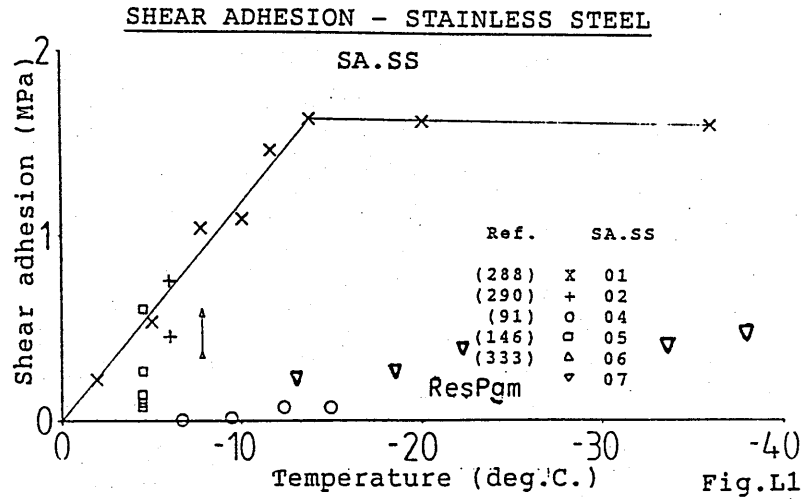
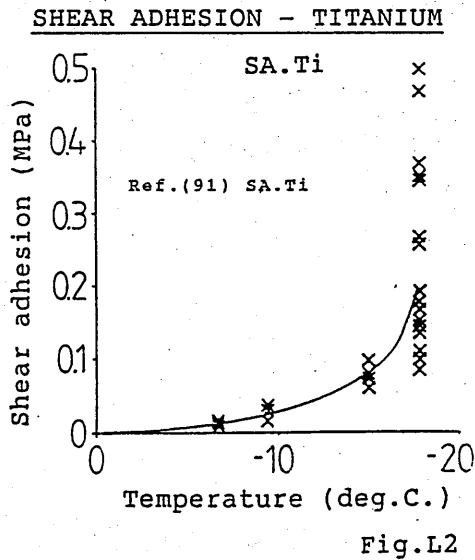
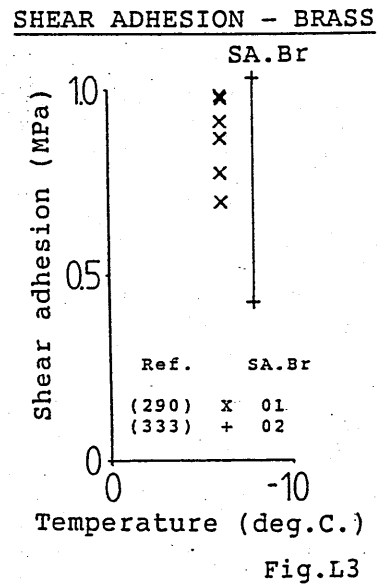
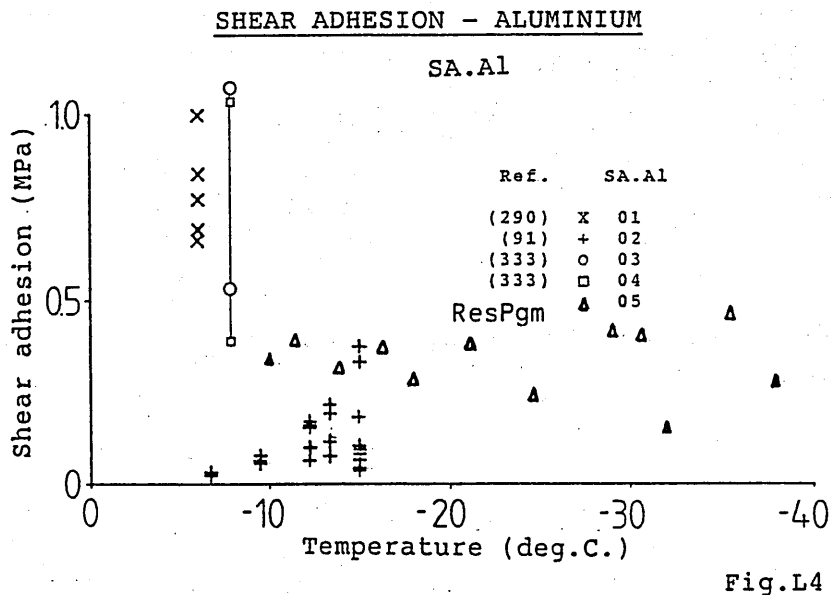


Fig.R18

Literature Survey Results

Ice Adhesion Database



SHEAR ADHESION - STEEL

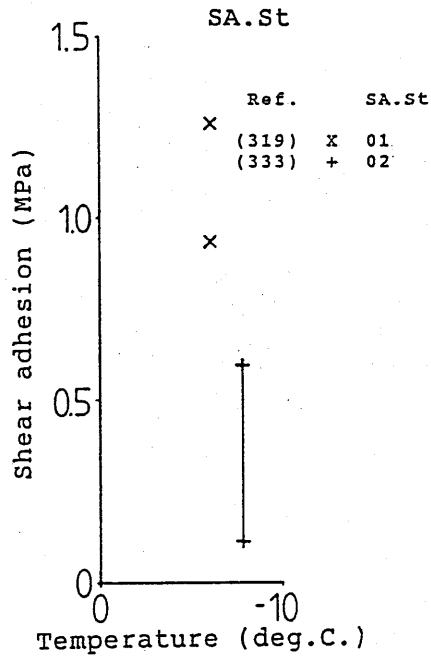


Fig.L5

SHEAR ADHESION - TEFLON

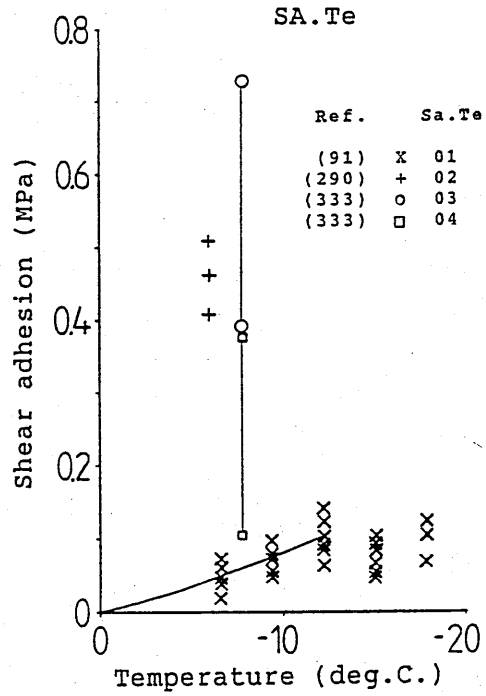


Fig.L6

SHEAR ADHESION - POLYSTYRENE

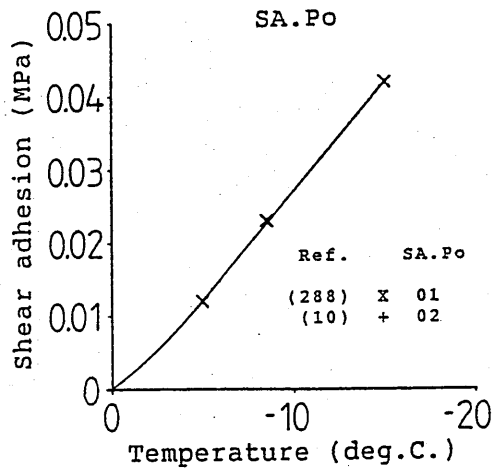


Fig.L7

SHEAR ADHESION - POLYACETAL

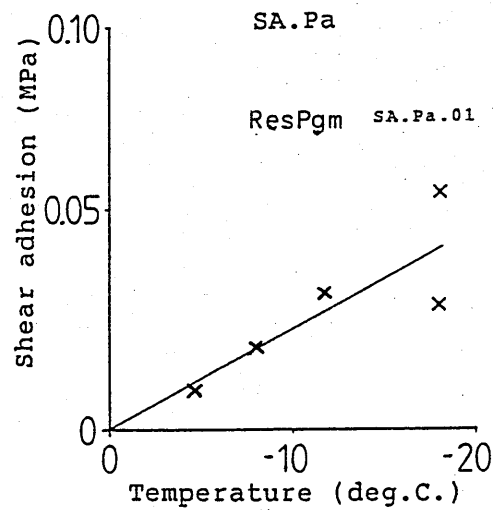


Fig.L8

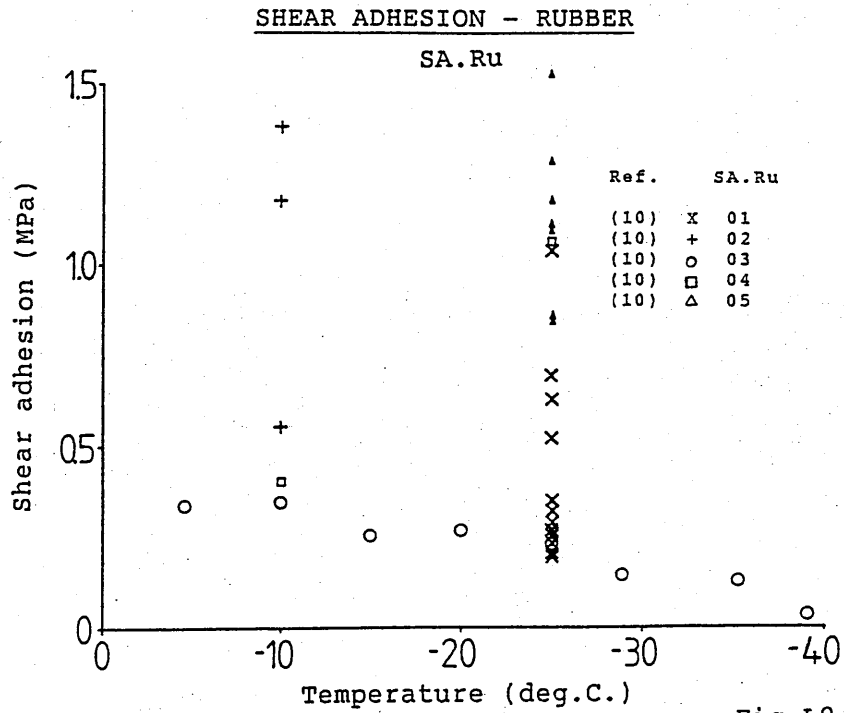


Fig.L9

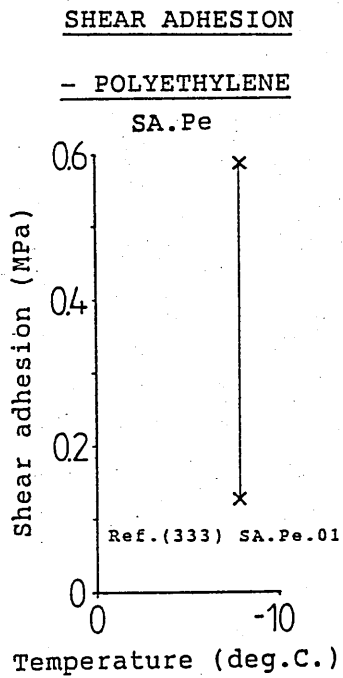


Fig.L10

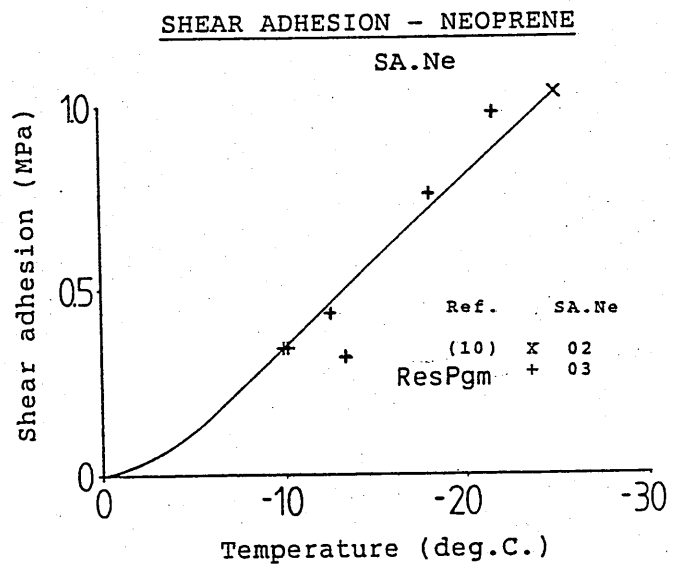


Fig.L11

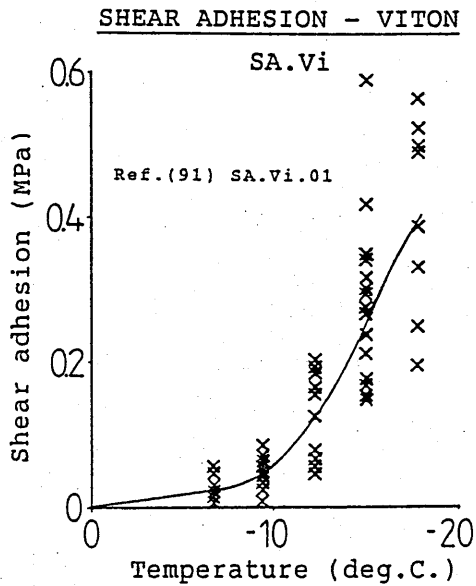


Fig.L12

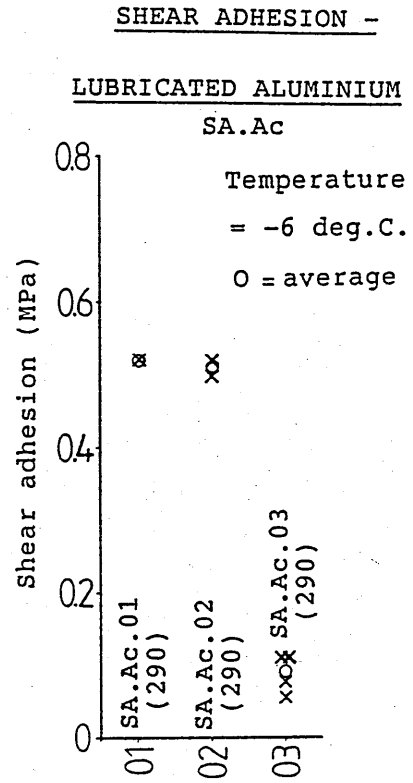


Fig.L13

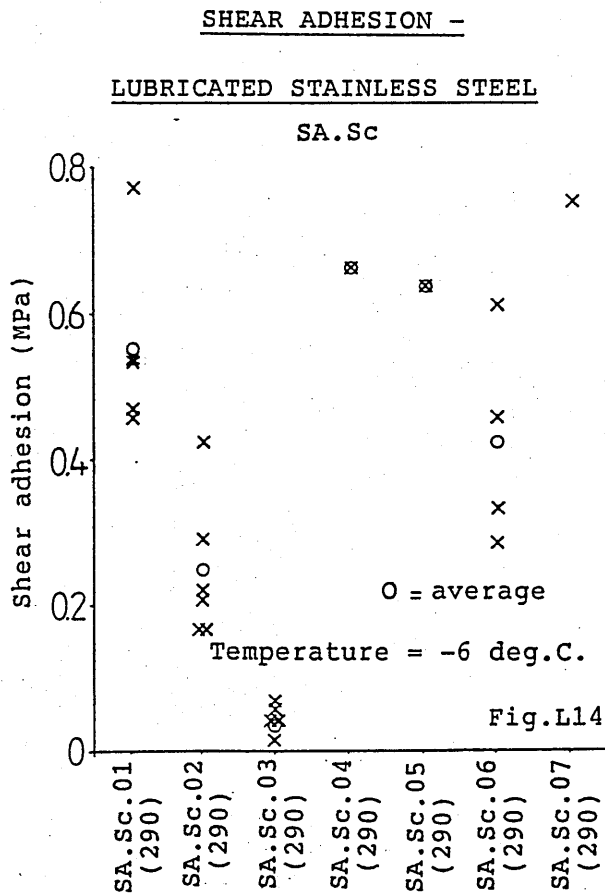


Fig.L14

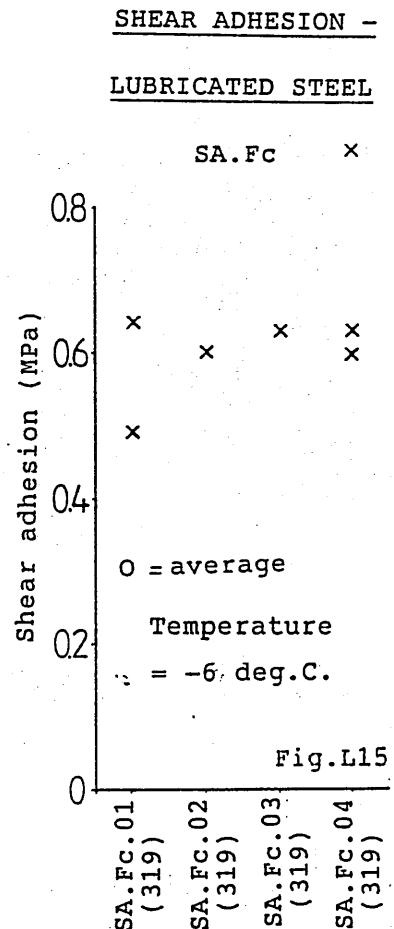
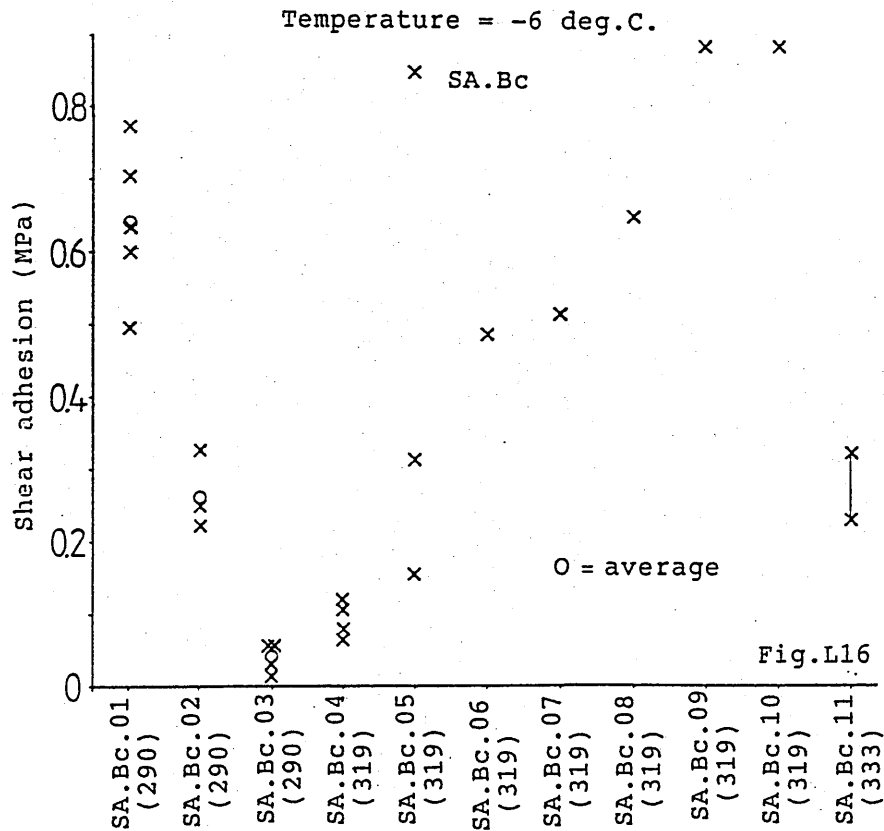


Fig.L15

SHEAR ADHESION - LUBRICATED BRASS



TENSILE ADHESION

- STAINLESS STEEL

SHEAR ADHESION - LUBRICATED TEFLON

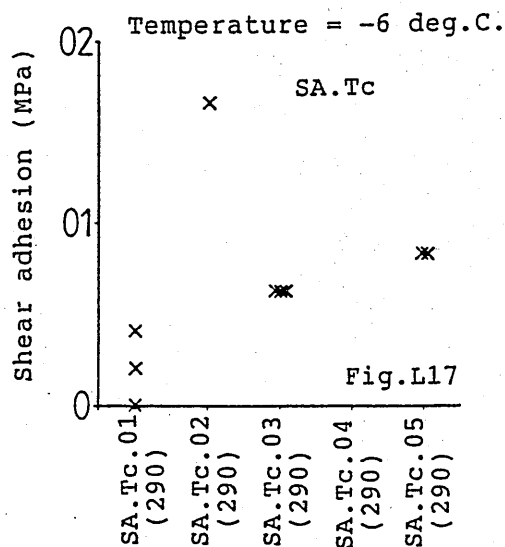
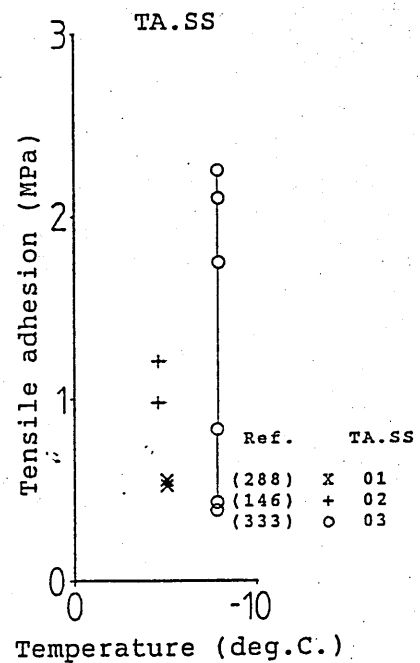


Fig.L18

TENSILE ADHESION

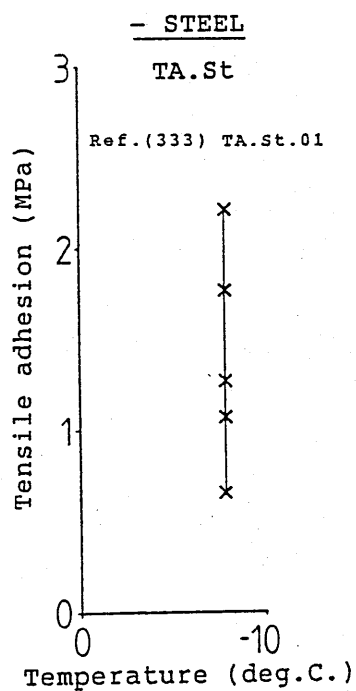


Fig.L19

TENSILE ADHESION

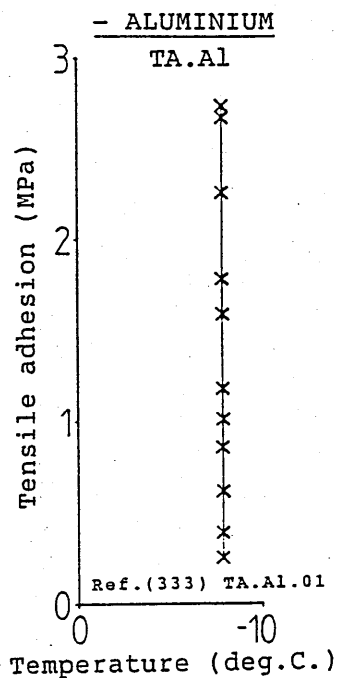


Fig.L20

TENSILE ADHESION

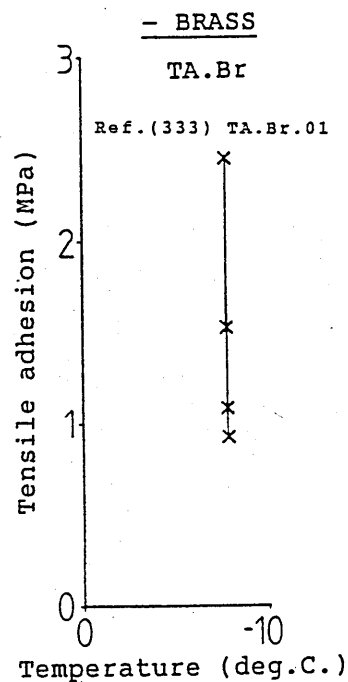


Fig.L21

TENSILE ADHESION - POLYSTYRENE

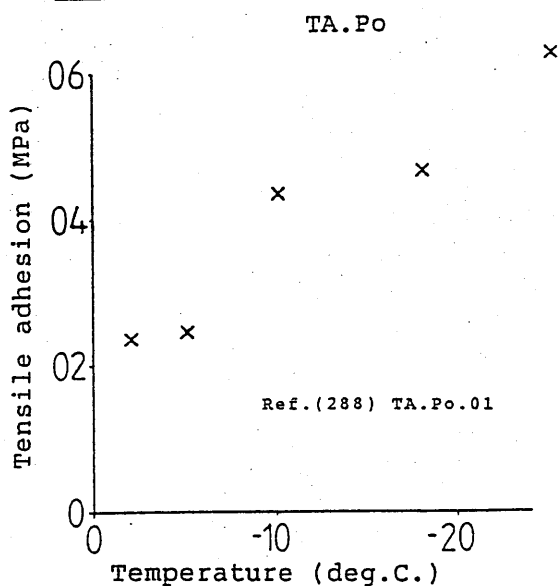


Fig.L22

TENSILE ADHESION

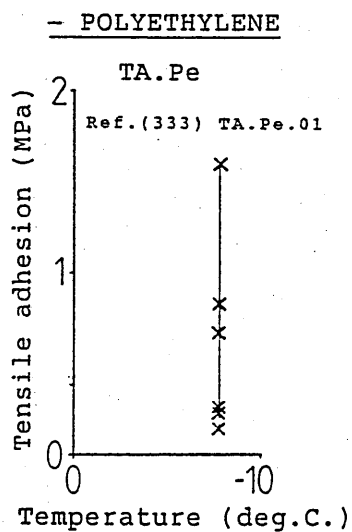


Fig.L23

TENSILE ADHESION

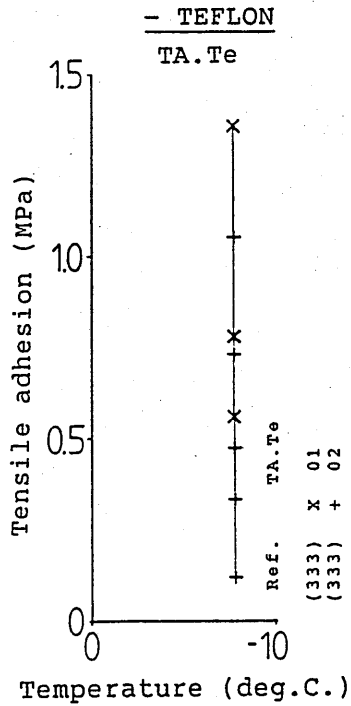


Fig.L24

TENSILE ADHESION

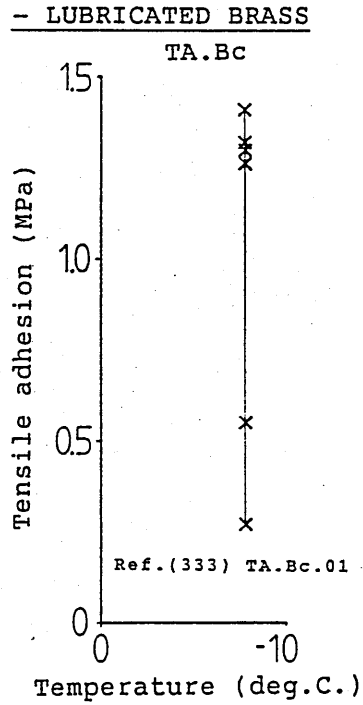


Fig.L25

ICE TENSILE STRENGTH

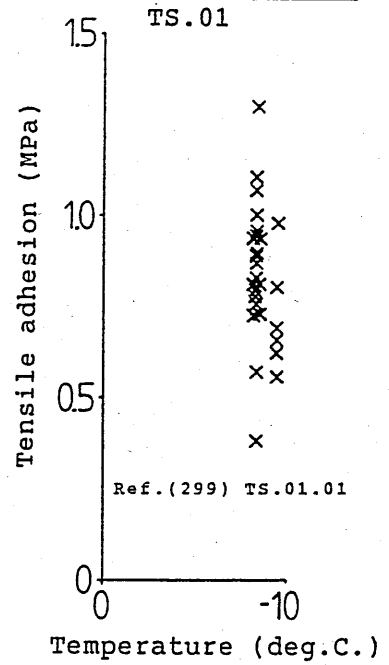


Fig.L26

SHEAR ADHESION - METAL

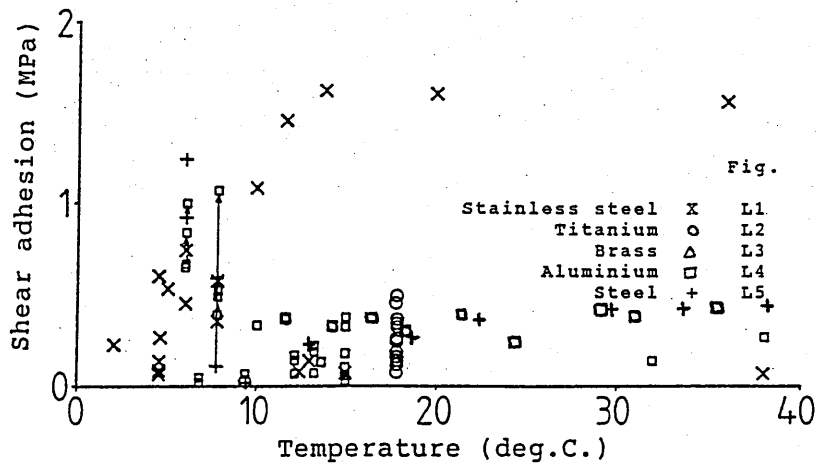


Fig.L27

SHEAR ADHESION - HARD NON-METAL

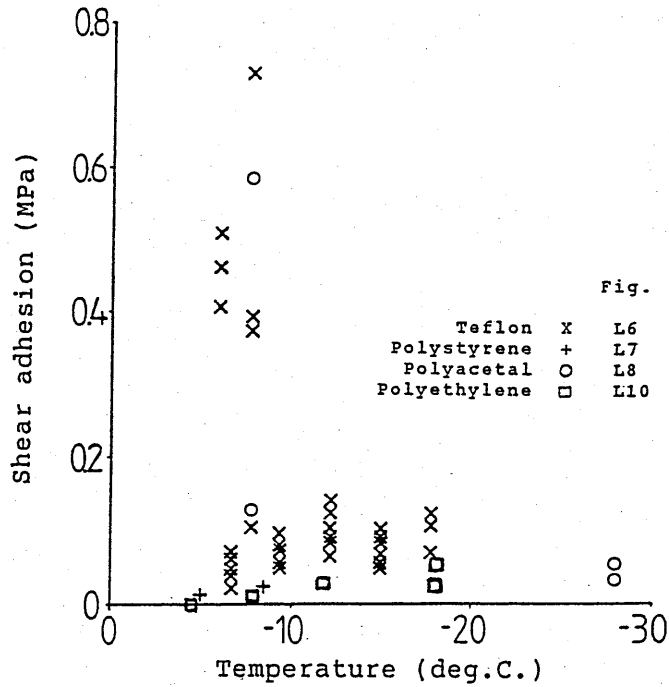


Fig.L28

SHEAR ADHESION - SOFT NON-METAL

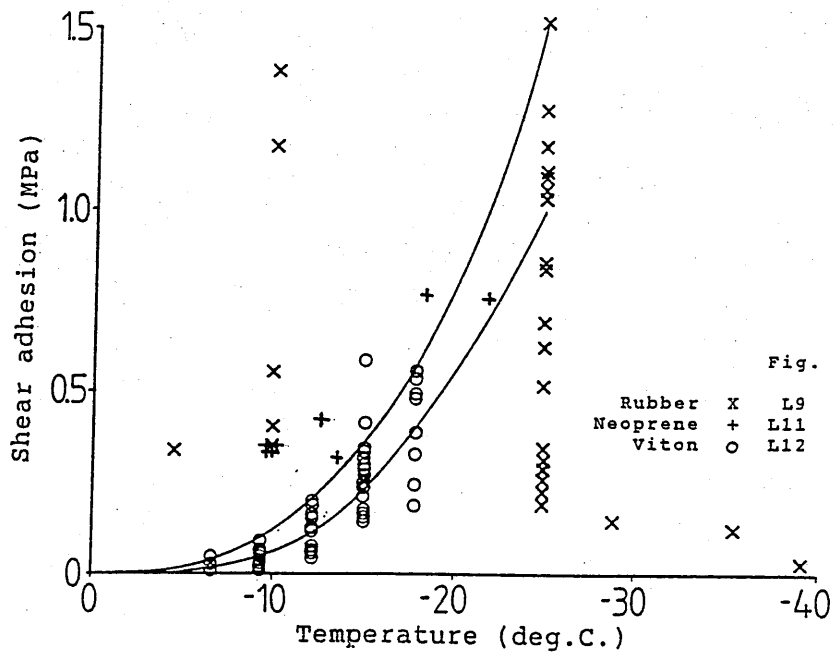


Fig.L29

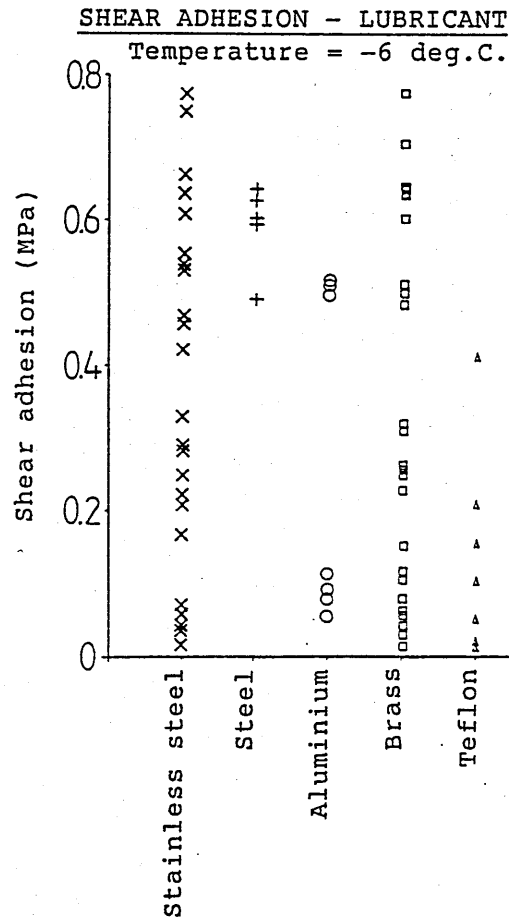


Fig.L30

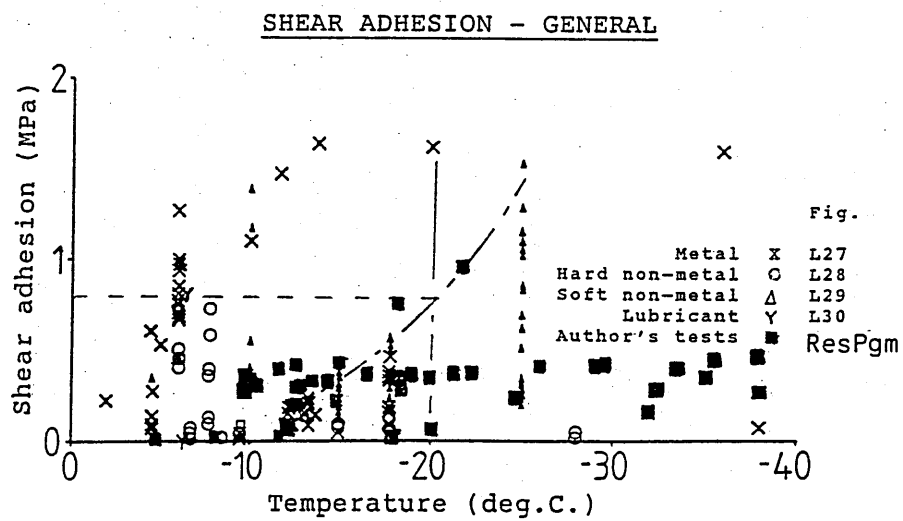


Fig.L31

Flight Test Photographs

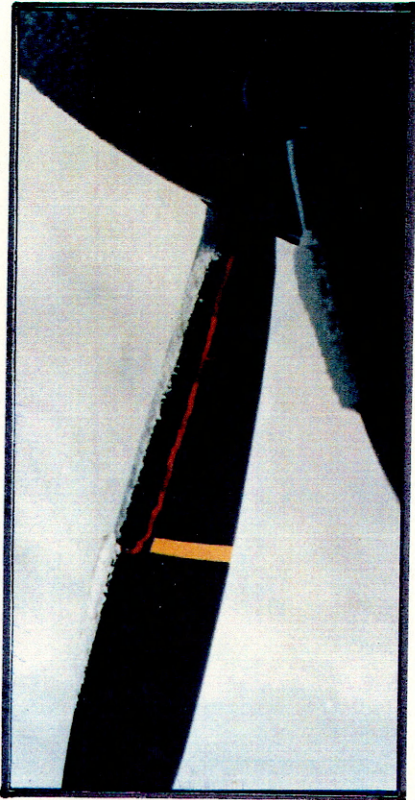


Fig.F1

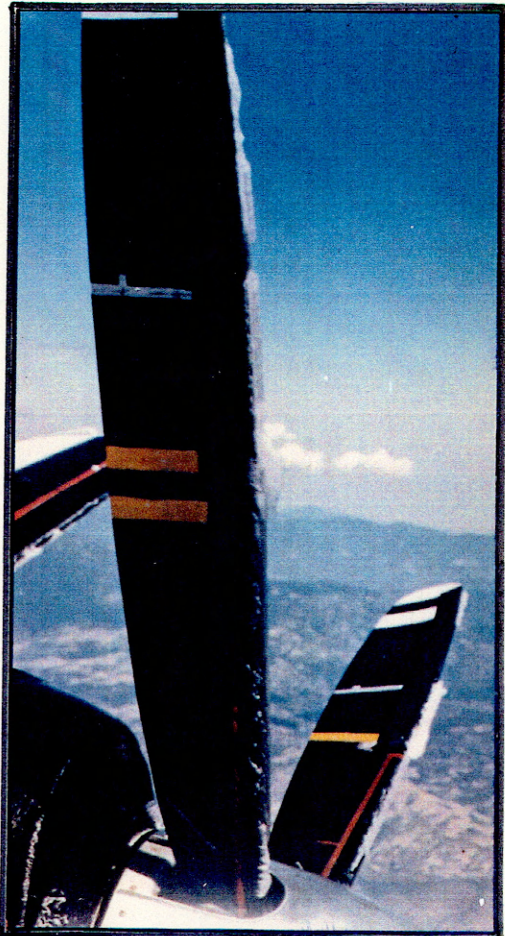


Fig.F2

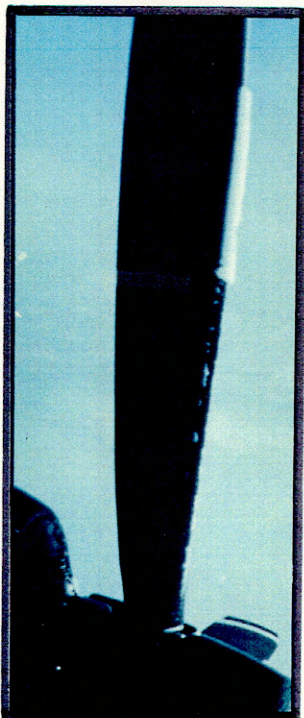


Fig.F3

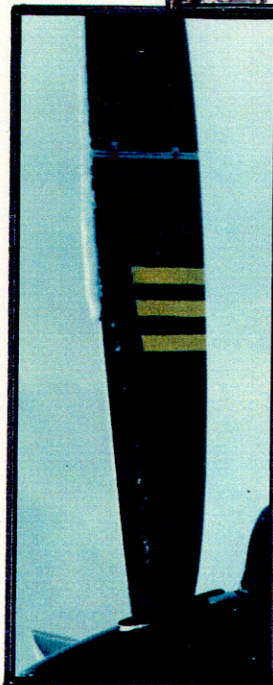


Fig.F4



Fig.F5

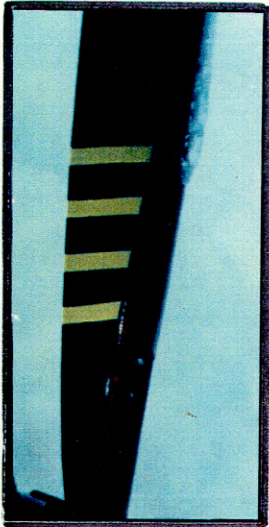


Fig.F6

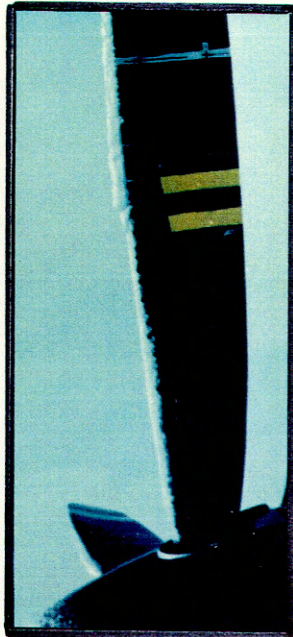


Fig.F7

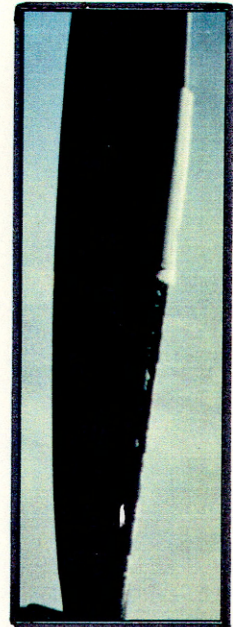


Fig.F8



Fig.F9

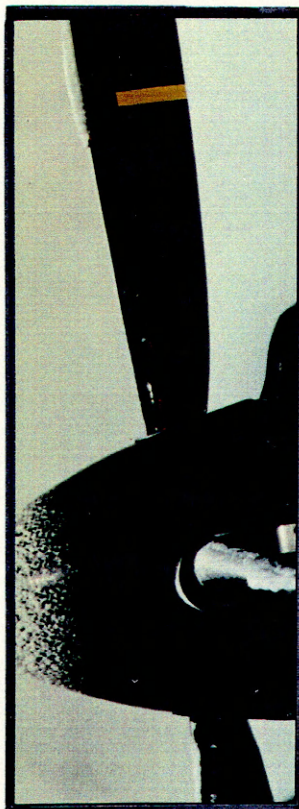


Fig.F10

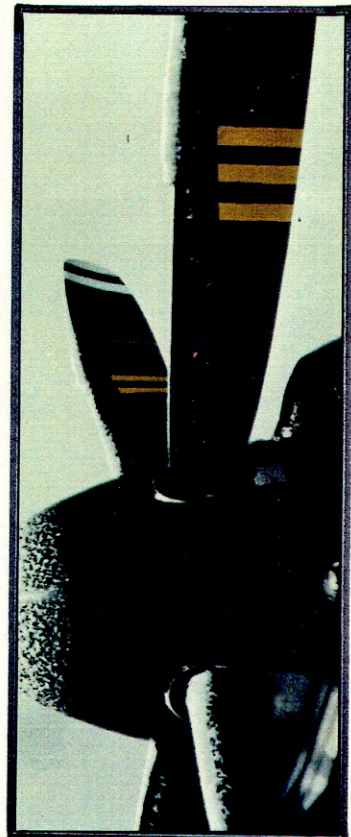


Fig.F11

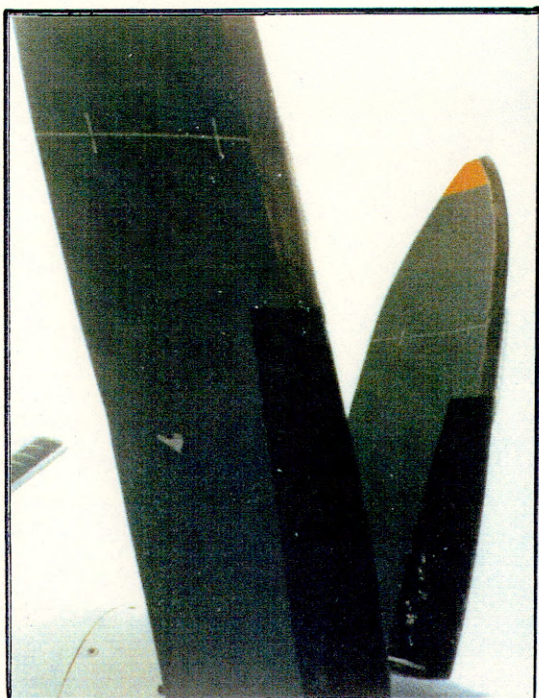


Fig.F12



Fig.F13



Fig.F14

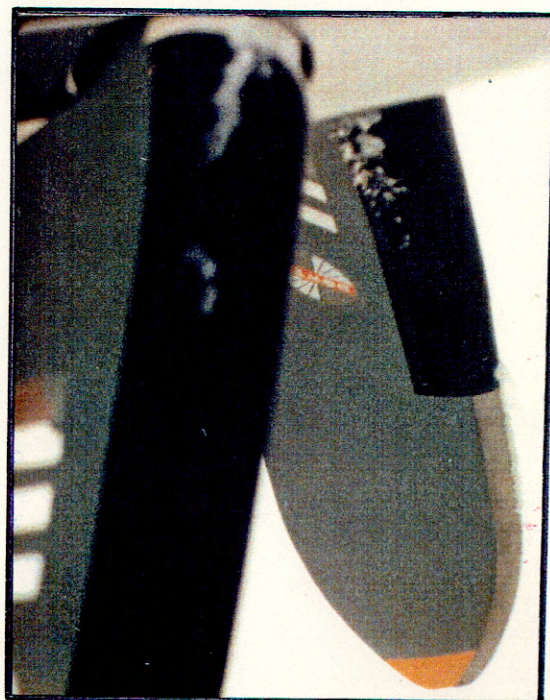


Fig.F15

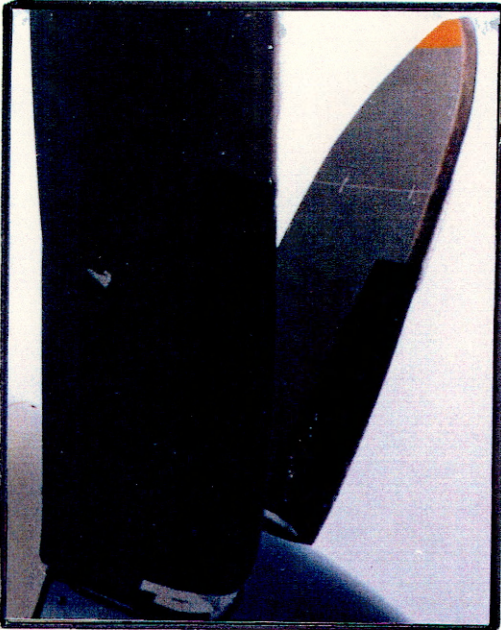


Fig.F16



Fig.F17

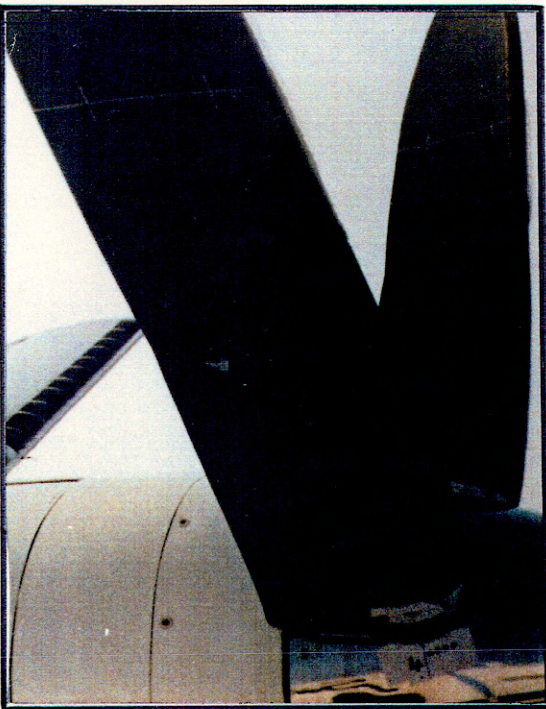


Fig.F18

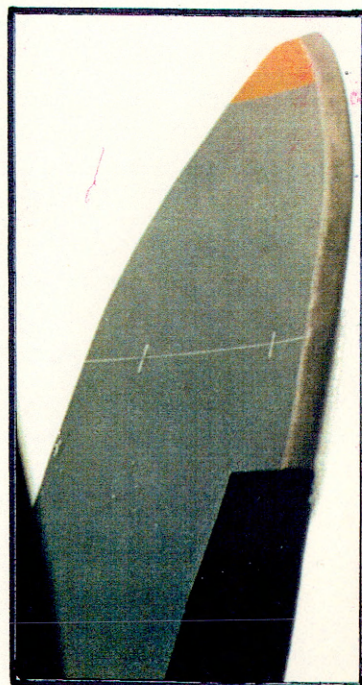


Fig.F19

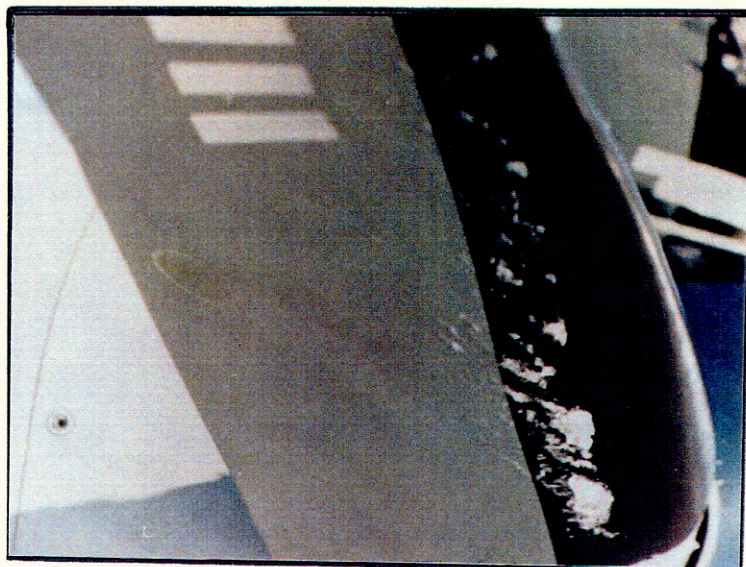


Fig.F20



Fig.F21

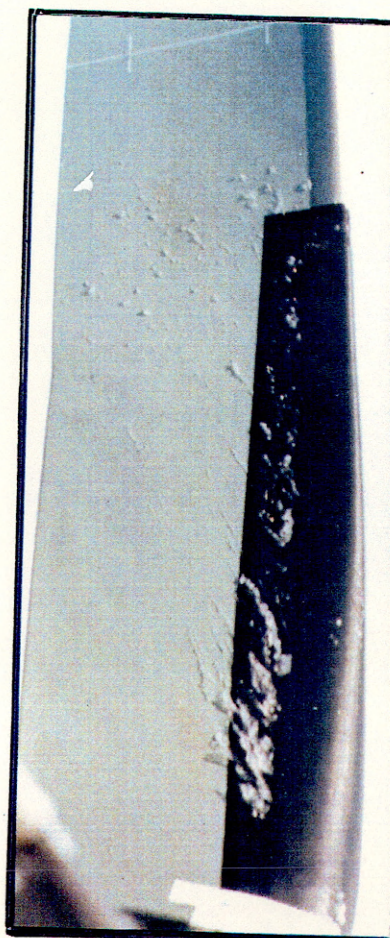


Fig.F22



Fig.F23



Fig.F24

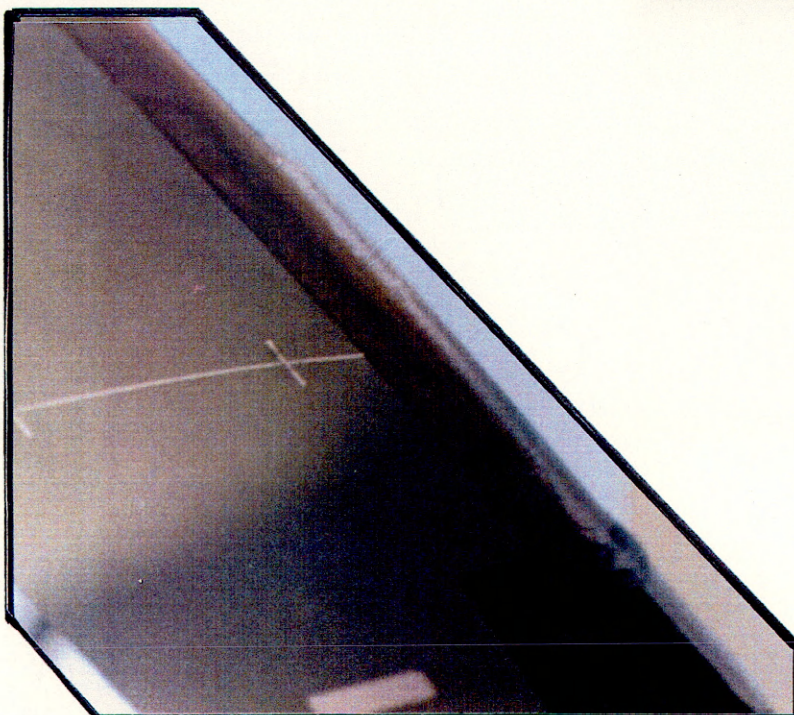


Fig.F25

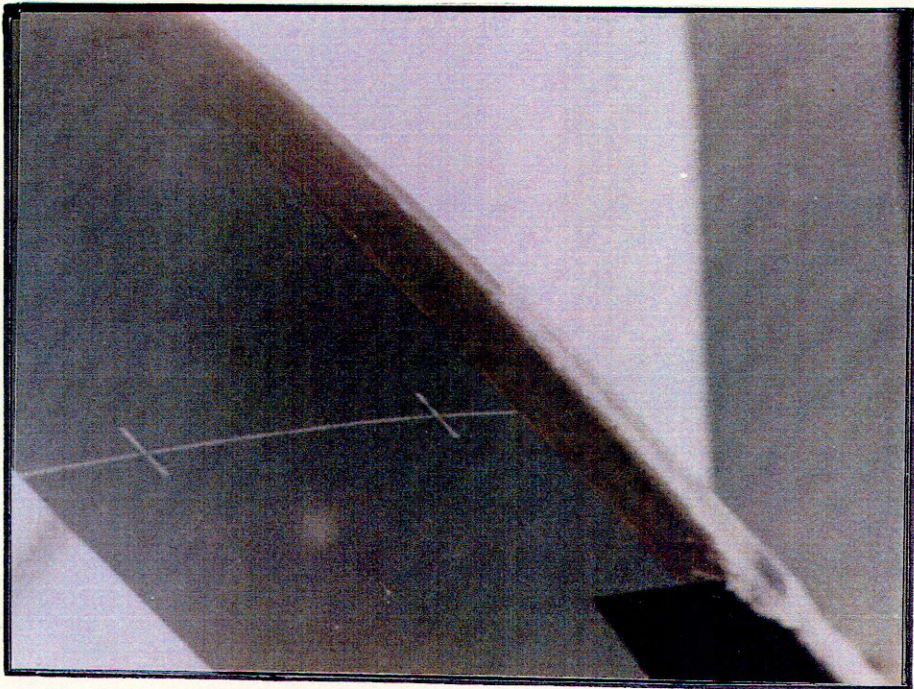


Fig.F26

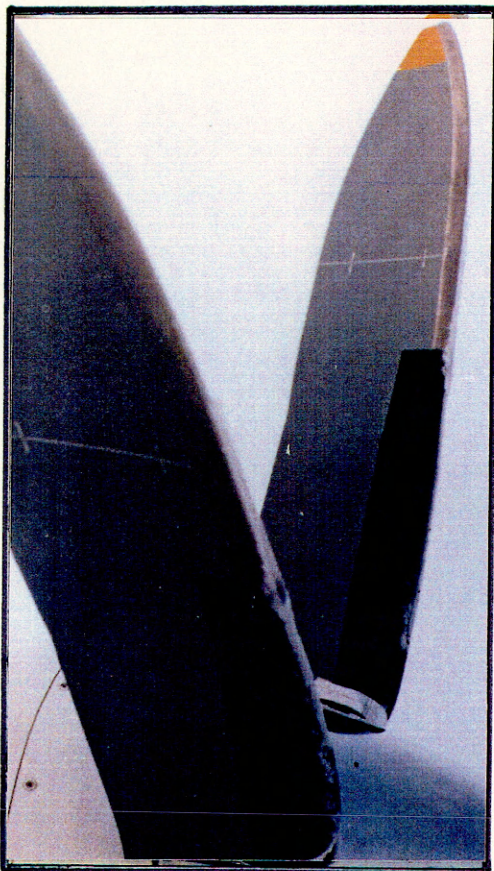


Fig.F27

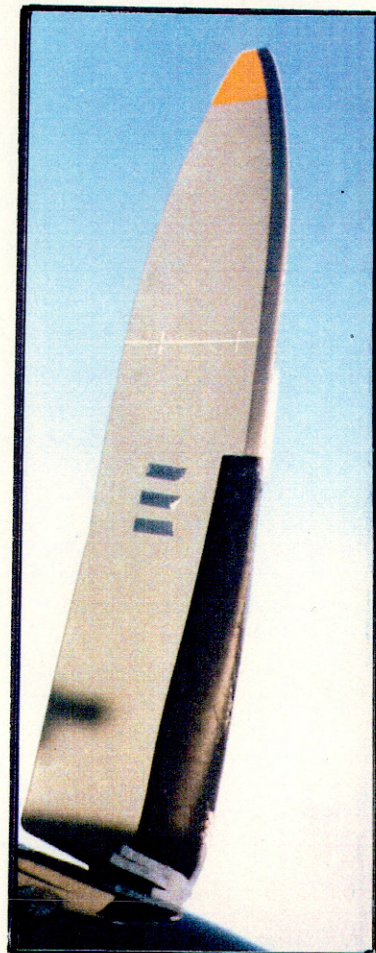


Fig.F28

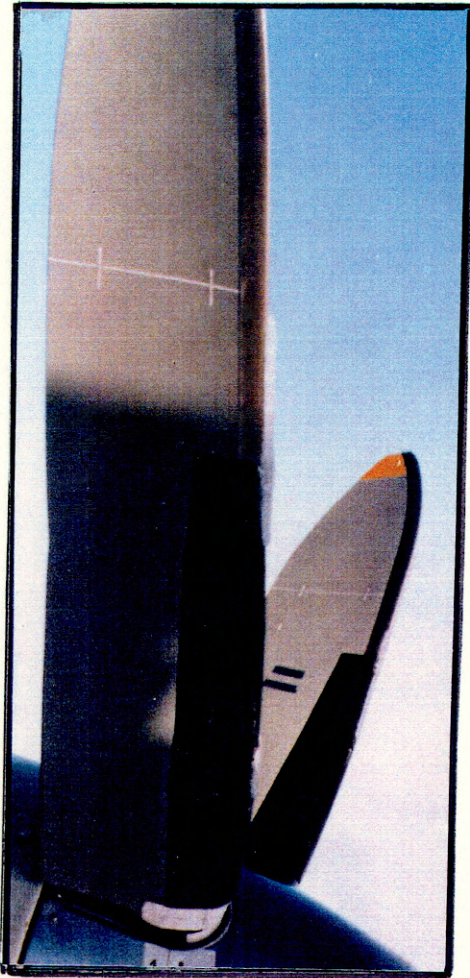


Fig.F29

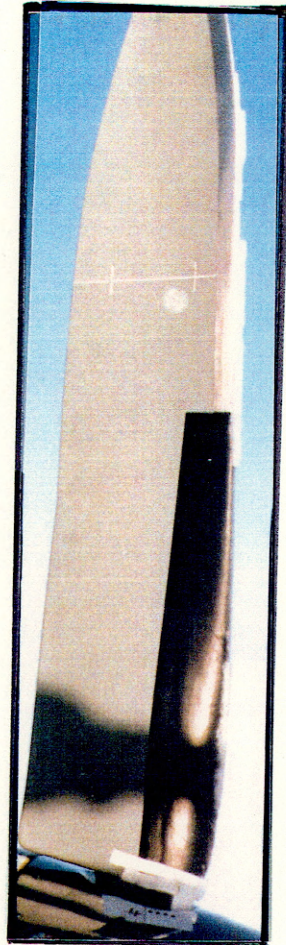


Fig.F30



Fig.F31

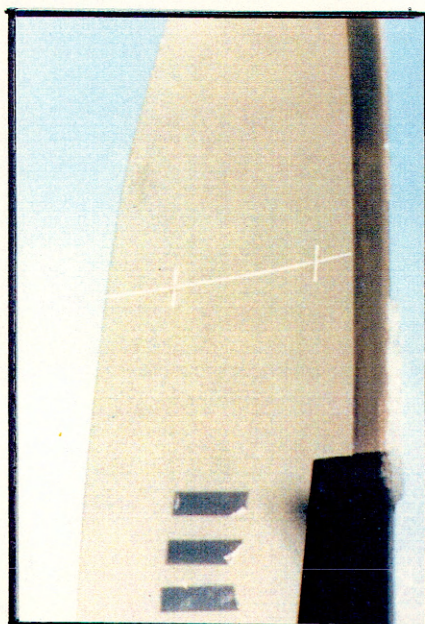
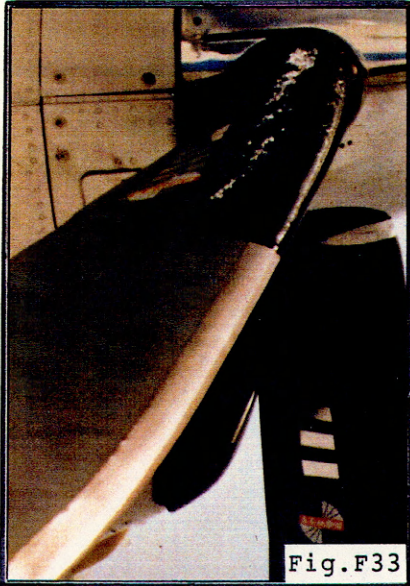
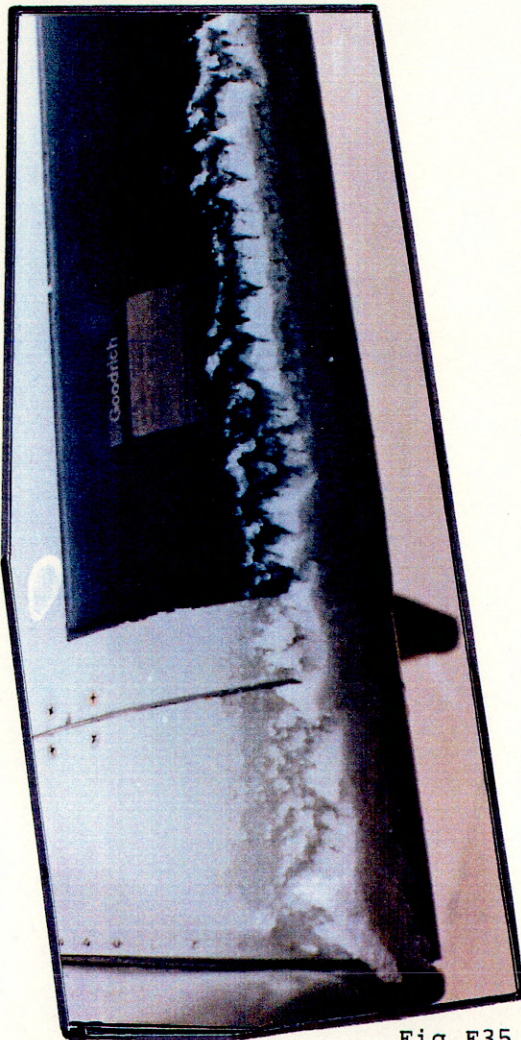


Fig.F32



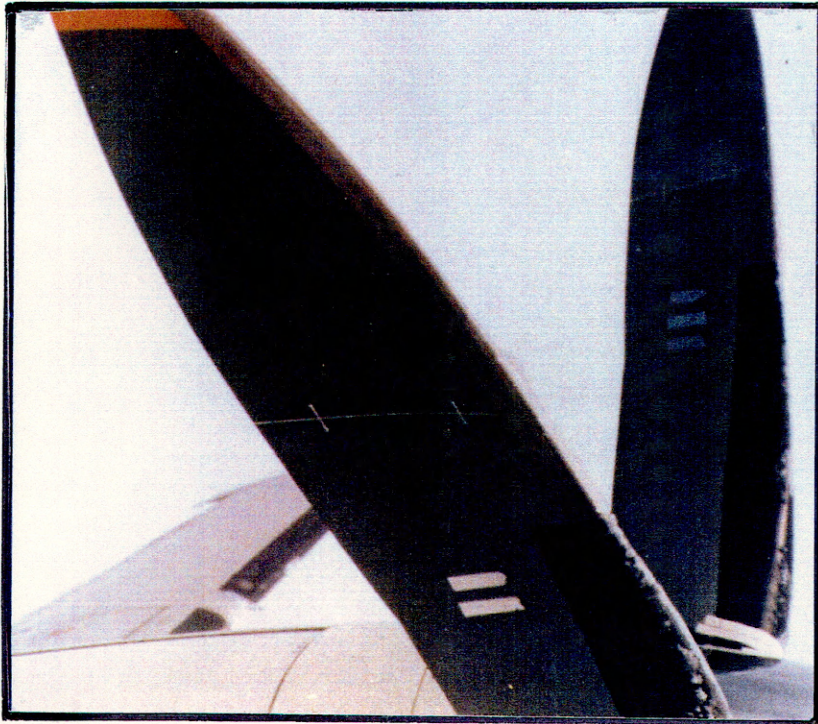


Fig.F37



Fig.F38



Fig.F39

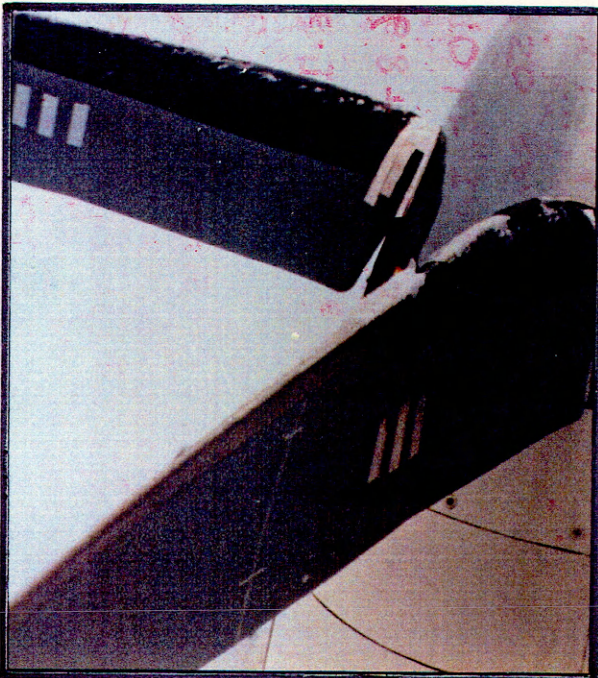


Fig. F40

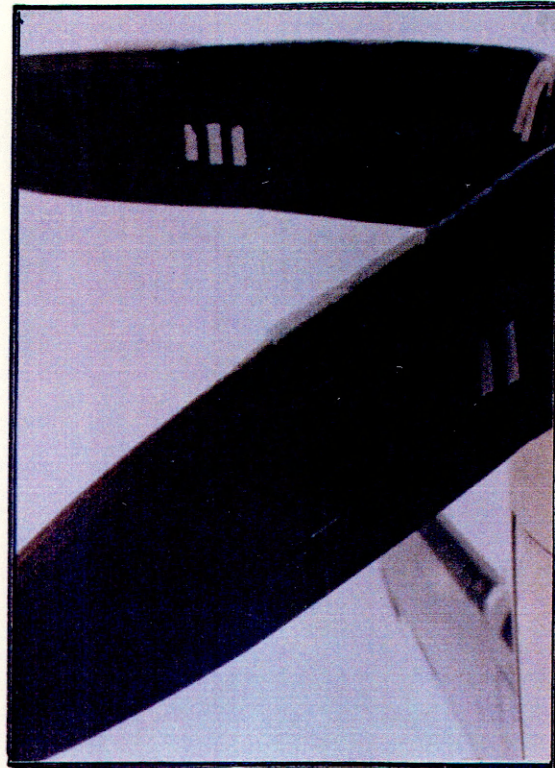


Fig. F41

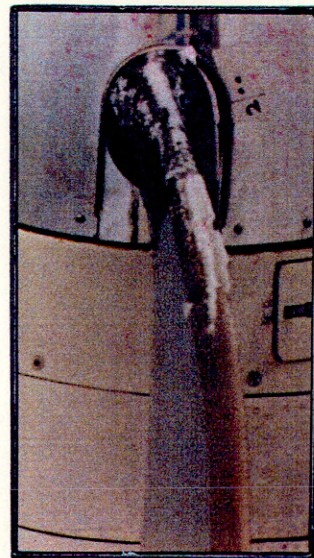


Fig. F42



Fig. F43

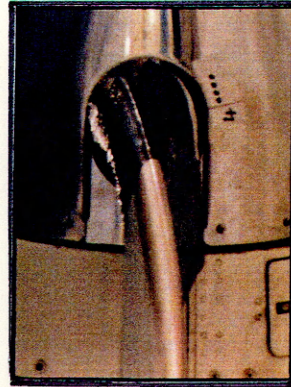


Fig. F44

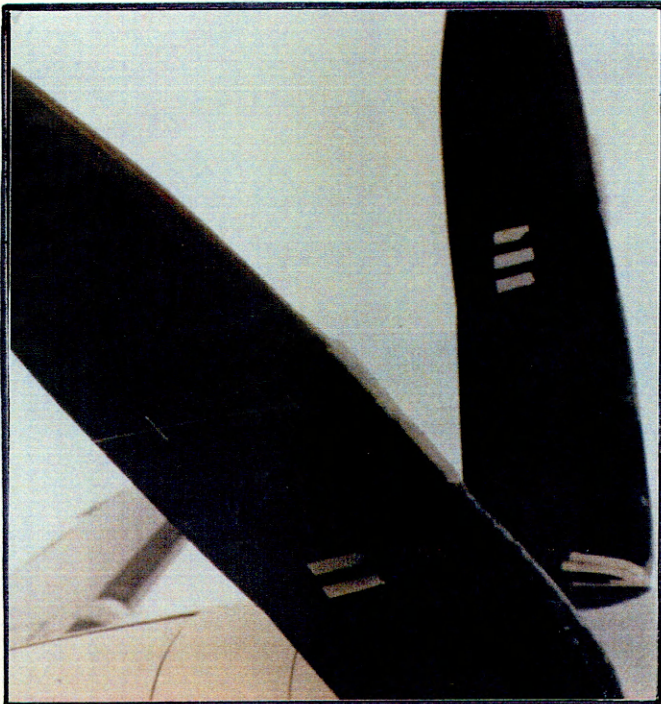


Fig.F45

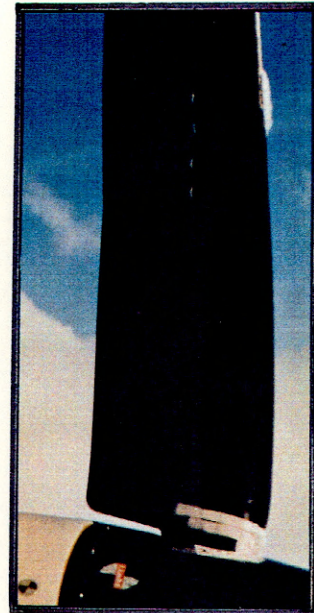


Fig.F46



Fig.F47

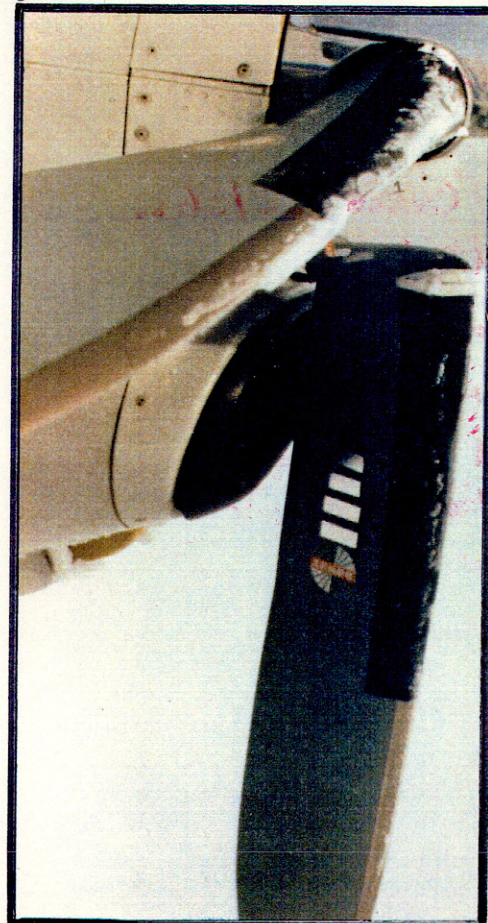


Fig.F48

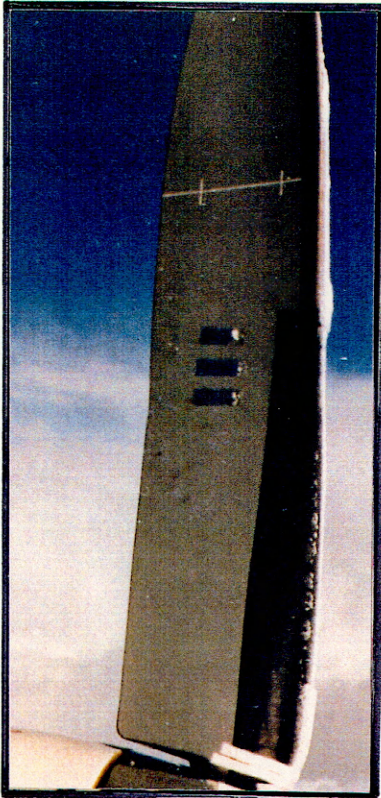


Fig.F49

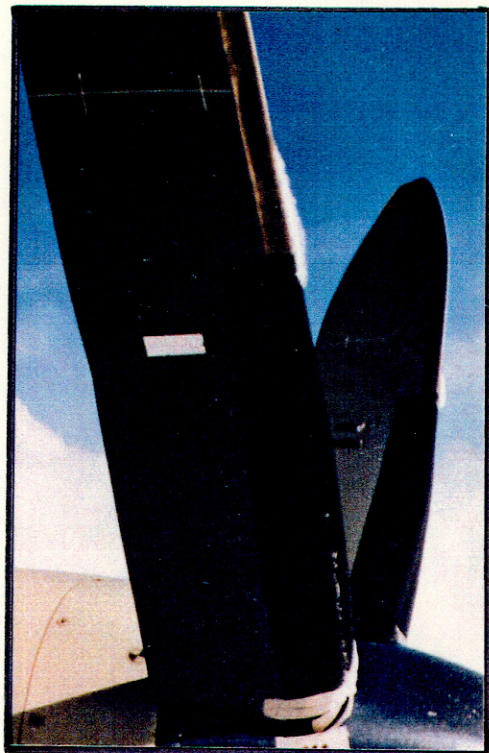


Fig.F50



Fig.F51

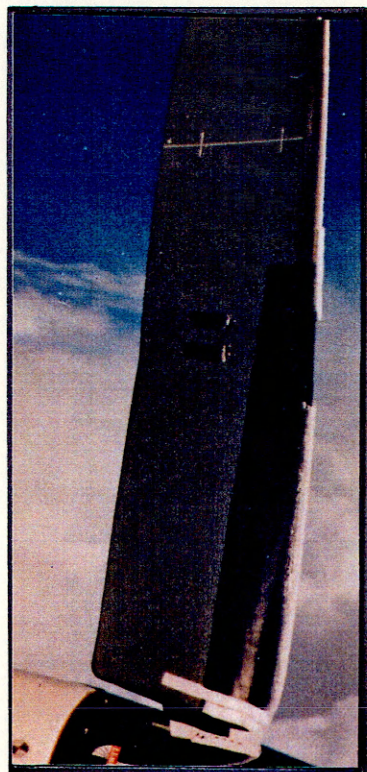


Fig.F52

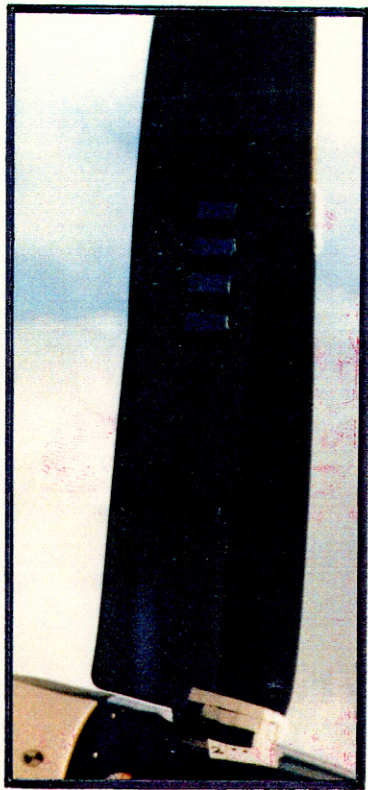


Fig.F53

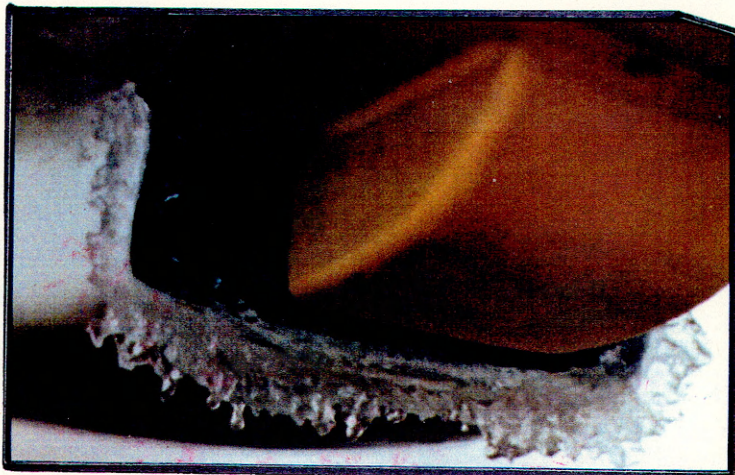


Fig.F54

Two-Dimensional Ice Accretion Computer Prediction Plots

Fig.P1

Lip Section	90°
Program	PTRAJ2
CLE	= 1.0
Lip chord (upper surface)	= 0.086 m
(lower surface)	= 0.117 m
Developed aerofoil chord	= 0.402 m

Fig.P2

Lip Section	135°
Program	PTRAJ2
CLE	= 1.0
Lip chord (upper surface)	= 0.017 m
(lower surface)	= 0.110 m
Developed aerofoil chord	= 0.339 m

Fig.P3

Lip Section	180°
Program	PTRAJ2
CLE	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.285 m

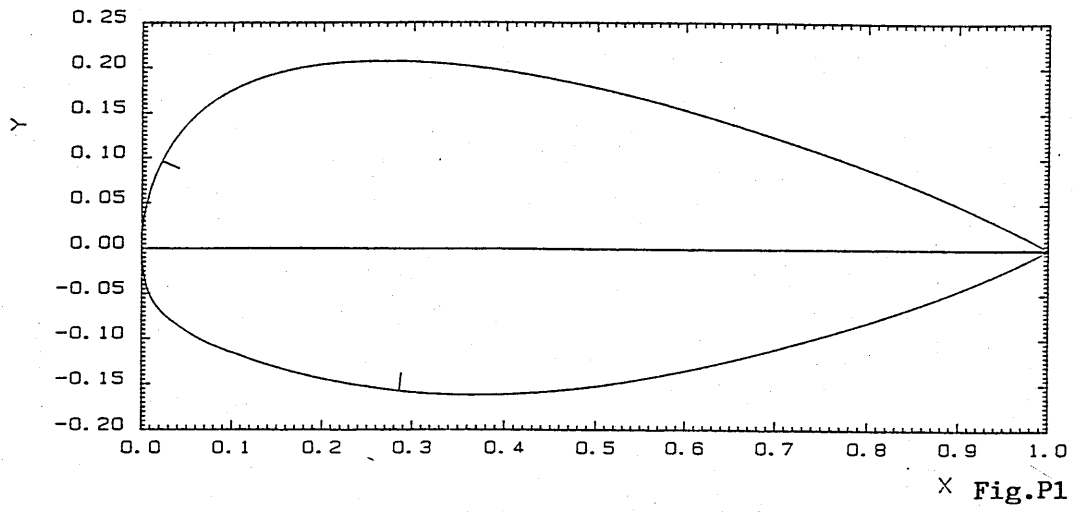
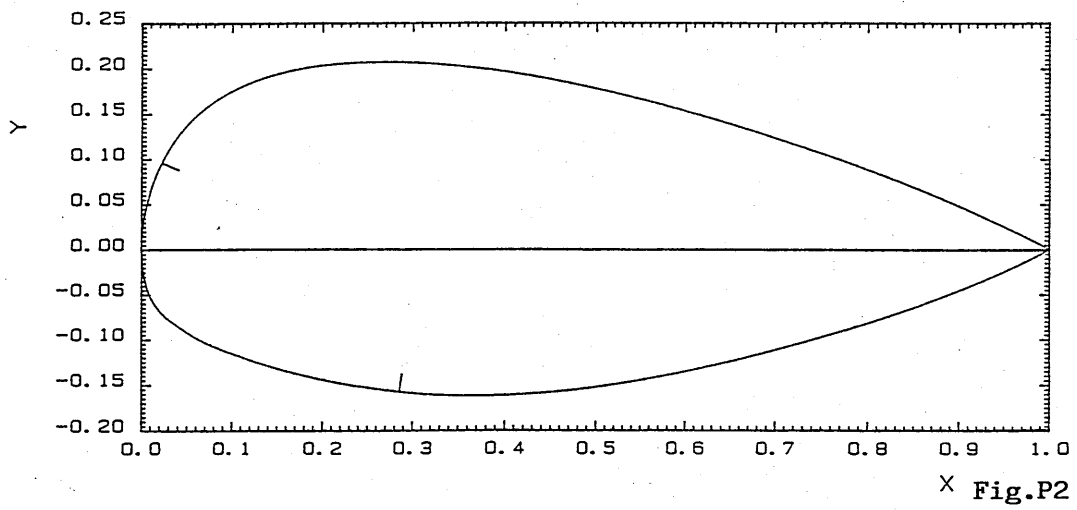
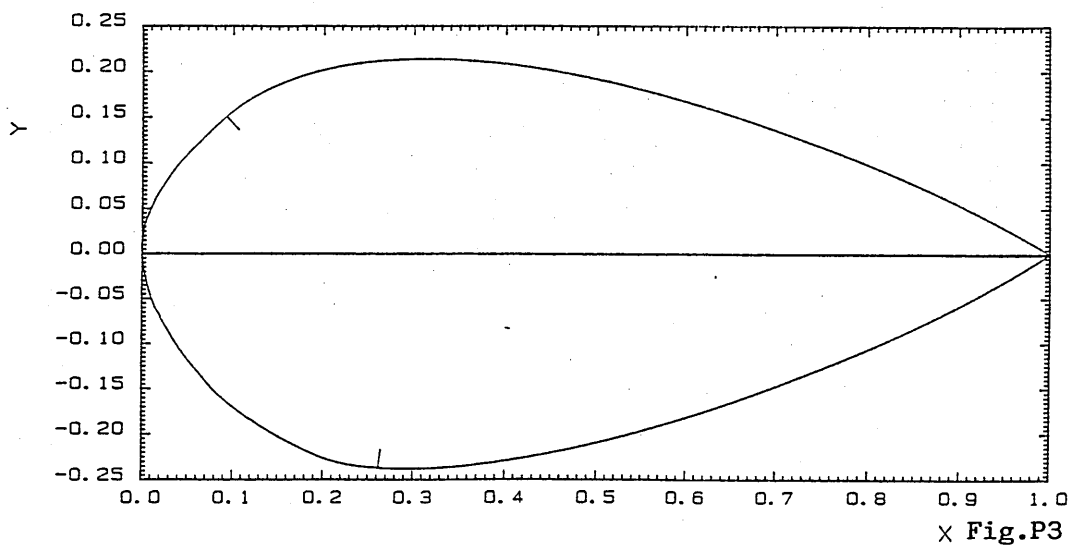


Fig.P4

Lip Section	180°
Program	PTRAJ2
CLE	= 1.1
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.318 m

Fig.P5

Lip Section	180°
Program	PTRAJ2
CLE	= 1.2
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.354 m

Fig.P6

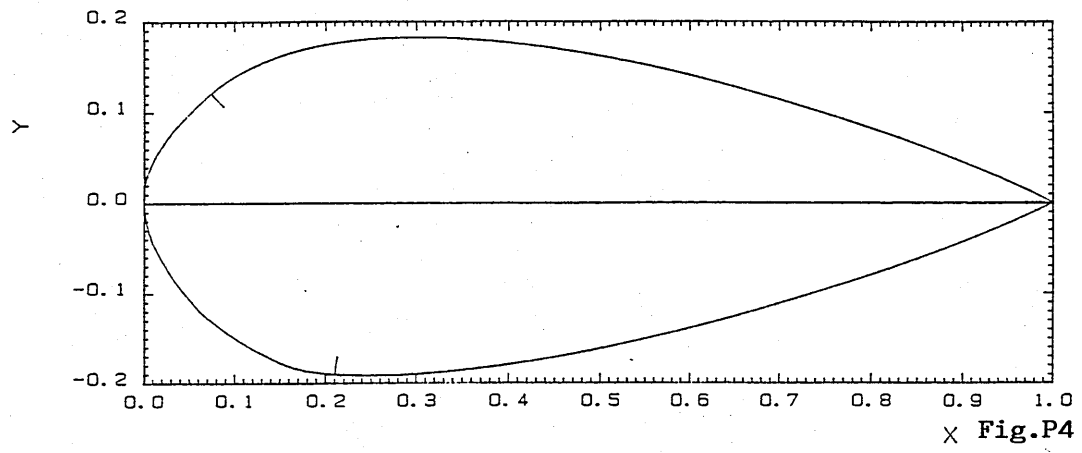
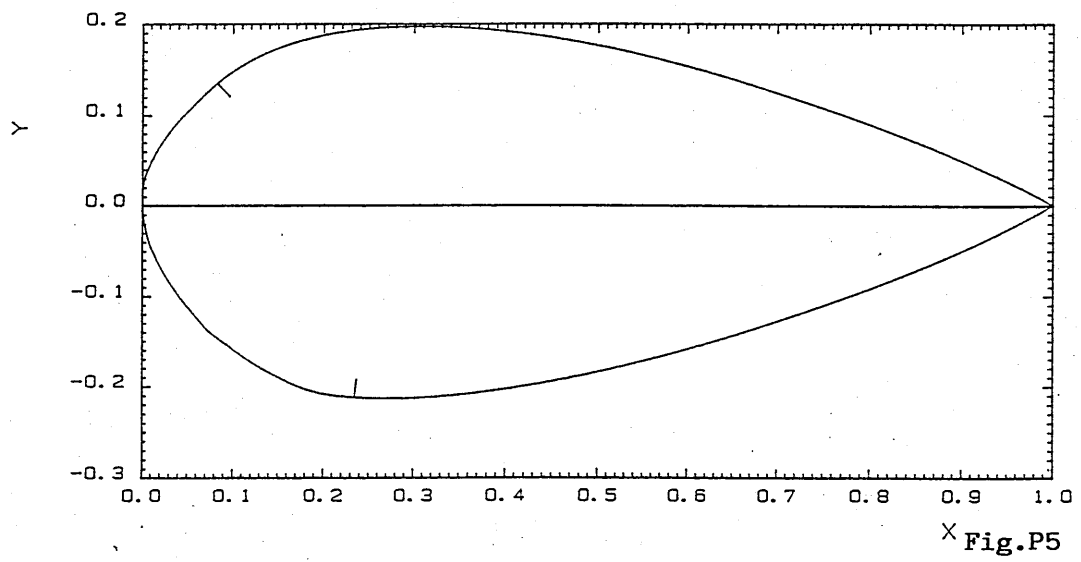
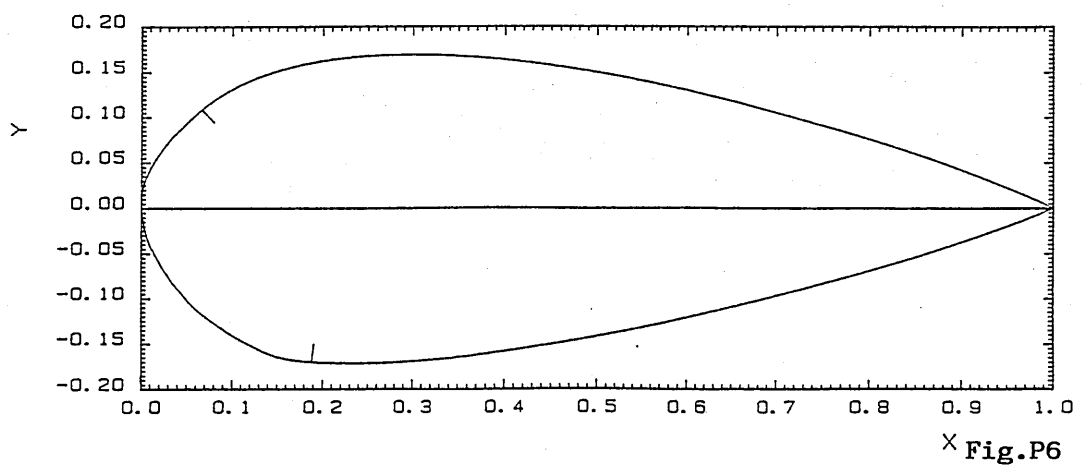
Lip Section	180°
Program	PTRAJ2
CLE	= 1.3
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.396 m

Fig.P7

Lip Section	180°
Program	PTRAJ2
CLE	= 1.4
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.442 m

Fig.P8

Lip Section	180°
Program	PTRAJ2
CLE	= 1.5
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.493 m



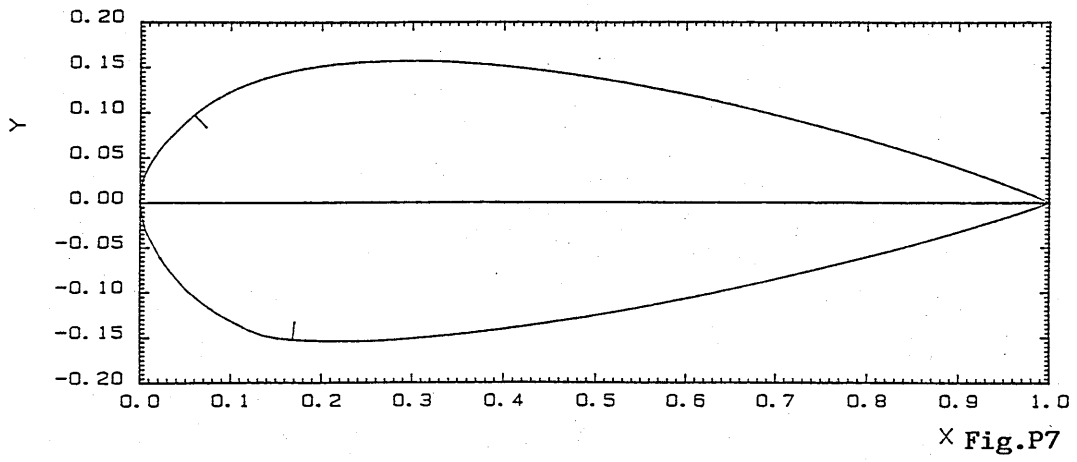
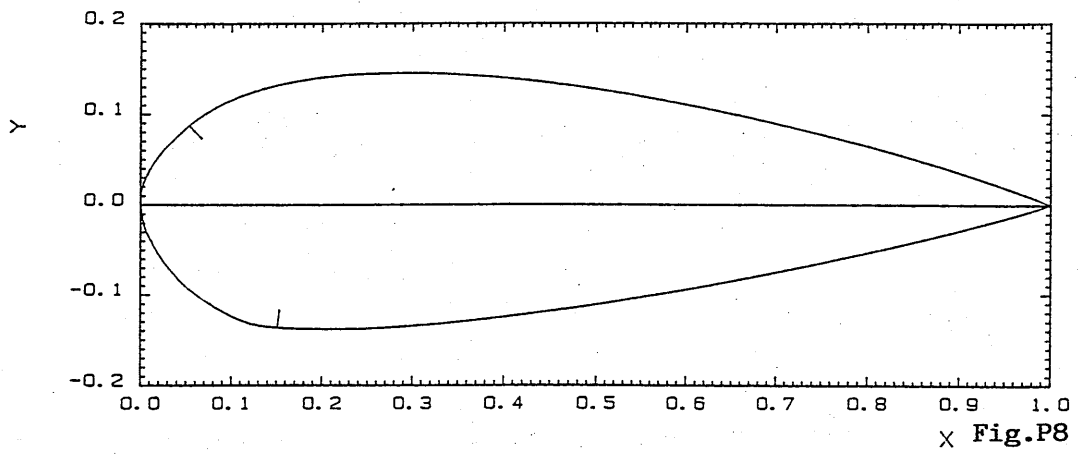
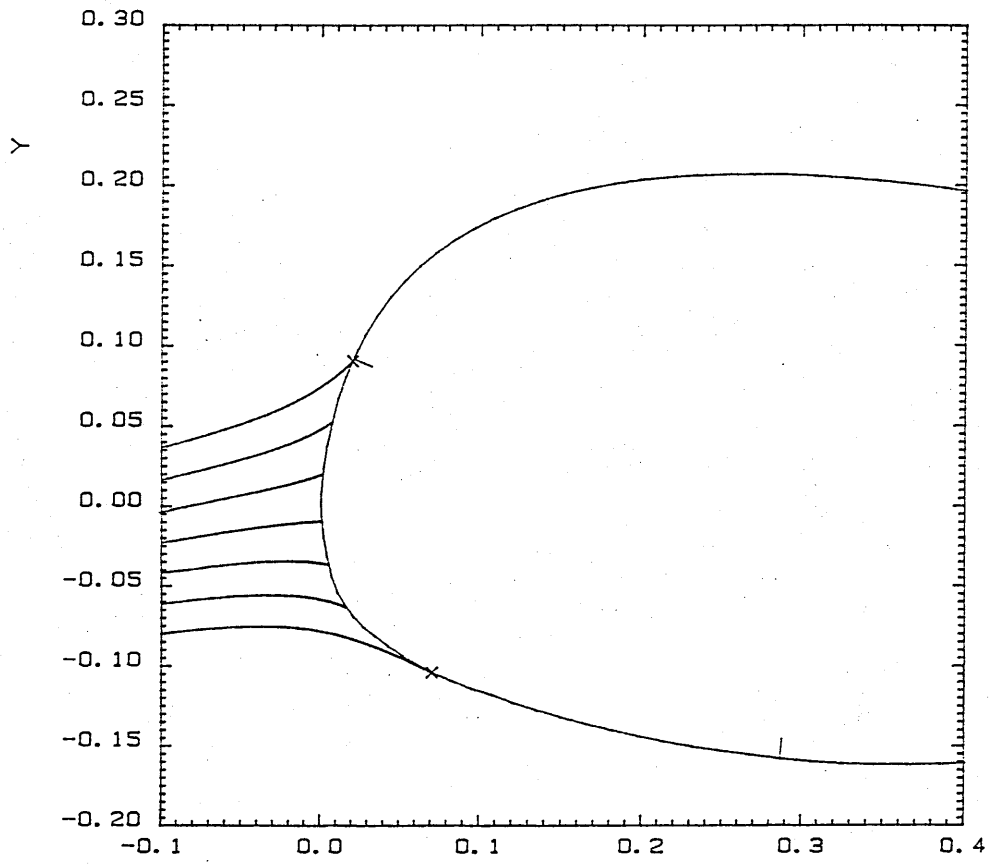


Fig.P9 (Case 1)

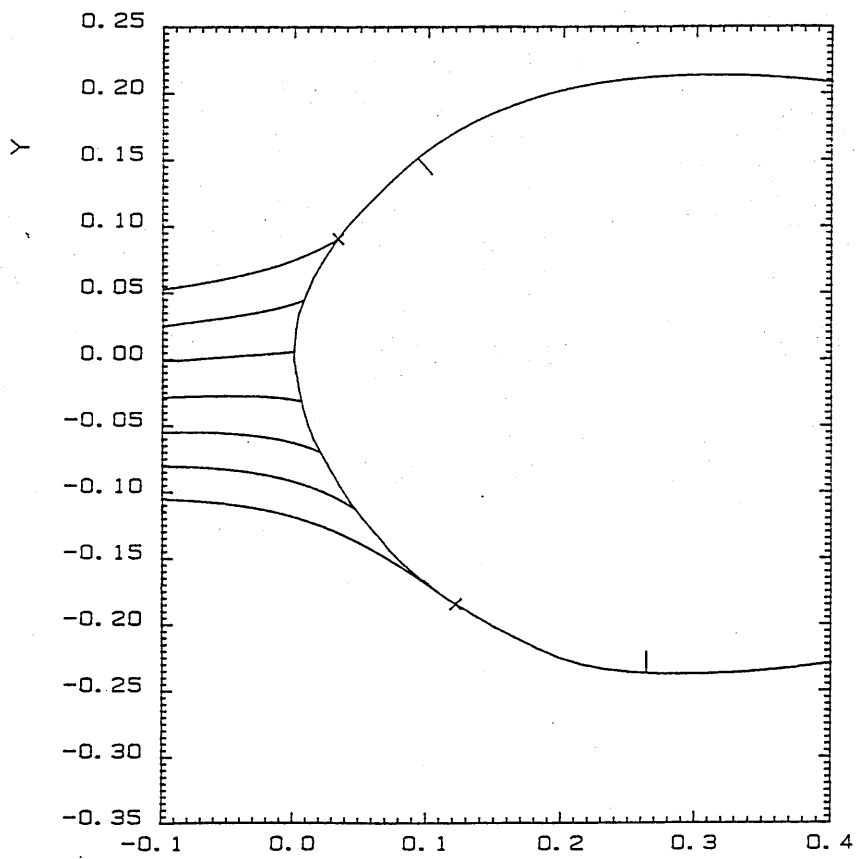
Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 38 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P29
Plot of Beta against s/c	= Fig.P49
Plot of Iced aerofoil	= Fig.P69
TRAJ3 equivalent plot	= Fig.P103

Fig.P10 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.2% developed aerofoil chord = 9.3% original lip section chord = 9.8% s/c = 28 mm aft over lip surface
Inner (lower) surface catch limit	= 12.1% developed aerofoil chord = 40.6% original lip section chord = 22.8% s/c = 65 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P30
Plot of Beta against s/c	= Fig.P50
Plot of Iced aerofoil	= Fig.P70
TRAJ3 equivalent plot	= Fig.P104



× Fig.P9



× Fig.P10

Fig.P11 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.1% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 17.8% developed aerofoil chord = 61.2% original lip section chord = 24.7% s/c = 99 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P31
Plot of Beta against s/c	= Fig.P51
Plot of Iced aerofoil	= Fig.P71
TRAJ3 equivalent plot	= Fig.P105

Fig.P12 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 21.6% original lip section chord = 13.5% s/c = 46 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P32
Plot of Beta against s/c	= Fig.P52
Plot of Iced aerofoil	= Fig.P72
TRAJ3 equivalent plot	= Fig.P106

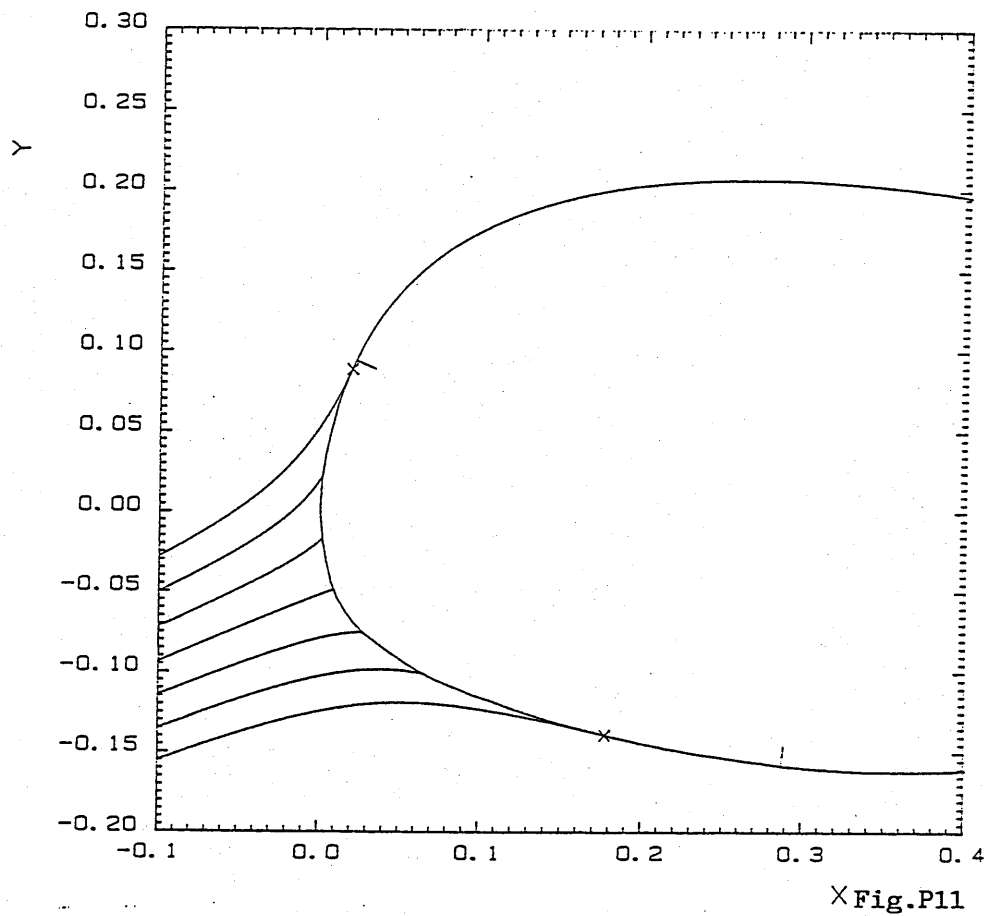
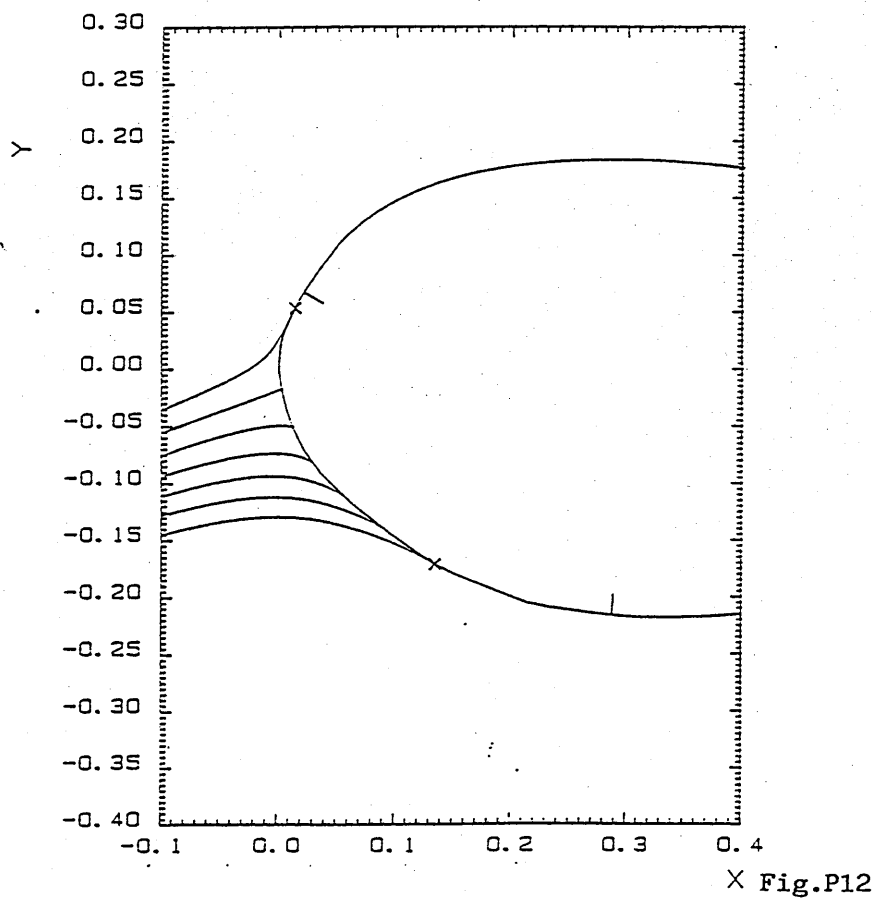
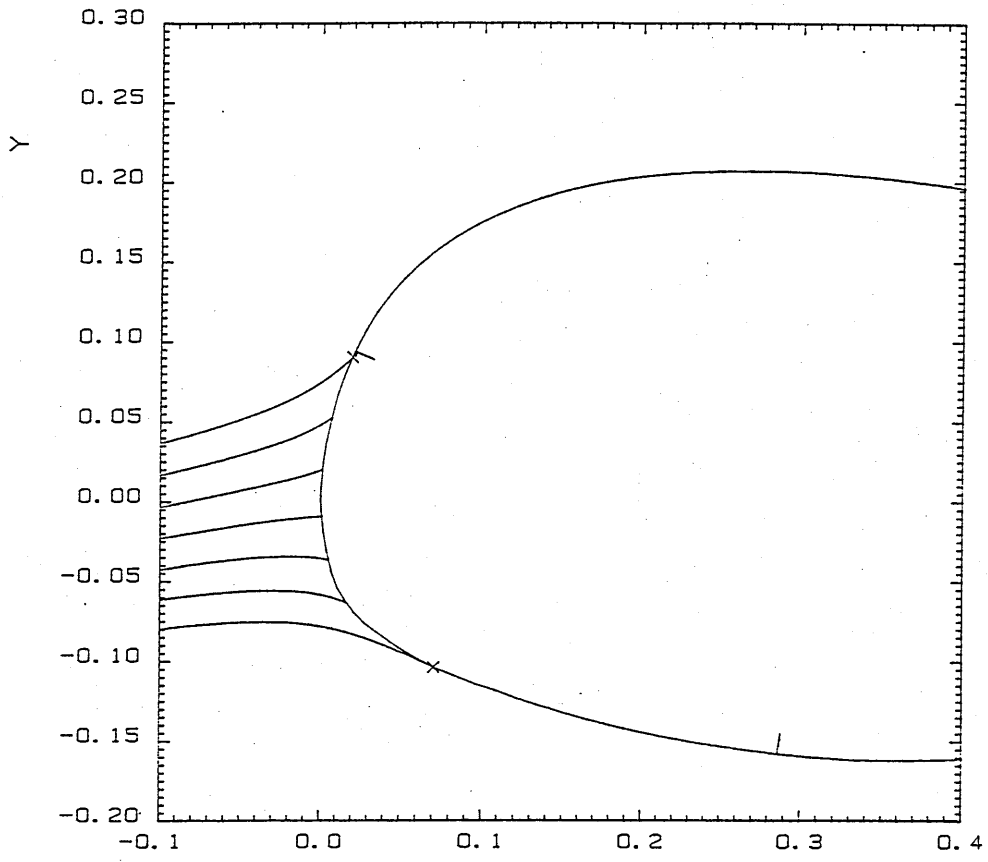


Fig.P13 (Case 5)

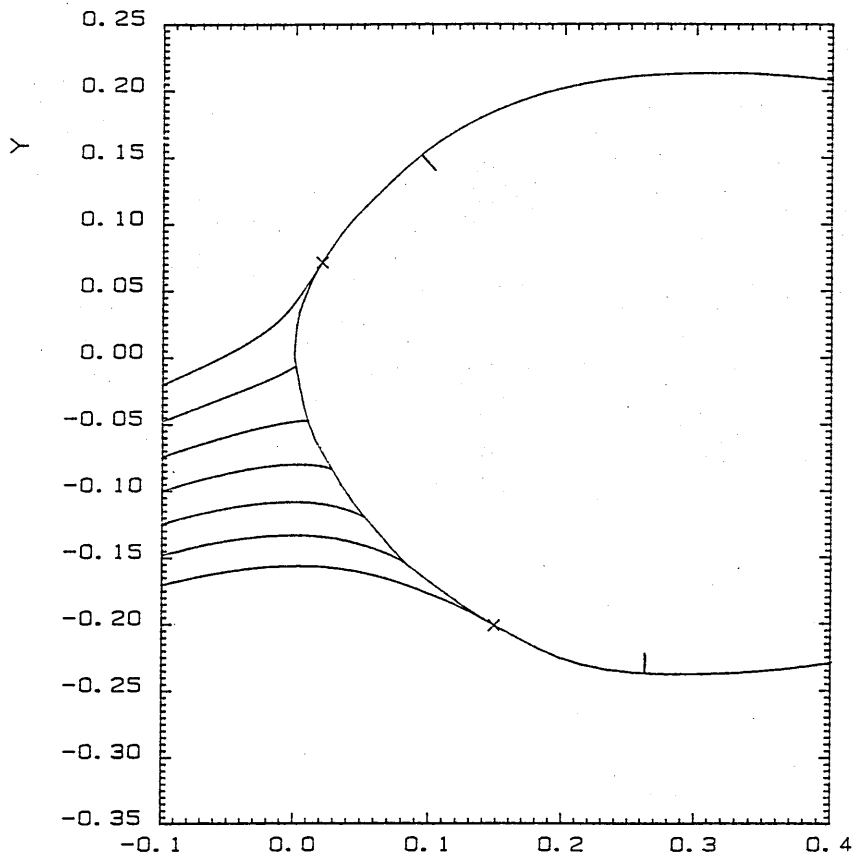
Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 μm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 54 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P33
Plot of Beta against s/c	= Fig.P53
Plot of Iced aerofoil	= Fig.P73
TRAJ3 equivalent plot	= Fig.P107

Fig.P14 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 μm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P34
Plot of Beta against s/c	= Fig.P54
Plot of Iced aerofoil	= Fig.P74
TRAJ3 equivalent plot	= Fig.P108



× Fig.P13



× Fig.P14

Fig.P15 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 1.4% developed aerofoil chord = 6.5% original lip section chord = 5.5% s/c = 22 mm aft over lip surface
Inner (lower) surface catch limit	= 13.2% developed aerofoil chord = 45.4% original lip section chord = 22.7% s/c = 91 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P35
Plot of Beta against s/c	= Fig.P55
Plot of Iced aerofoil	= Fig.P75
TRAJ3 equivalent plot	= Fig.P109

Fig.P16 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.2% developed aerofoil chord = 23.9% original lip section chord = 5.5% s/c = 19 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 41.3% original lip section chord = 22.7% s/c = 77 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P36
Plot of Beta against s/c	= Fig.P56
Plot of Iced aerofoil	= Fig.P76
TRAJ3 equivalent plot	= Fig.P110

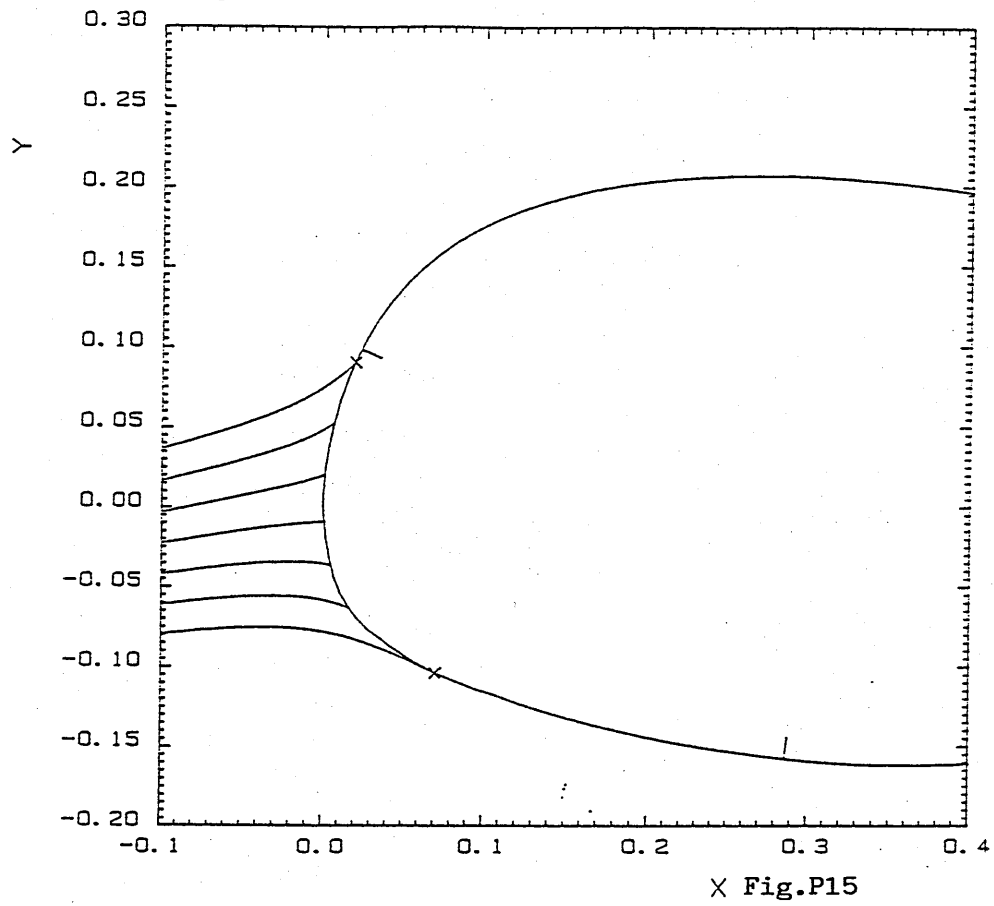
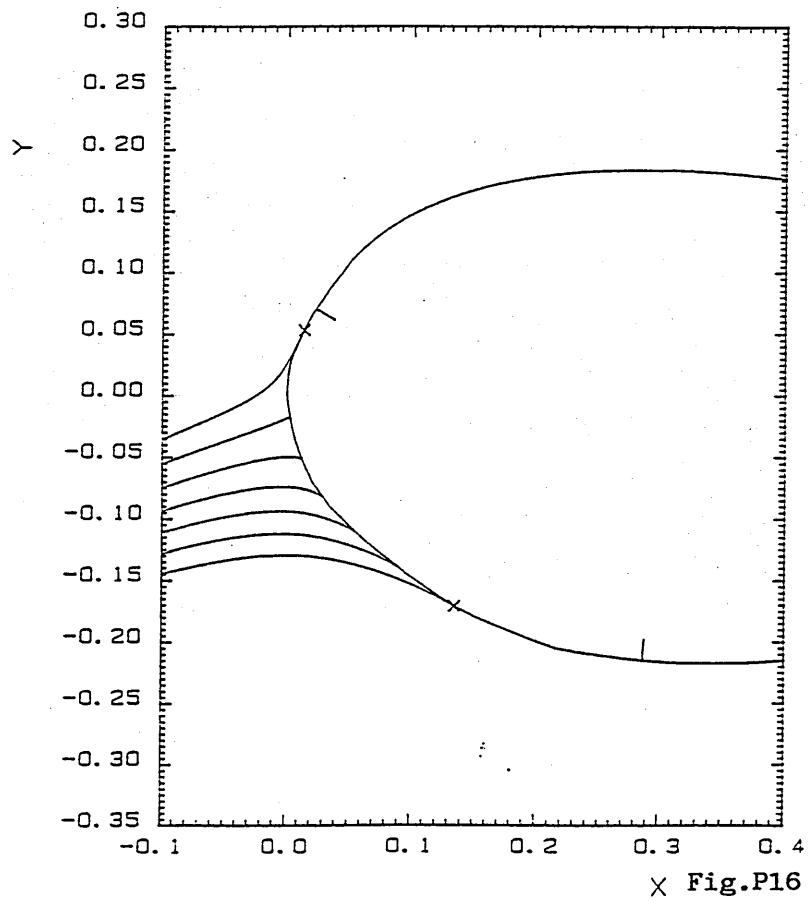


Fig.P17 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 6.7% original lip section chord = 4.0% s/c = 11 mm aft over lip surface
Inner (lower) surface catch limit	= 15.0% developed aerofoil chord = 50.3% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P37
Plot of Beta against s/c	= Fig.P57
Plot of Iced aerofoil	= Fig.P77
TRAJ3 equivalent plot	= Fig.P111

Fig.P18 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.1
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.8% developed aerofoil chord = 29.7% original lip section chord = 8.3% s/c = 26 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 50.1% original lip section chord = 23.3% s/c = 74 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P38
Plot of Beta against s/c	= Fig.P58
Plot of Iced aerofoil	= Fig.P78
TRAJ3 equivalent plot	= Fig.P112

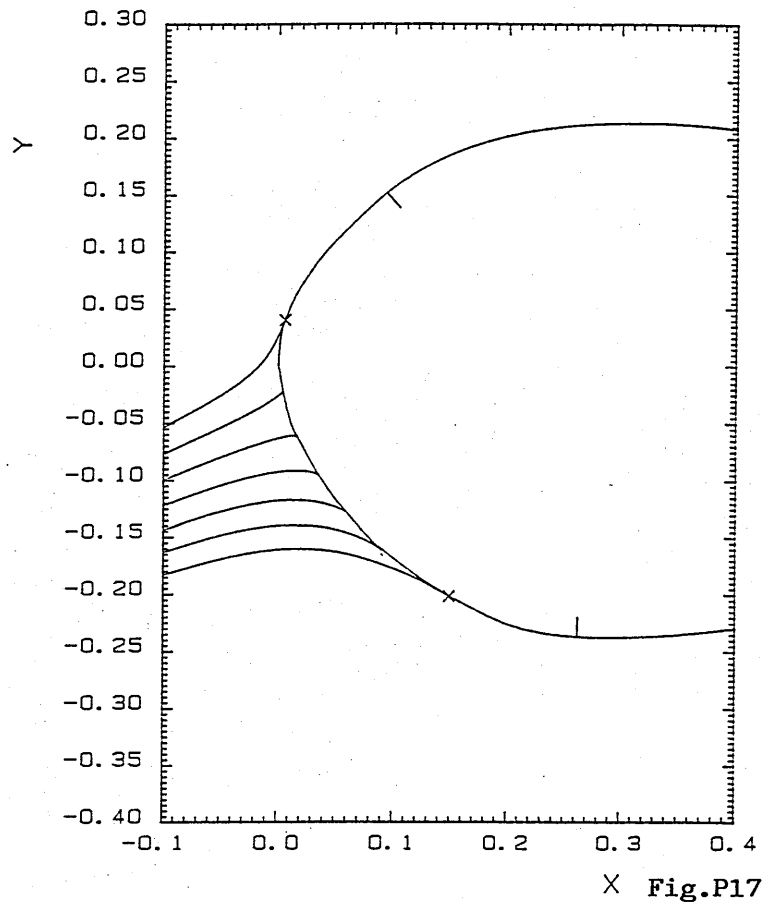
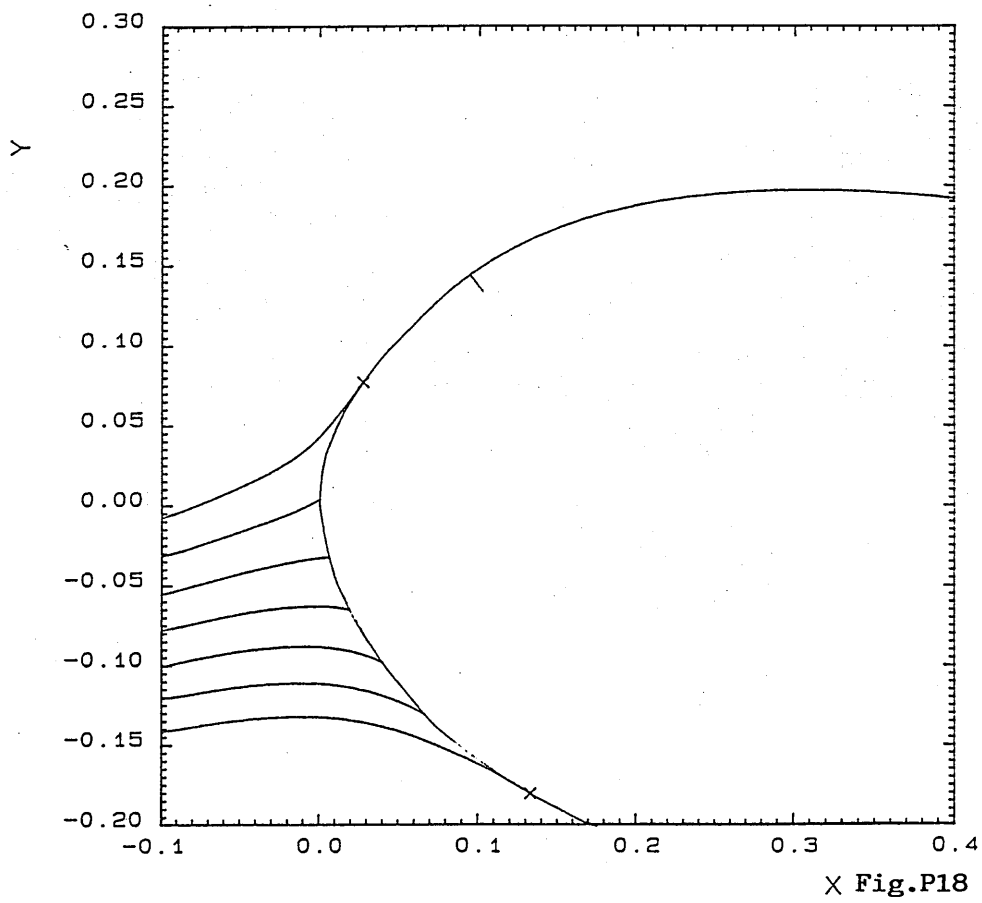


Fig.P19 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.2
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.354 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.1% developed aerofoil chord = 48.4% original lip section chord = 10.2% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 39.6% original lip section chord = 23.0% s/c = 81 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P39
Plot of Beta against s/c	= Fig.P59
Plot of Iced aerofoil	= Fig.P79
TRAJ3 equivalent plot	= Fig.P113

Fig.P20 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.3
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.396 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.8% developed aerofoil chord = 63.4% original lip section chord = 10.5% s/c = 42 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 44.3% original lip section chord = 17.4% s/c = 69 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P40
Plot of Beta against s/c	= Fig.P60
Plot of Iced aerofoil	= Fig.P80
TRAJ3 equivalent plot	= Fig.P114

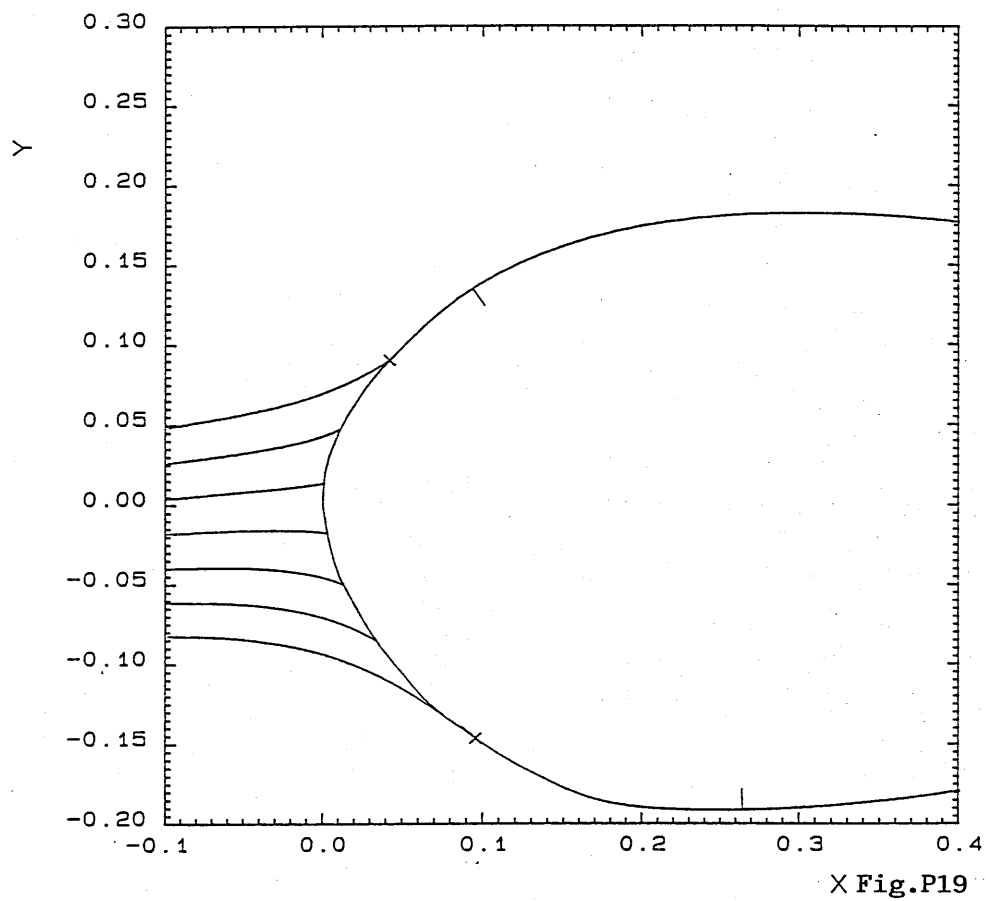
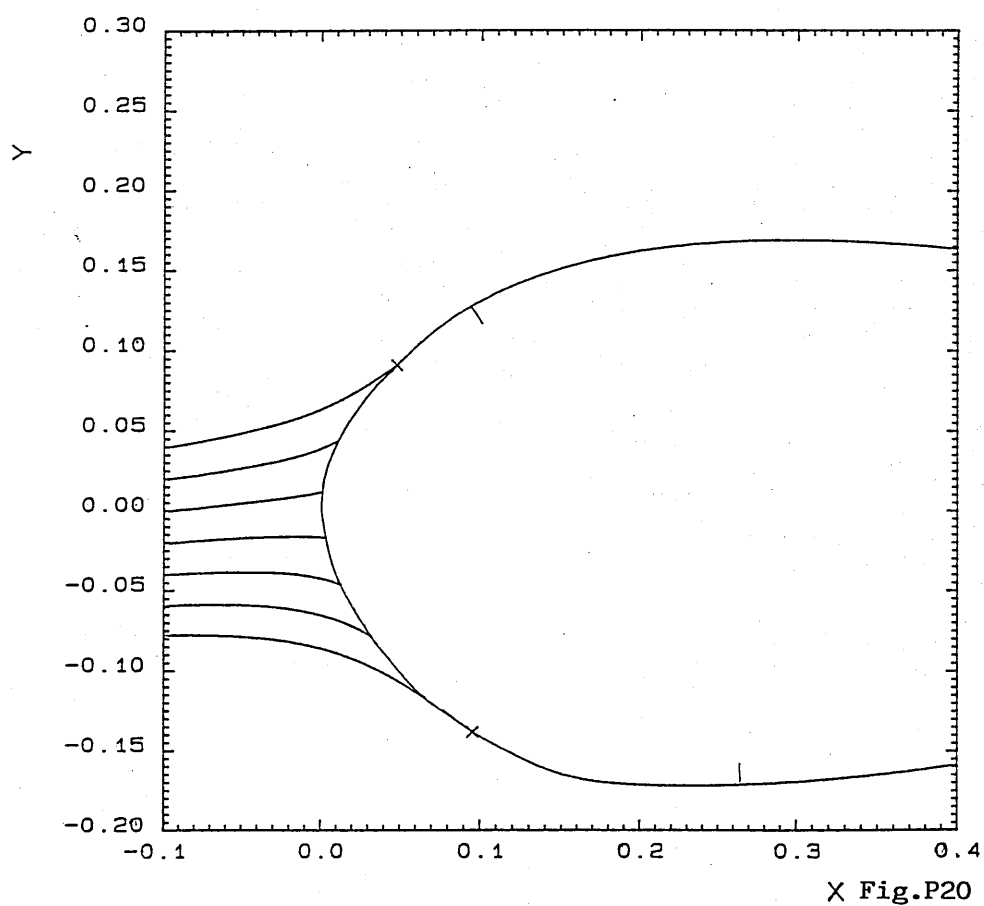


Fig.P21 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.4
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.442 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 76.6% original lip section chord = 10.8% s/c = 48 mm aft over lip surface
Inner (lower) surface catch limit	= 8.1% developed aerofoil chord = 42.1% original lip section chord = 15.2% s/c = 67 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P41
Plot of Beta against s/c	= Fig.P61
Plot of Iced aerofoil	= Fig.P81
TRAJ3 equivalent plot	= Fig.P115

Fig.P22 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.5
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.493 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.8% developed aerofoil chord = 95.3% original lip section chord = 11.0% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 5.1% developed aerofoil chord = 29.6% original lip section chord = 10.9% s/c = 54 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P42
Plot of Beta against s/c	= Fig.P62
Plot of Iced aerofoil	= Fig.P92
TRAJ3 equivalent plot	= Fig.P116

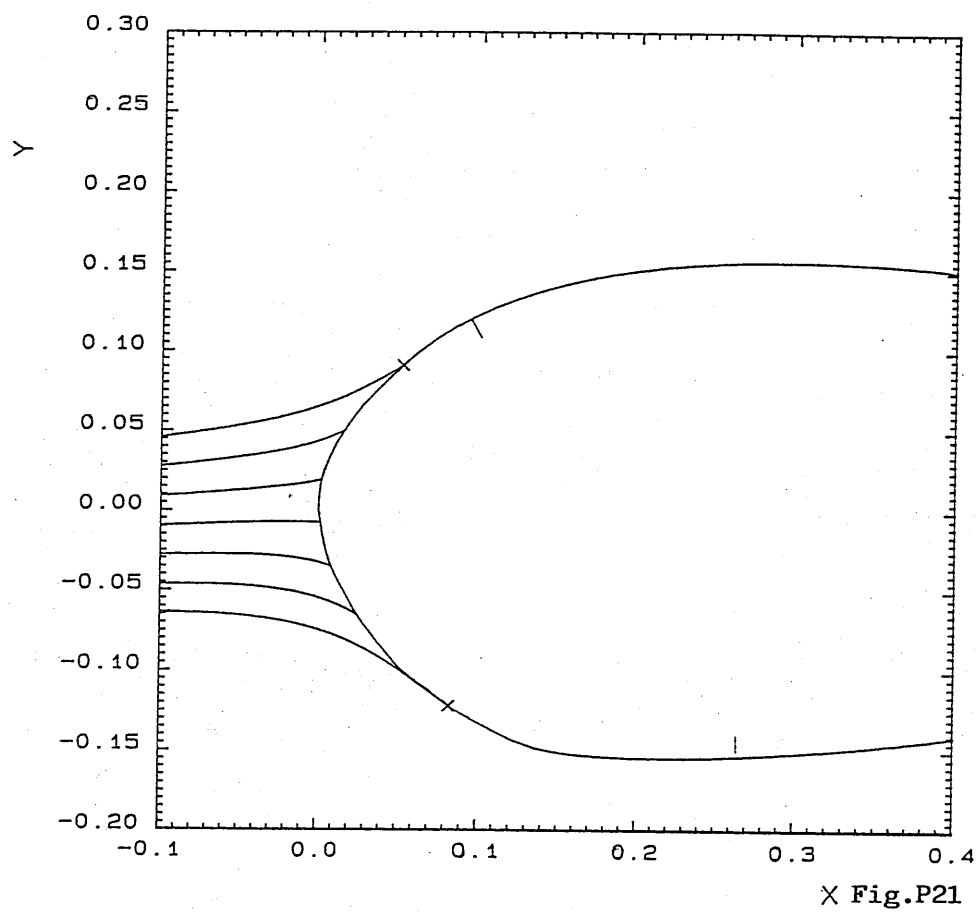
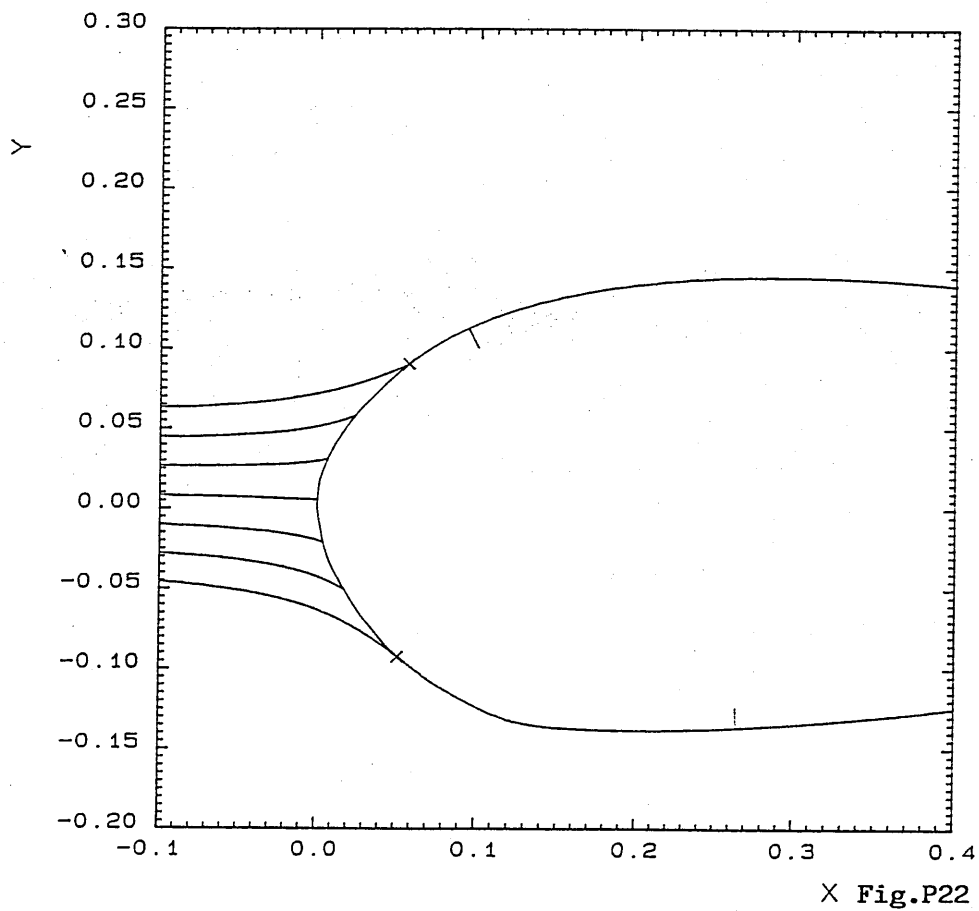
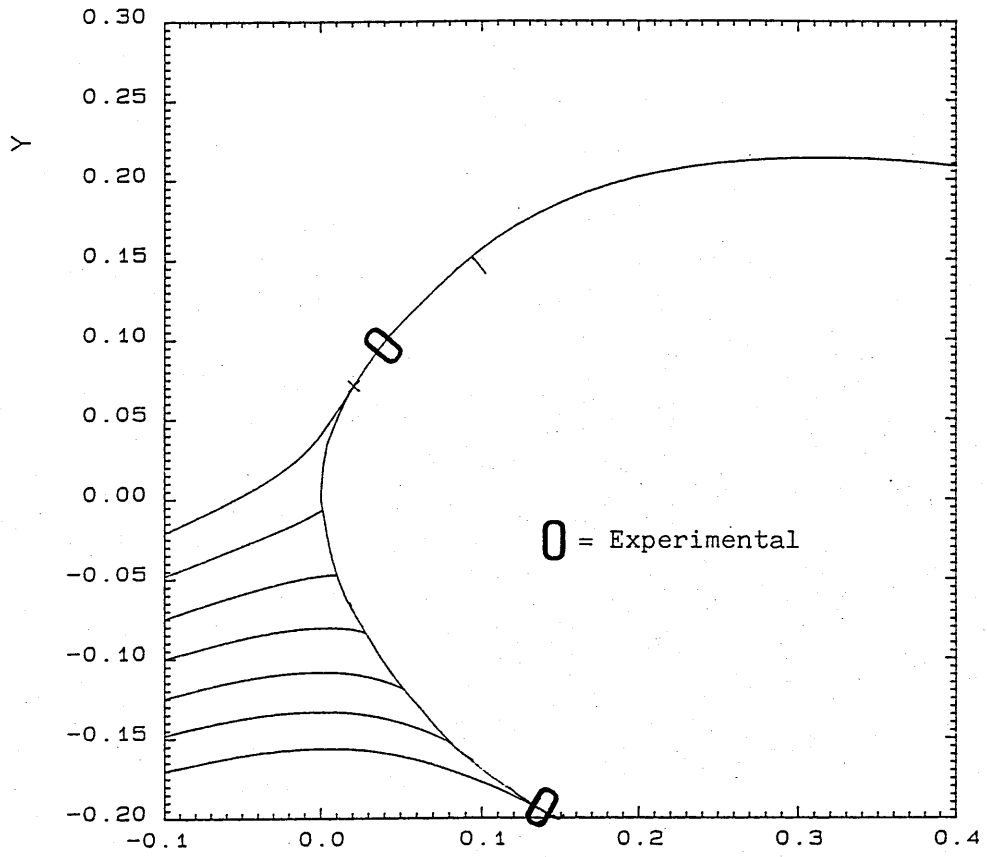


Fig.P23 (Case 15)

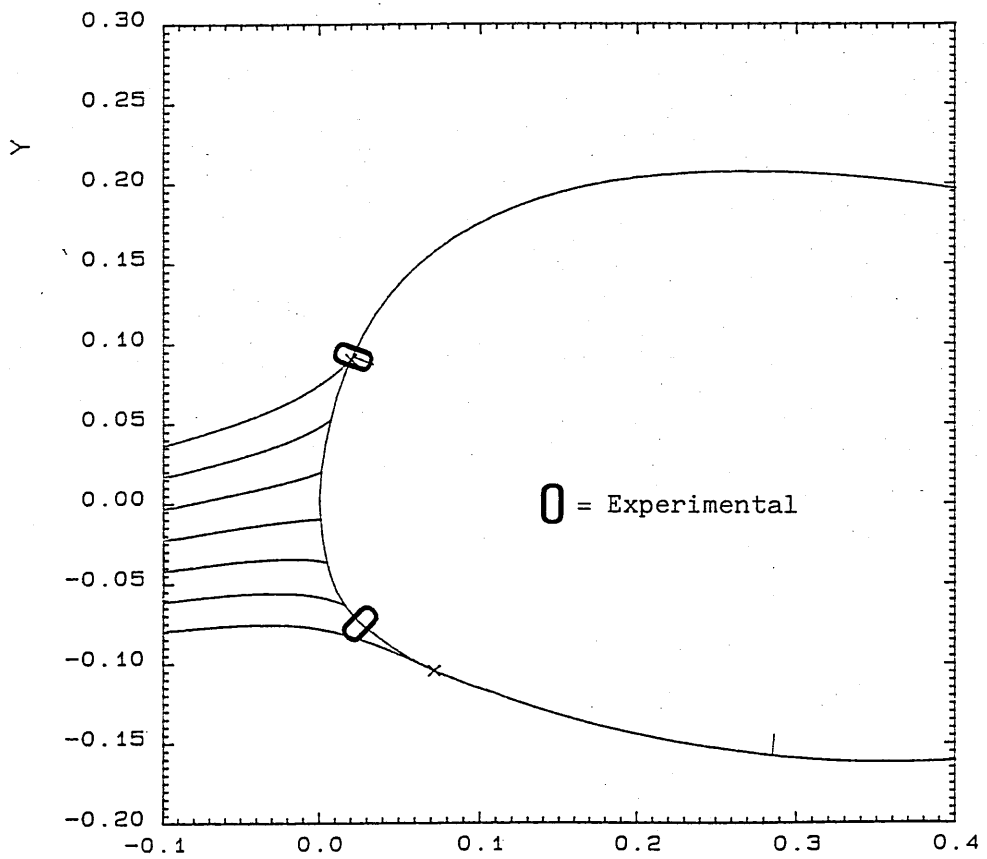
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Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P43
Plot of Beta against s/c	= Fig.P63
Plot of Iced aerofoil	= Fig.P83
TRAJ3 equivalent plot	= Fig.P117

Fig.P24 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.1% developed aerofoil chord = 24.4% original lip section chord = 13.6% s/c = 55 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P44
Plot of Beta against s/c	= Fig.P64
Plot of Iced aerofoil	= Fig.P84
TRAJ3 equivalent plot	= Fig.P118



X Fig.P23



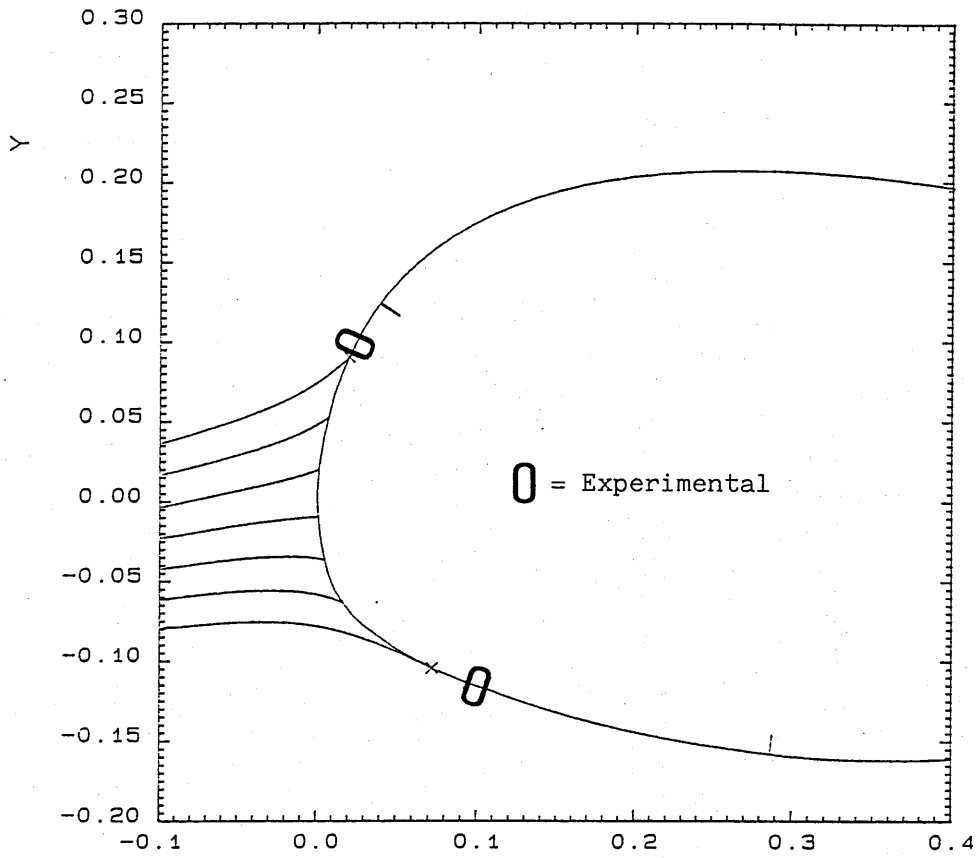
X Fig.P24

Fig.P25 (Case 17)

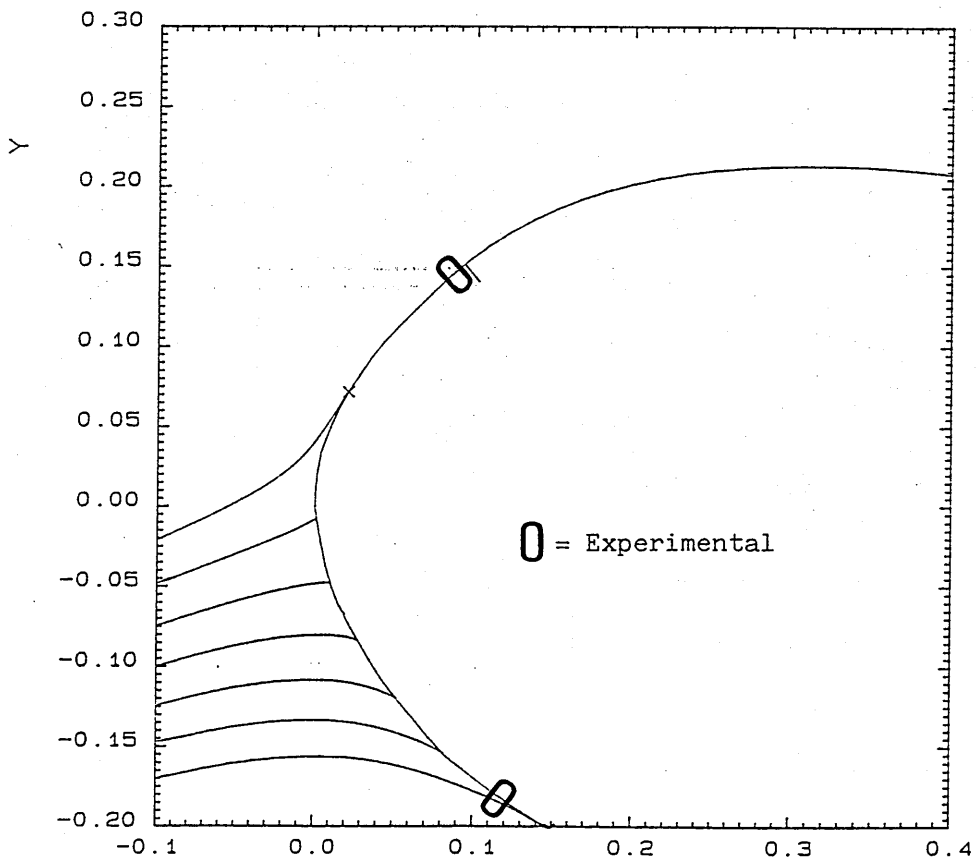
Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.2% developed aerofoil chord = 22.2% original lip section chord = 13.7% s/c = 46 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P45
Plot of Beta against s/c	= Fig.P65
Plot of Iced aerofoil	= Fig.P85
TRAJ3 equivalent plot	= Fig.P119

Fig.P26 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.9% developed aerofoil chord = 20.1% original lip section chord = 7.5% s/c = 24 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 55.7% original lip section chord = 26.0% s/c = 83 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P46
Plot of Beta against s/c	= Fig.P66
Plot of Iced aerofoil	= Fig.P86
TRAJ3 equivalent plot	= Fig.P120



X Fig.P25



X Fig.P26

Fig.P27 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.1% s/c = 38 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P47
Plot of Beta against s/c	= Fig.P67
Plot of Iced aerofoil	= Fig.P87
TRAJ3 equivalent plot	= Fig.P121

Fig.P28 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.2% s/c = 38 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P48
Plot of Beta against s/c	= Fig.P68
Plot of Iced aerofoil	= Fig.P88
TRAJ3 equivalent plot	= Fig.P122

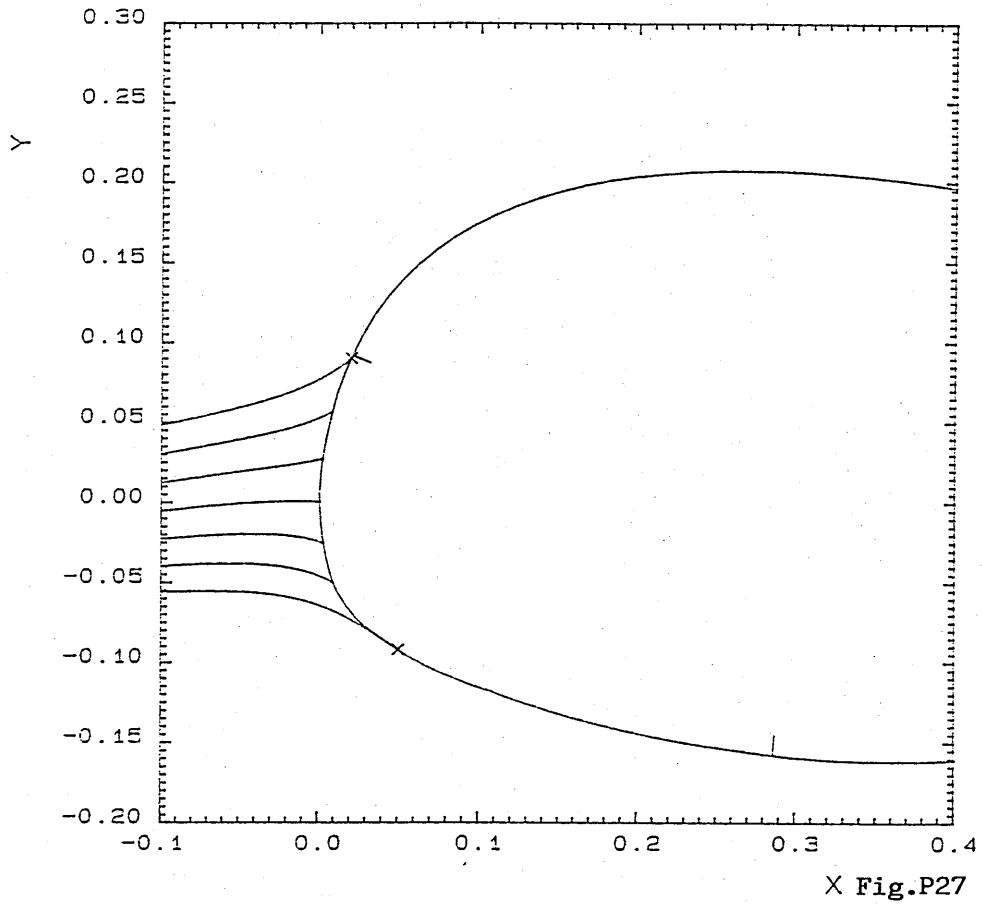
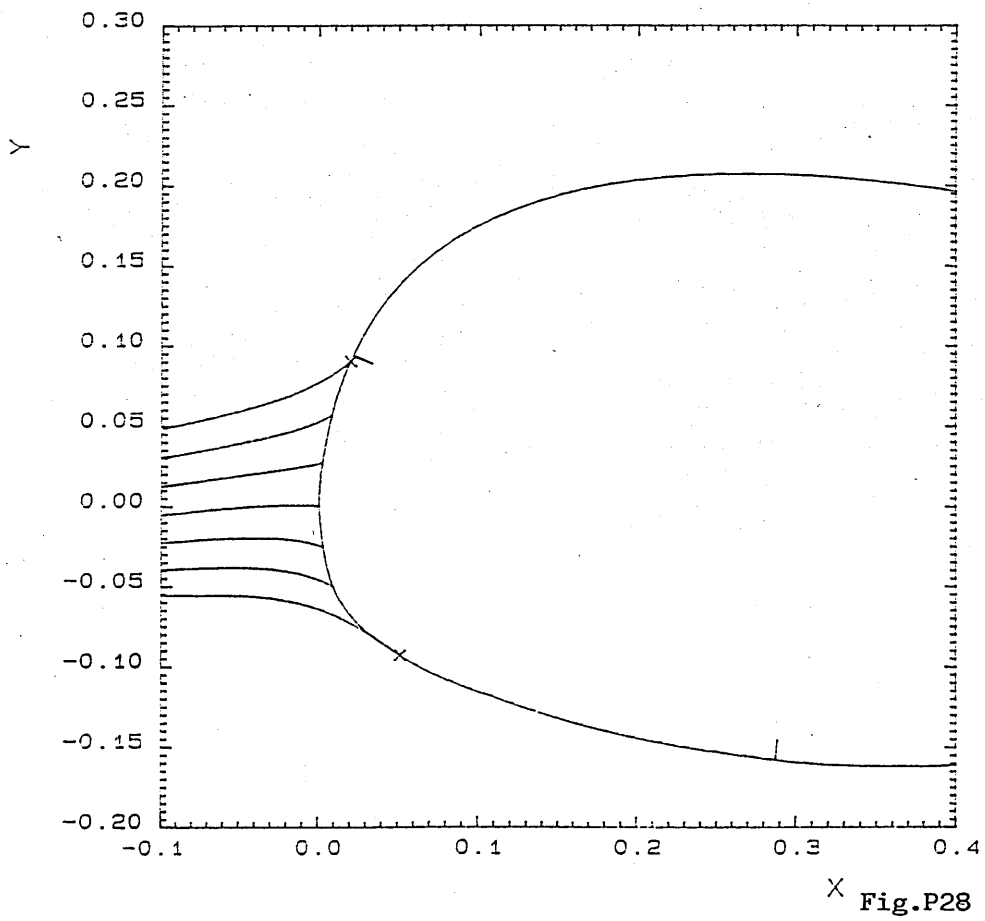


Fig.P29 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P9
Plot of Beta against s/c	= Fig.P49
Plot of Iced aerofoil	= Fig.P69
TRAJ3 equivalent plot	= Fig.P123

Fig.P30 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.2% developed aerofoil chord = 9.3% original lip section chord = 9.8% s/c = 28 mm aft over lip surface
Inner (lower) surface catch limit	= 12.1% developed aerofoil chord = 40.6% original lip section chord = 22.8% s/c = 65 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P10
Plot of Beta against s/c	= Fig.P50
Plot of Iced aerofoil	= Fig.P70
TRAJ3 equivalent plot	= Fig.P124

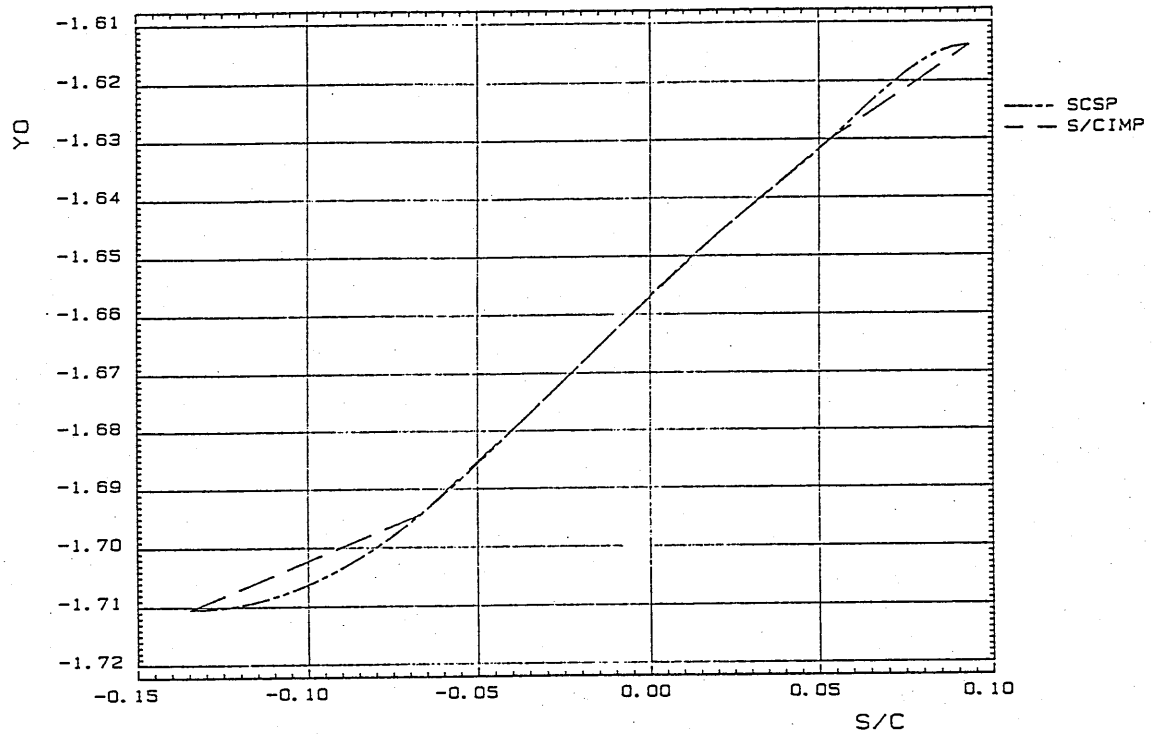


Fig.P29

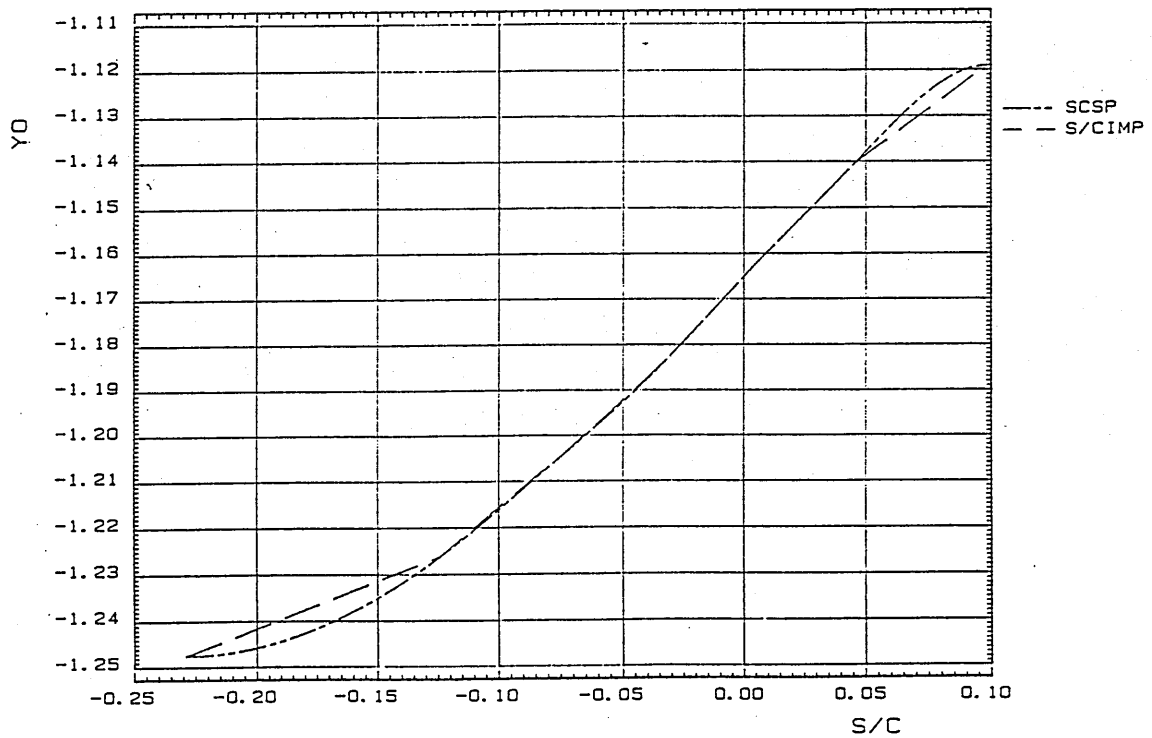


Fig.P30

Fig.P31 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.1% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 17.8% developed aerofoil chord = 61.2% original lip section chord = 24.7% s/c = 99 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P11
Plot of Beta against s/c	= Fig.P51
Plot of Iced aerofoil	= Fig.P71
TRAJ3 equivalent plot	= Fig.P125

Fig.P32 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 21.6% original lip section chord = 13.5% s/c = 46 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P12
Plot of Beta against s/c	= Fig.P52
Plot of Iced aerofoil	= Fig.P72
TRAJ3 equivalent plot	= Fig.P126

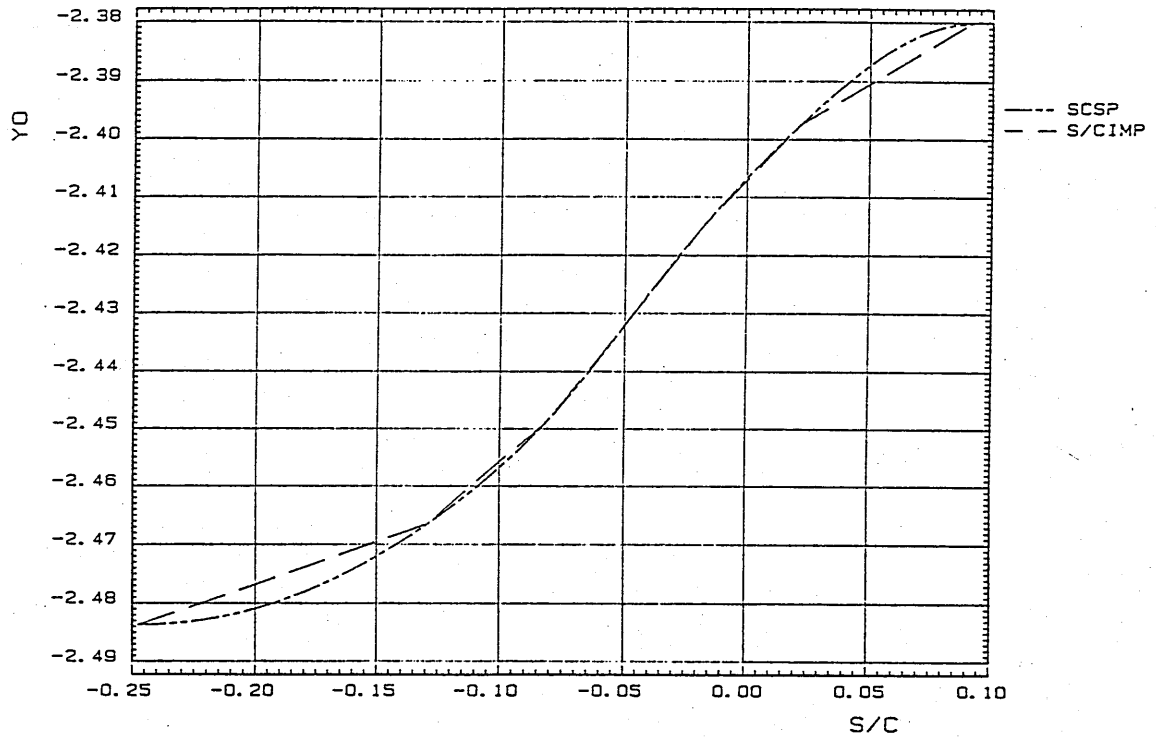


Fig.P31

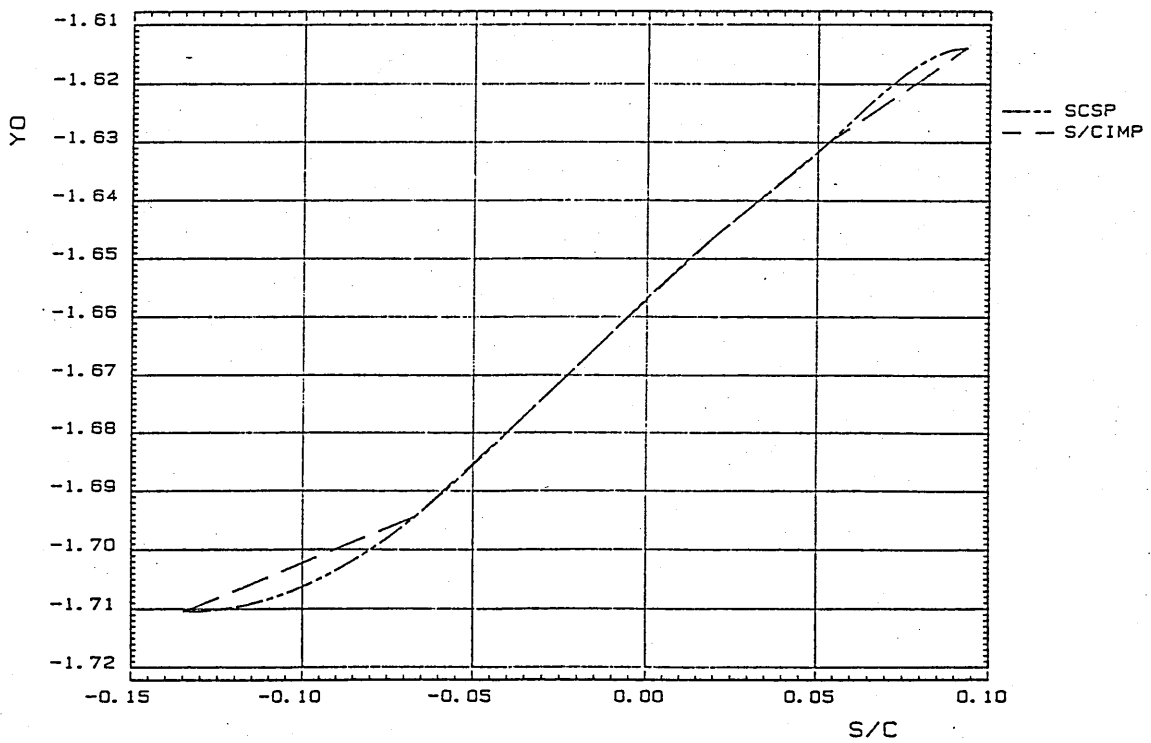


Fig.P32

Fig.P33 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 54 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P13
Plot of Beta against s/c	= Fig.P53
Plot of Iced aerofoil	= Fig.P73
TRAJ3 equivalent plot	= Fig.P127

Fig.P34 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P14
Plot of Beta against s/c	= Fig.P54
Plot of Iced aerofoil	= Fig.P74
TRAJ3 equivalent plot	= Fig.P128

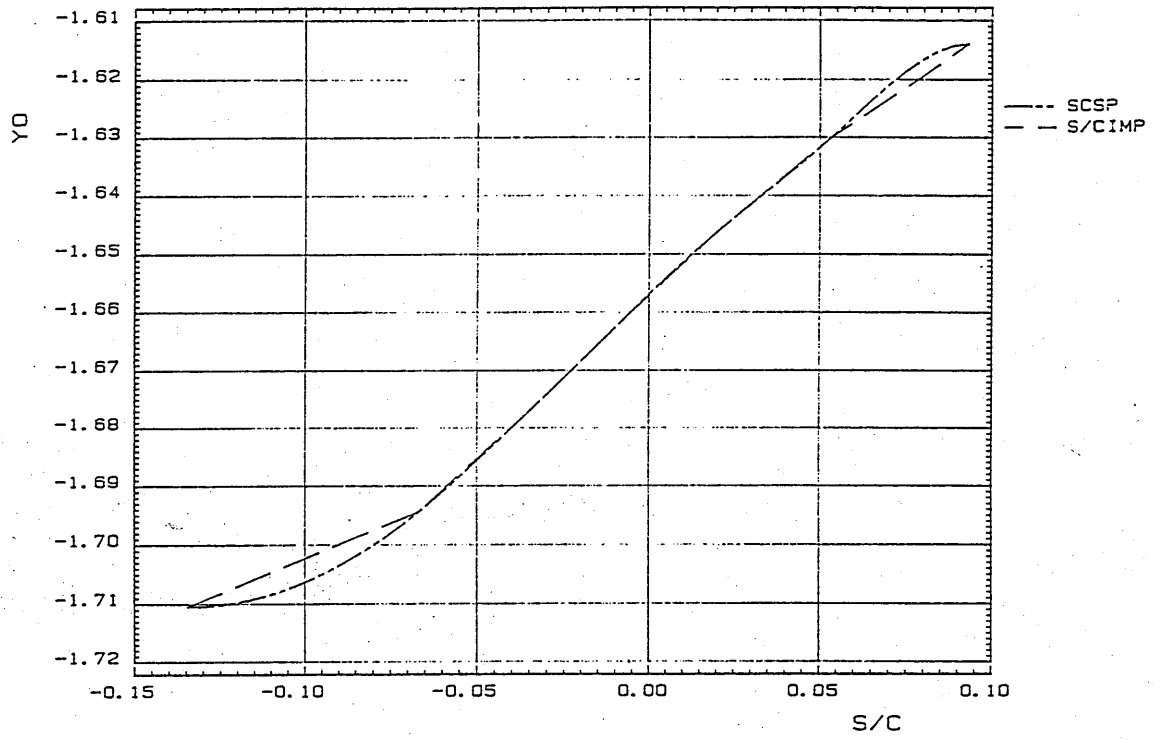


Fig.P33

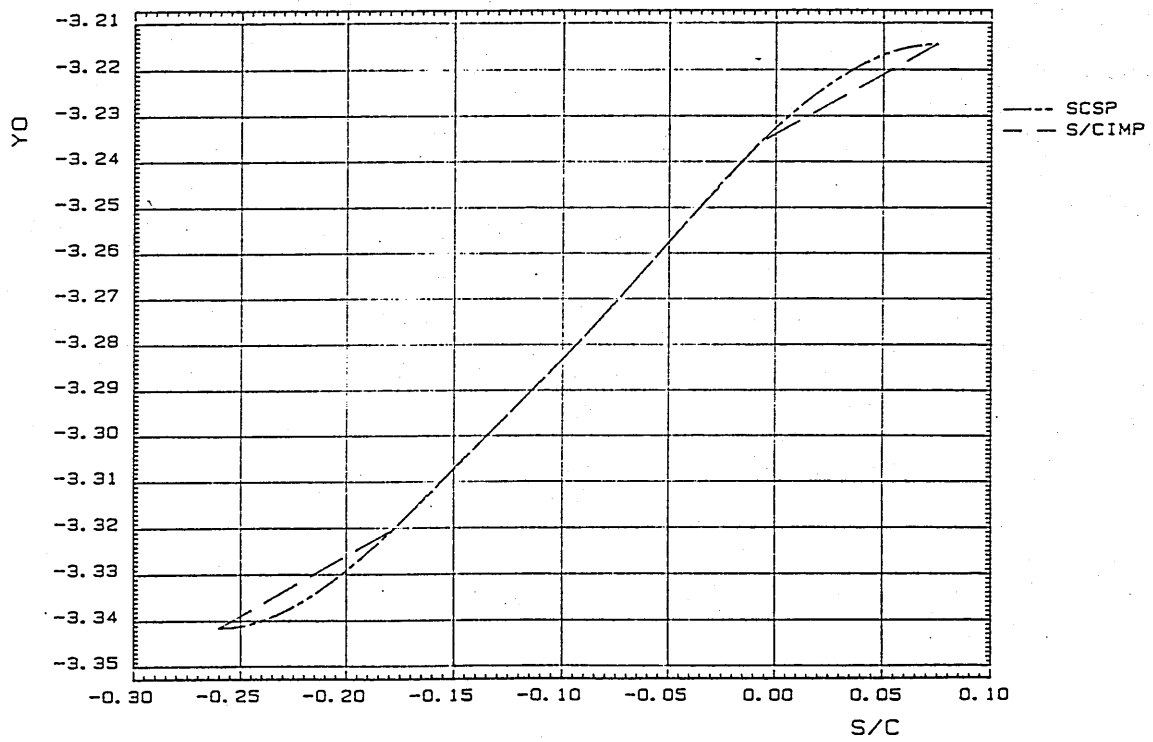


Fig.P34

Fig.P35 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 1.4% developed aerofoil chord = 6.5% original lip section chord = 5.5% s/c = 22 mm aft over lip surface
Inner (lower) surface catch limit	= 13.2% developed aerofoil chord = 45.4% original lip section chord = 22.7% s/c = 91 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P15
Plot of Beta against s/c	= Fig.P55
Plot of Iced aerofoil	= Fig.P75
TRAJ3 equivalent plot	= Fig.P129

Fig.P36 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.2% developed aerofoil chord = 23.9% original lip section chord = 5.5% s/c = 19 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 41.3% original lip section chord = 22.7% s/c = 77 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P16
Plot of Beta against s/c	= Fig.P56
Plot of Iced aerofoil	= Fig.P76
TRAJ3 equivalent plot	= Fig.P130

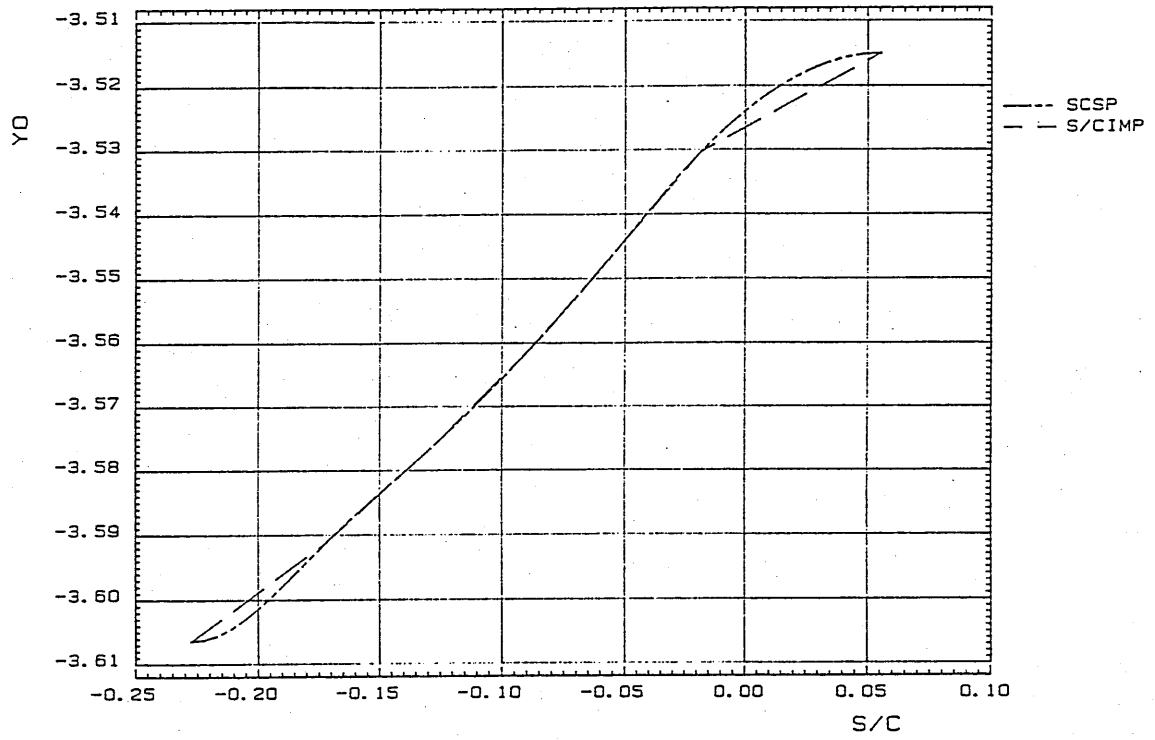


Fig.P35

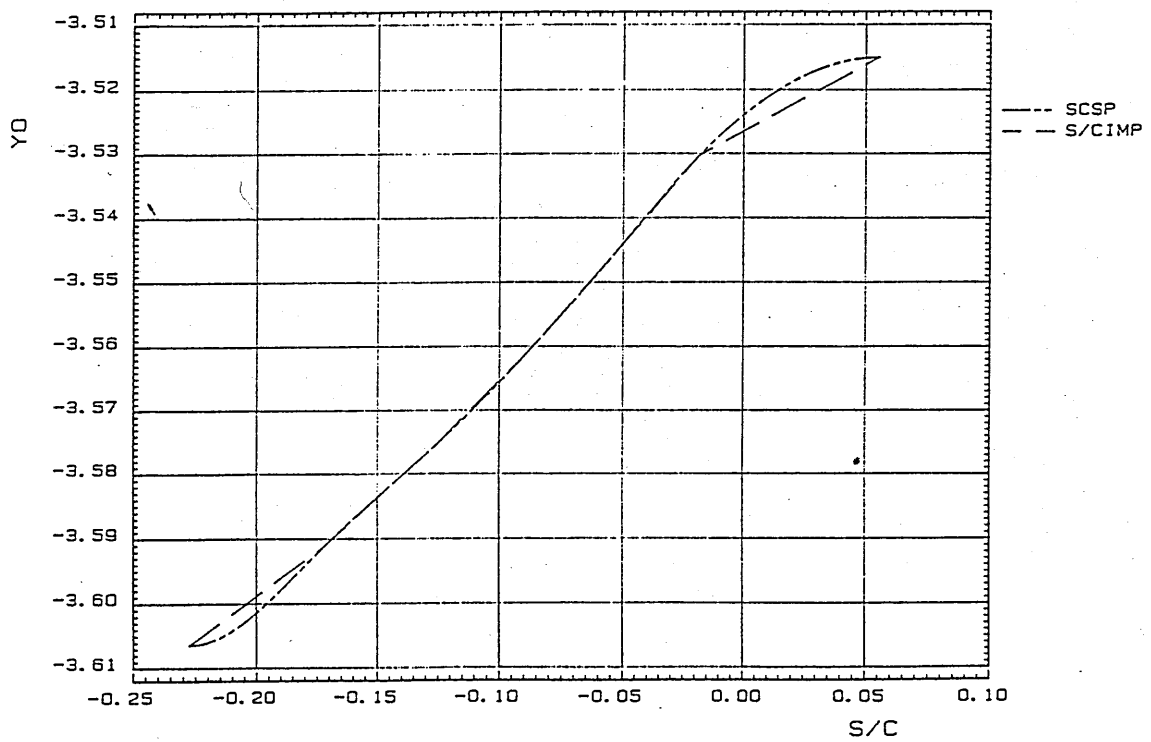


Fig.P36

Fig.P37 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 6.7% original lip section chord = 4.0% s/c = 11 mm aft over lip surface
Inner (lower) surface catch limit	= 15.0% developed aerofoil chord = 50.3% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P17
Plot of Beta against s/c	= Fig.P57
Plot of Iced aerofoil	= Fig.P77
TRAJ3 equivalent plot	= Fig.P131

Fig.P38 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.1
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.8% developed aerofoil chord = 29.7% original lip section chord = 8.3% s/c = 26 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 50.1% original lip section chord = 23.3% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P18
Plot of Beta against s/c	= Fig.P58
Plot of Iced aerofoil	= Fig.P78
TRAJ3 equivalent plot	= Fig.P132

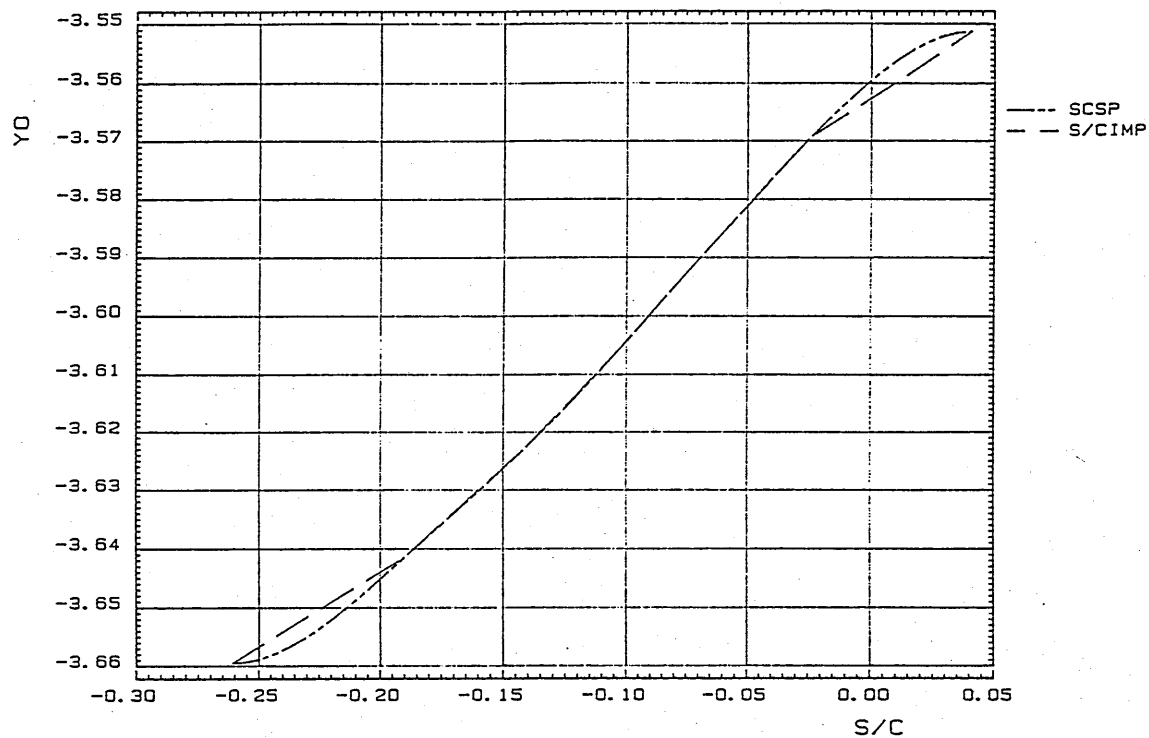


Fig.P37

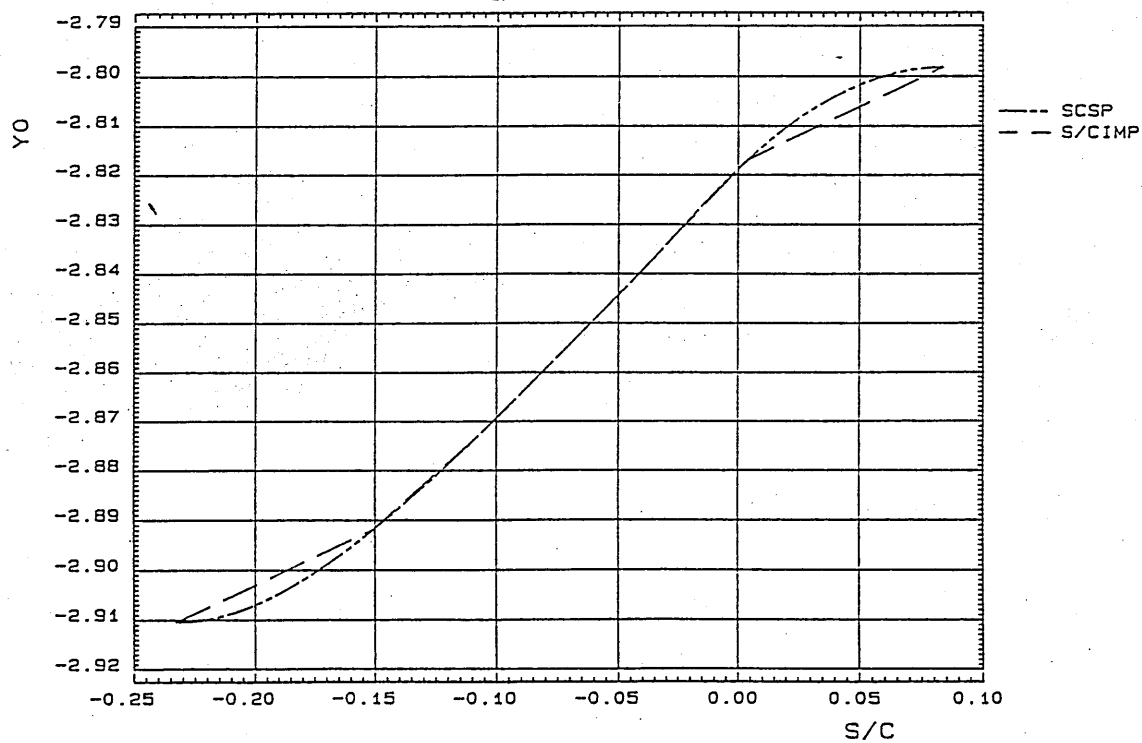


Fig.P38

Fig.P39 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.2
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.354 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.1% developed aerofoil chord = 48.4% original lip section chord = 10.2% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 39.6% original lip section chord = 23.0% s/c = 81 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P19
Plot of Beta against s/c	= Fig.P59
Plot of Iced aerofoil	= Fig.P79
TRAJ3 equivalent plot	= Fig.P133

Fig.P40 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.3
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.396 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.8% developed aerofoil chord = 63.4% original lip section chord = 10.5% s/c = 42 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 44.3% original lip section chord = 17.4% s/c = 69 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P20
Plot of Beta against s/c	= Fig.P60
Plot of Iced aerofoil	= Fig.P80
TRAJ3 equivalent plot	= Fig.P134

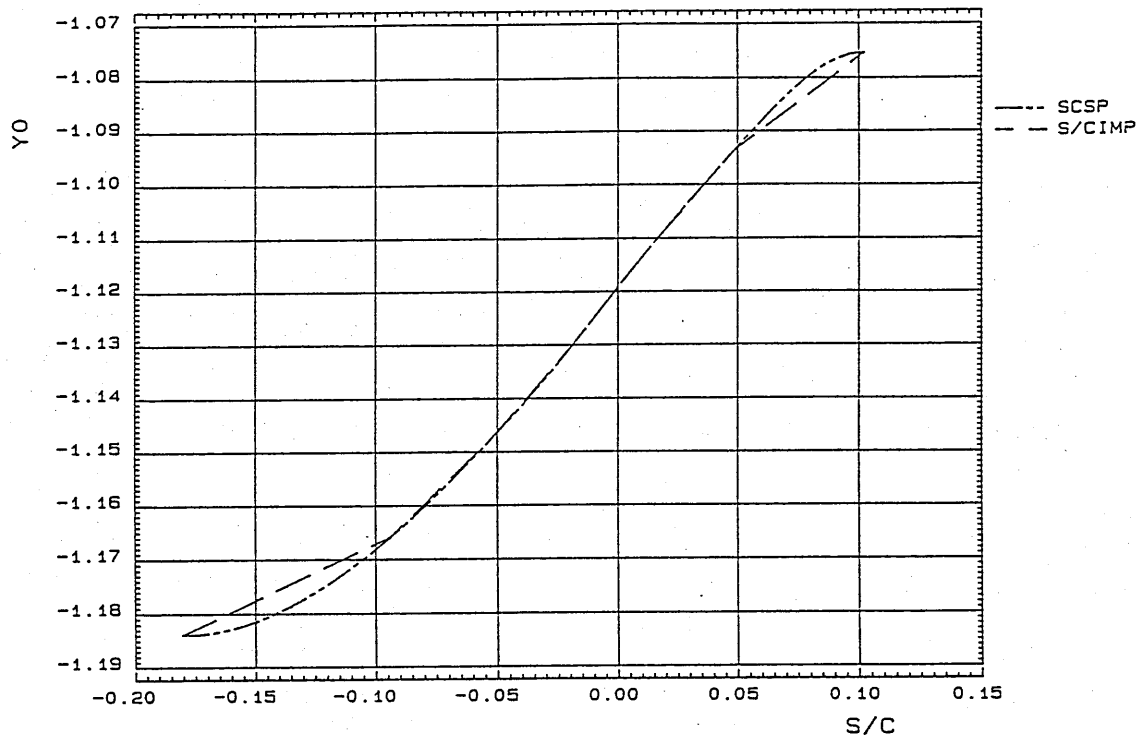


Fig.P39

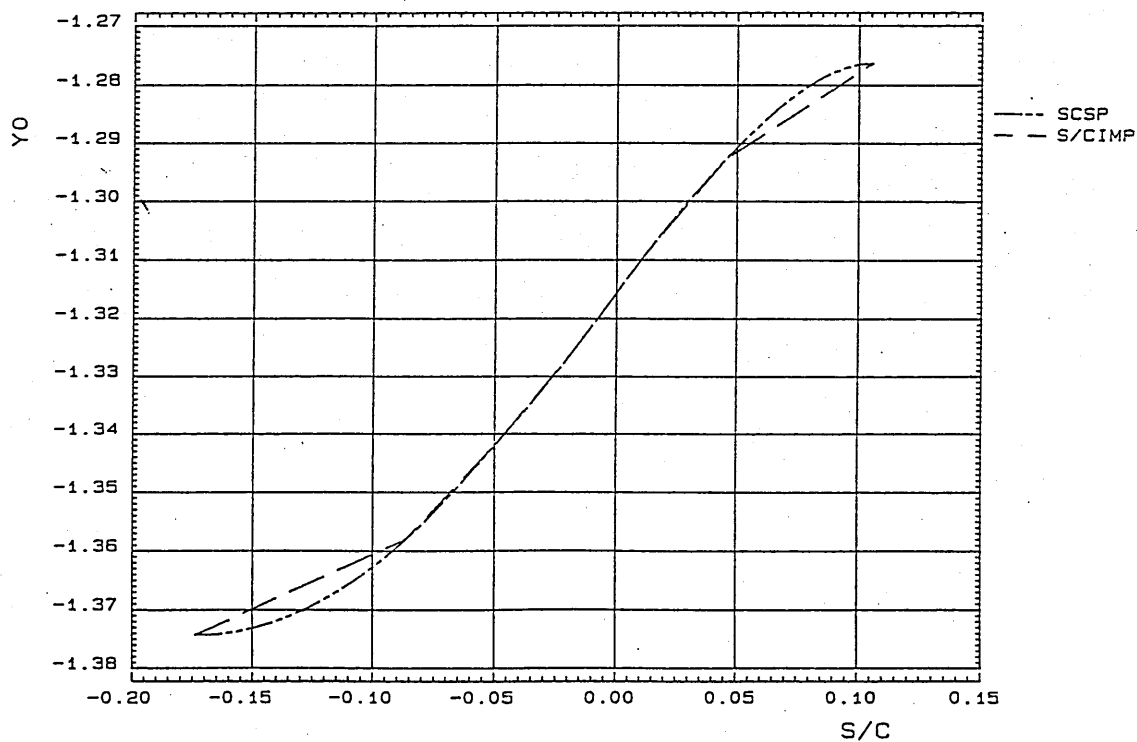


Fig.P40

Fig.P41 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.4
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.442 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 76.6% original lip section chord = 10.8% s/c = 48 mm aft over lip surface
Inner (lower) surface catch limit	= 8.1% developed aerofoil chord = 42.1% original lip section chord = 15.2% s/c = 67 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P21
Plot of Beta against s/c	= Fig.P61
Plot of Iced aerofoil	= Fig.P81
TRAJ3 equivalent plot	= Fig.P135

Fig.P42 (Case14)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.5
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.493 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.8% developed aerofoil chord = 95.3% original lip section chord = 11.0% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 5.1% developed aerofoil chord = 29.6% original lip section chord = 10.9% s/c = 54 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P22
Plot of Beta against s/c	= Fig.P62
Plot of Iced aerofoil	= Fig.P92
TRAJ3 equivalent plot	= Fig.P136

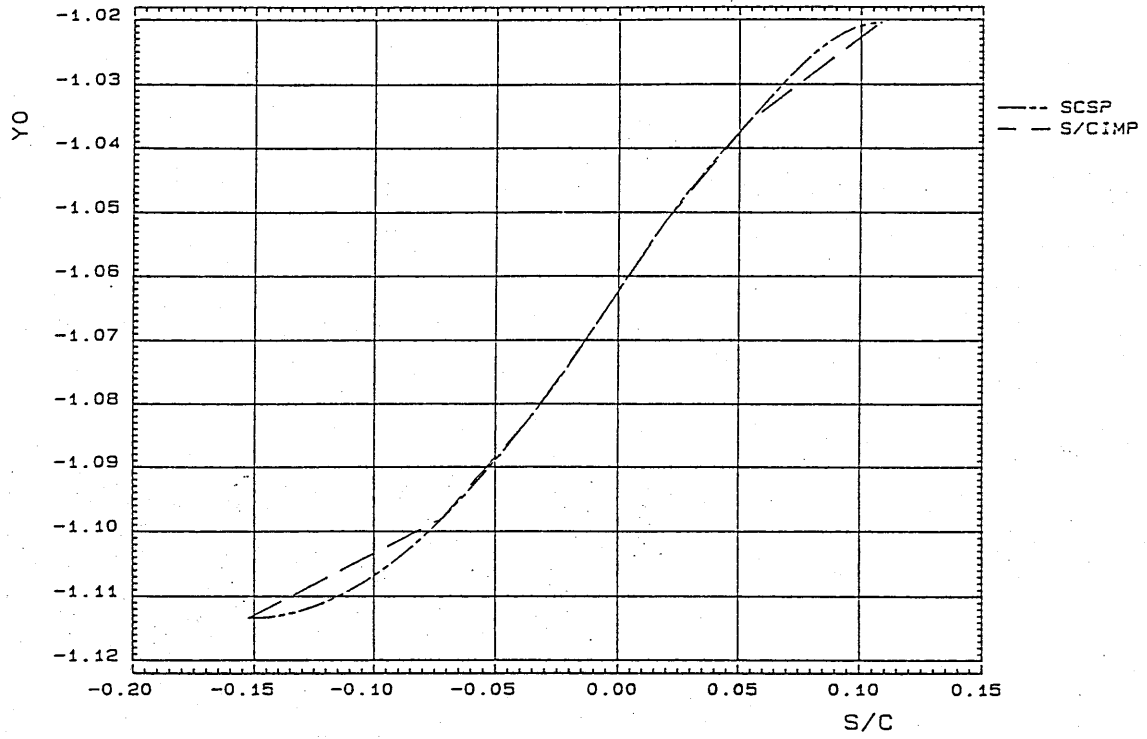


Fig.P41

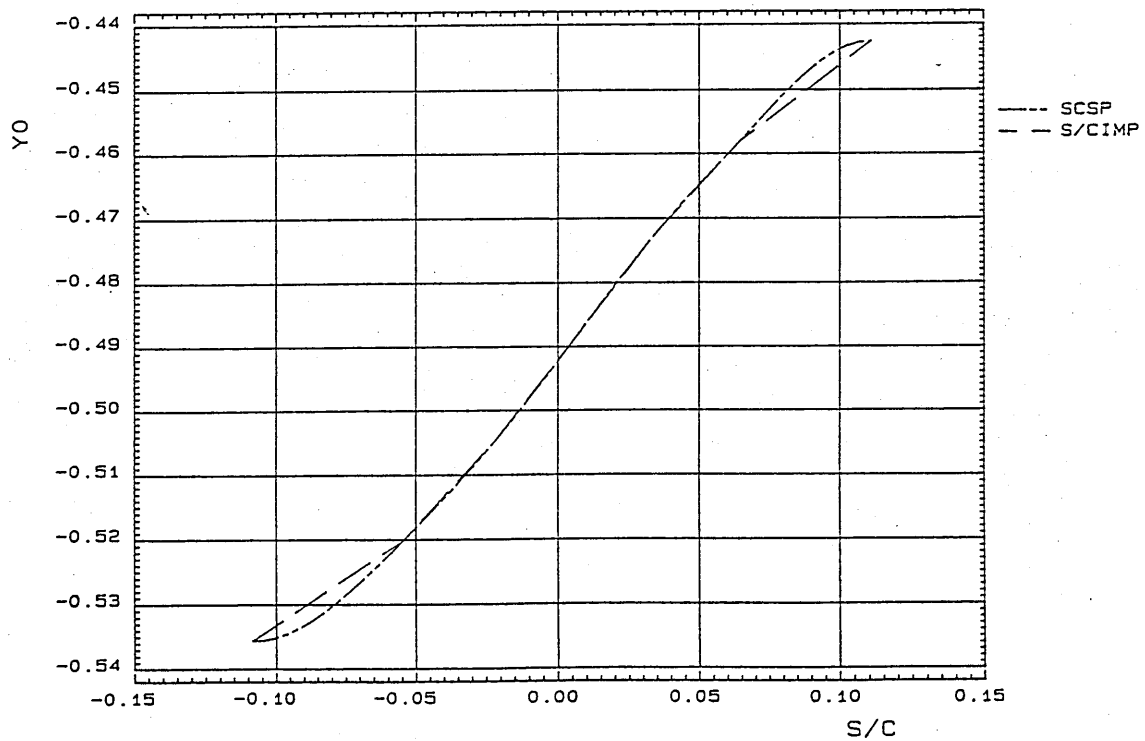


Fig.P42

Fig.P43 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P23
Plot of Beta against s/c	= Fig.P63
Plot of Iced aerofoil	= Fig.P83
TRAJ3 equivalent plot	= Fig.P137

Fig.P44 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.1% developed aerofoil chord = 24.4% original lip section chord = 13.6% s/c = 55 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P24
Plot of Beta against s/c	= Fig.P64
Plot of Iced aerofoil	= Fig.P84
TRAJ3 equivalent plot	= Fig.P138

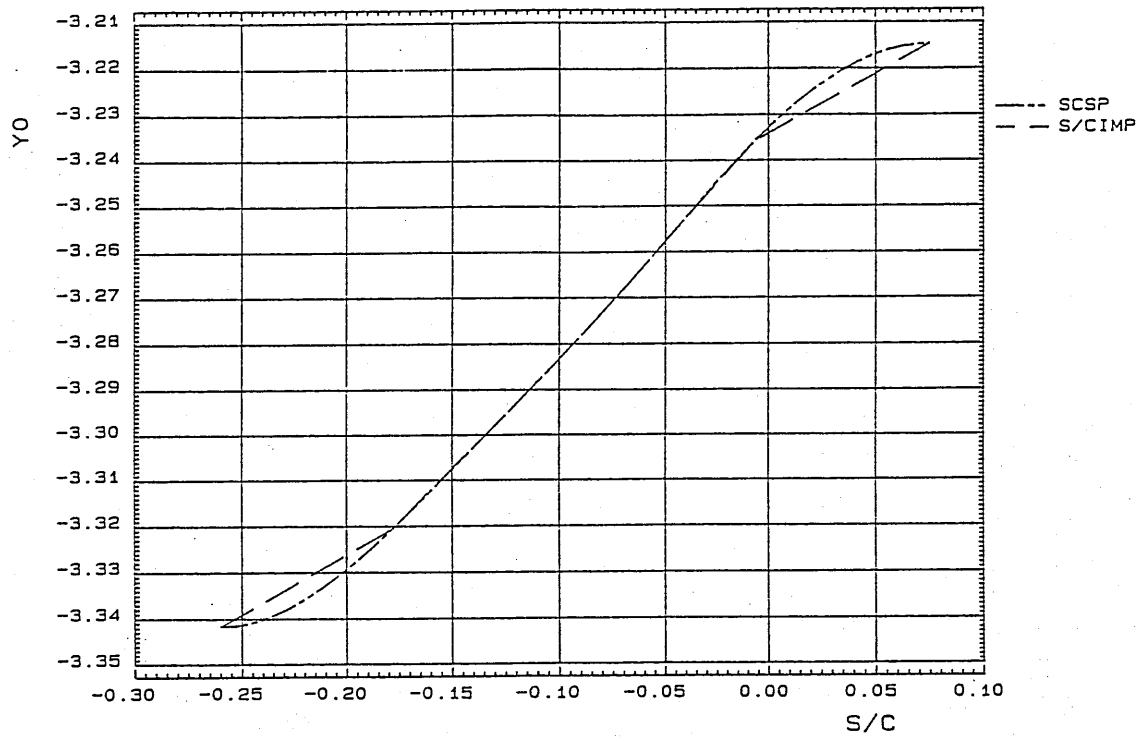


Fig.P43

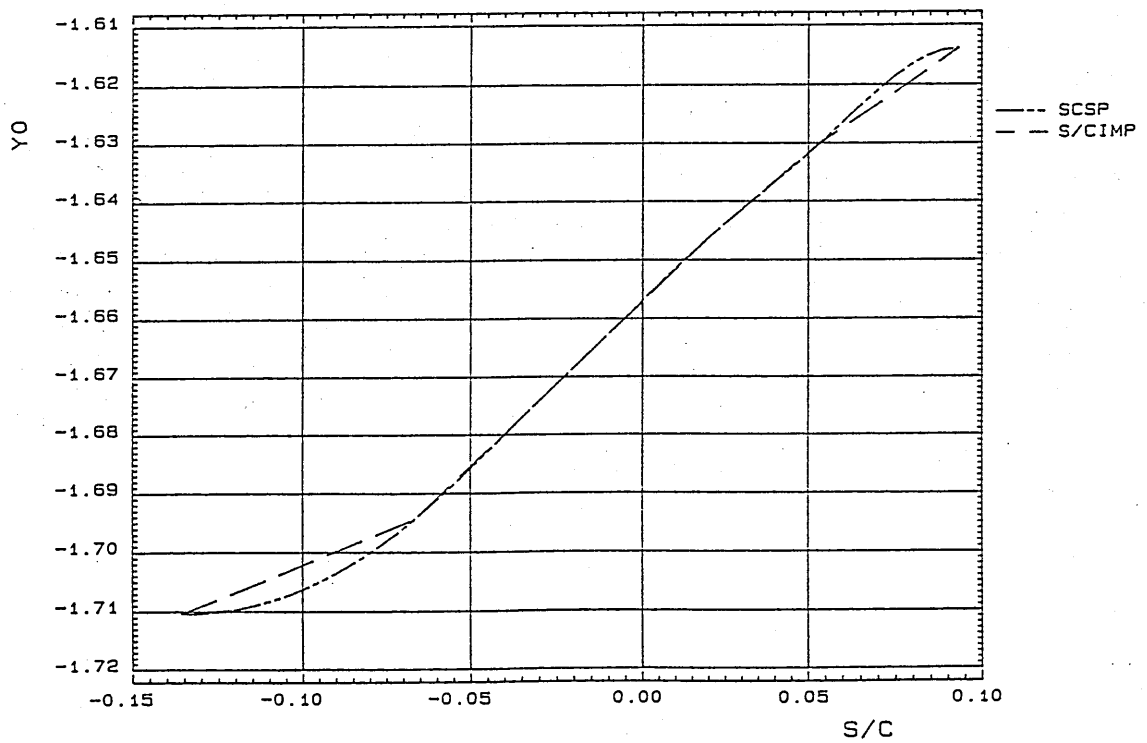


Fig.P44

Fig.P45 (Case 17)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.2% developed aerofoil chord = 22.2% original lip section chord = 13.7% s/c = 46 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P25
Plot of Beta against s/c	= Fig.P65
Plot of Iced aerofoil	= Fig.P85
TRAJ3 equivalent plot	= Fig.P139

Fig.P46 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.9% developed aerofoil chord = 20.1% original lip section chord = 7.5% s/c = 24 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 55.7% original lip section chord = 26.0% s/c = 83 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P26
Plot of Beta against s/c	= Fig.P66
Plot of Iced aerofoil	= Fig.P86
TRAJ3 equivalent plot	= Fig.P140

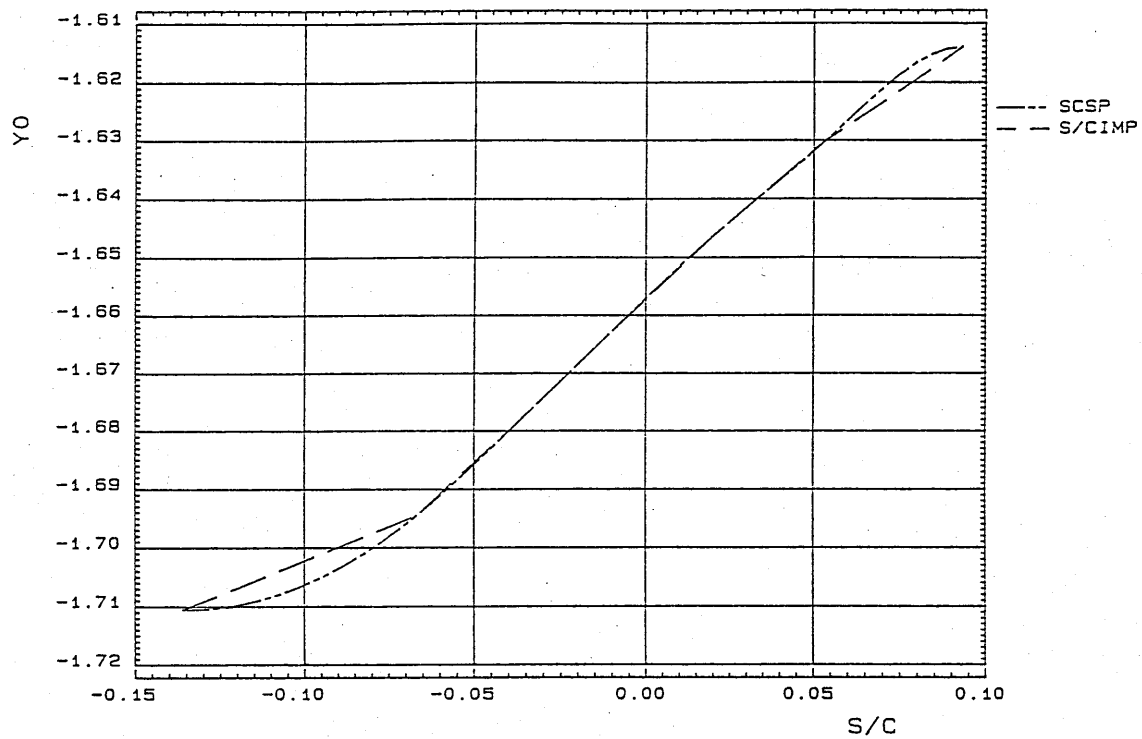


Fig.P45

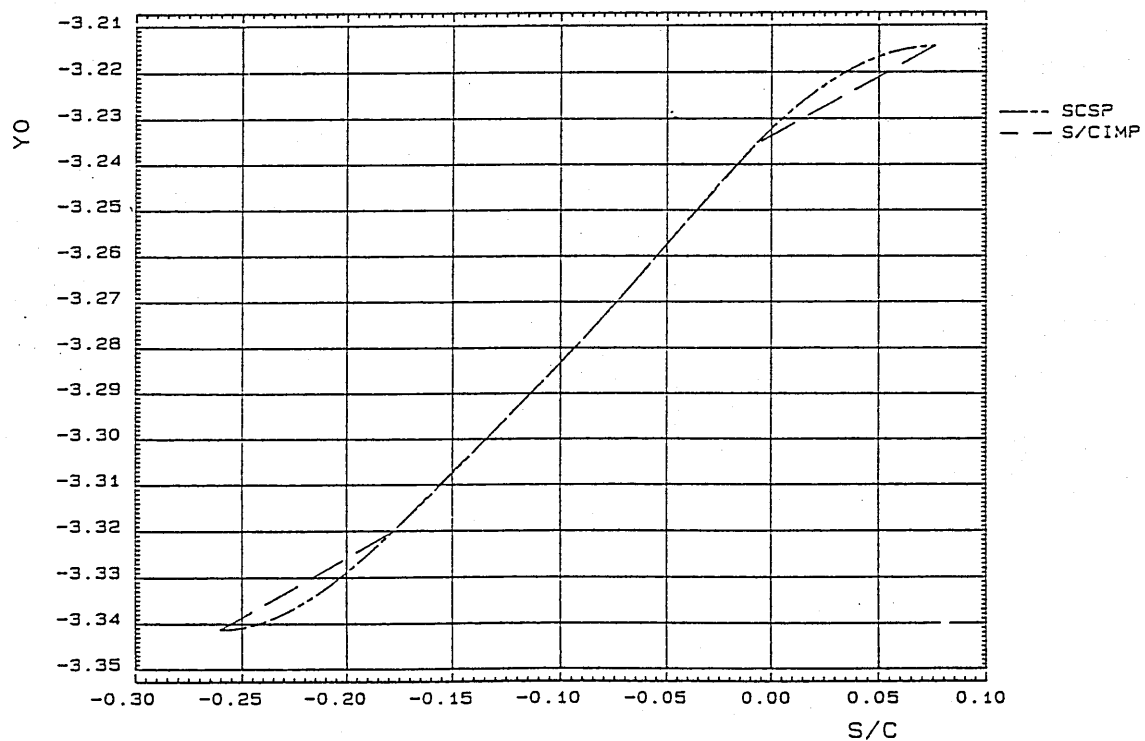


Fig.P46

Fig.P47 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.1% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P27
Plot of Beta against s/c	= Fig.P67
Plot of Iced aerofoil	= Fig.P87
TRAJ3 equivalent plot	= Fig.P141

Fig.P48 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.2% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P28
Plot of Beta against s/c	= Fig.P68
Plot of Iced aerofoil	= Fig.P88
TRAJ3 equivalent plot	= Fig.P142

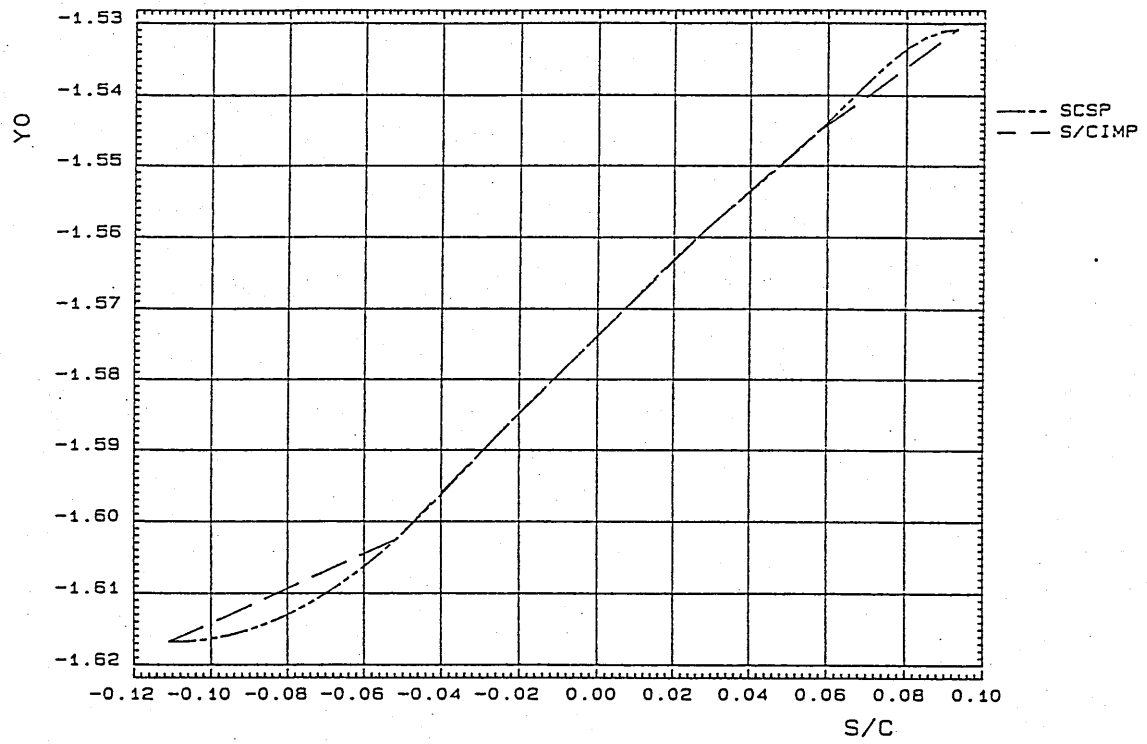


Fig.P47

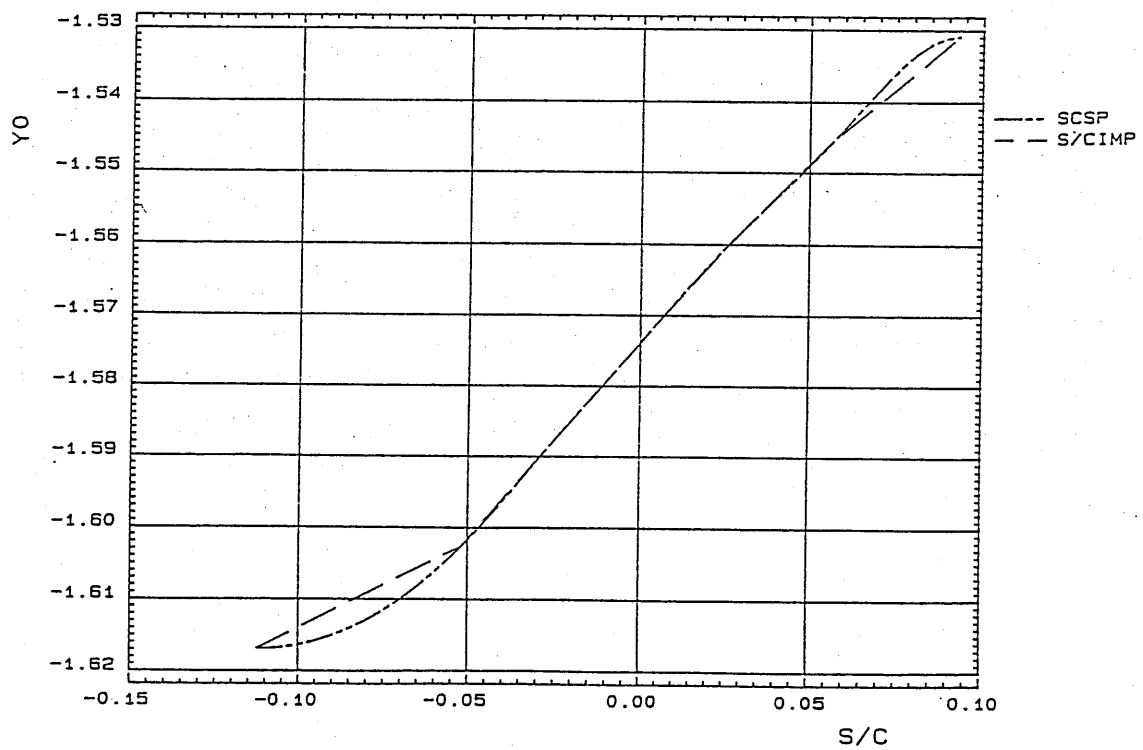


Fig.P48

Fig.P49 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P9
Plot of Scimp and Scsp against s/c	= Fig.P29
Plot of Iced aerofoil	= Fig.P69
TRAJ3 equivalent plot	= Fig.P143

Fig.P50 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.2% developed aerofoil chord = 9.3% original lip section chord = 9.8% s/c = 28 mm aft over lip surface
Inner (lower) surface catch limit	= 12.1% developed aerofoil chord = 40.6% original lip section chord = 22.8% s/c = 65 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P10
Plot of Scimp and Scsp against s/c	= Fig.P30
Plot of Iced aerofoil	= Fig.P70
TRAJ3 equivalent plot	= Fig.P144

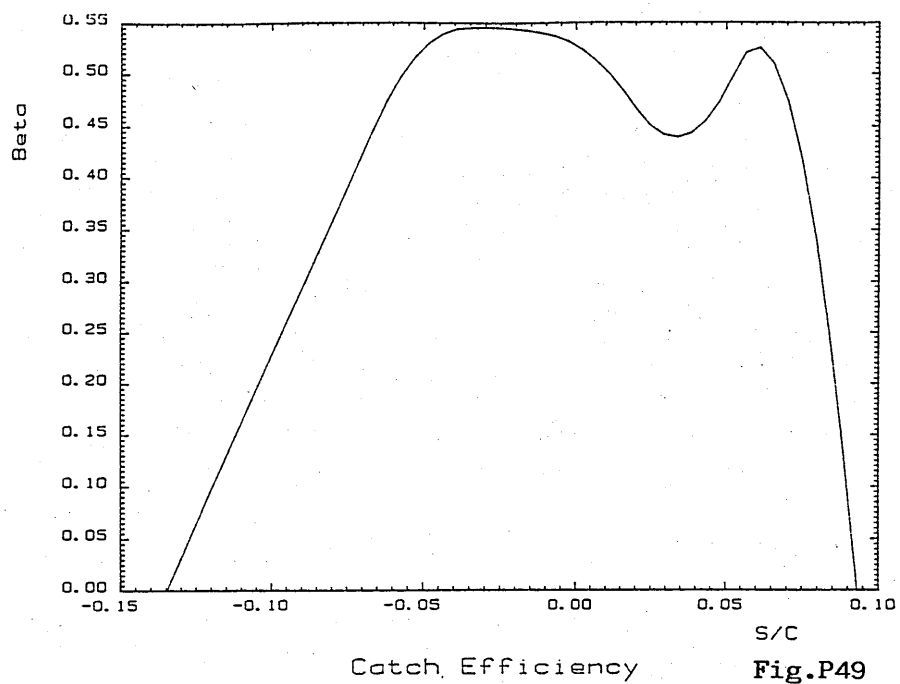
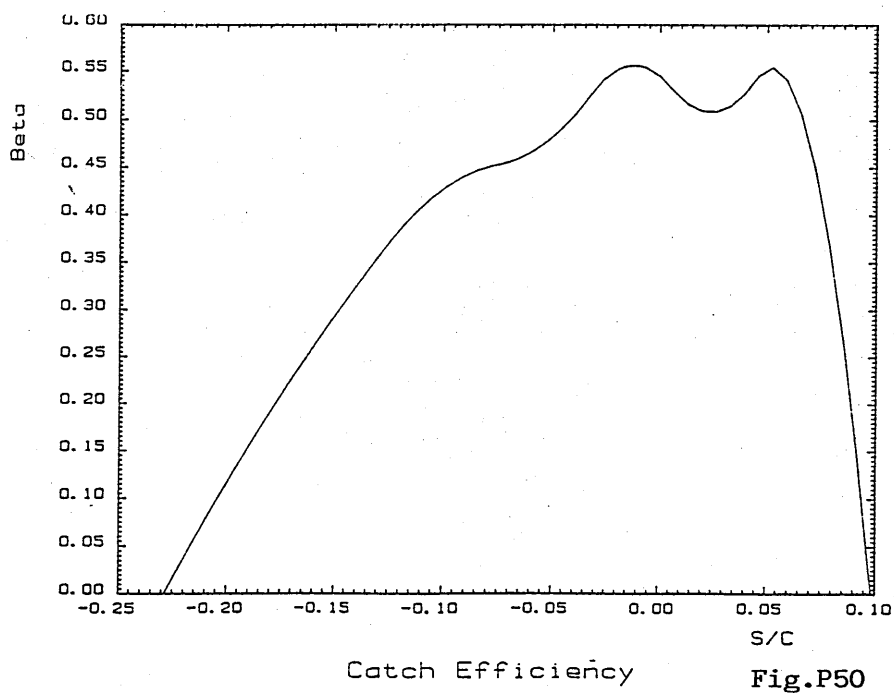


Fig.P51 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.1% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 17.8% developed aerofoil chord = 61.2% original lip section chord = 24.7% s/c = 99 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P11
Plot of Scimp and Scsp against s/c	= Fig.P31
Plot of Iced aerofoil	= Fig.P71
TRAJ3 equivalent plot	= Fig.P145

Fig.P52 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 21.6% original lip section chord = 13.5% s/c = 46 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P12
Plot of Scimp and Scsp against s/c	= Fig.P32
Plot of Iced aerofoil	= Fig.P72
TRAJ3 equivalent plot	= Fig.P146

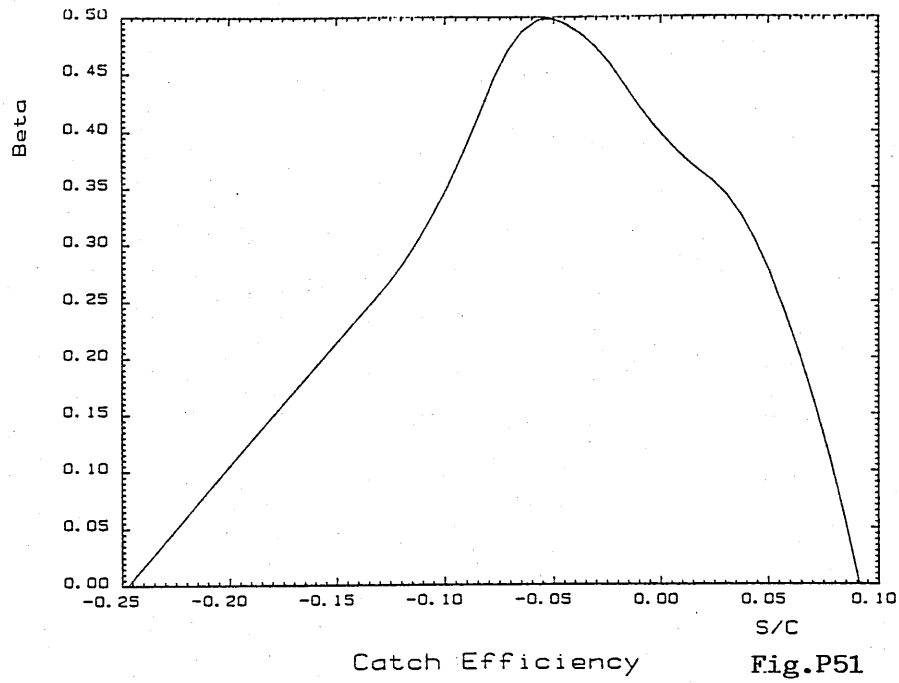
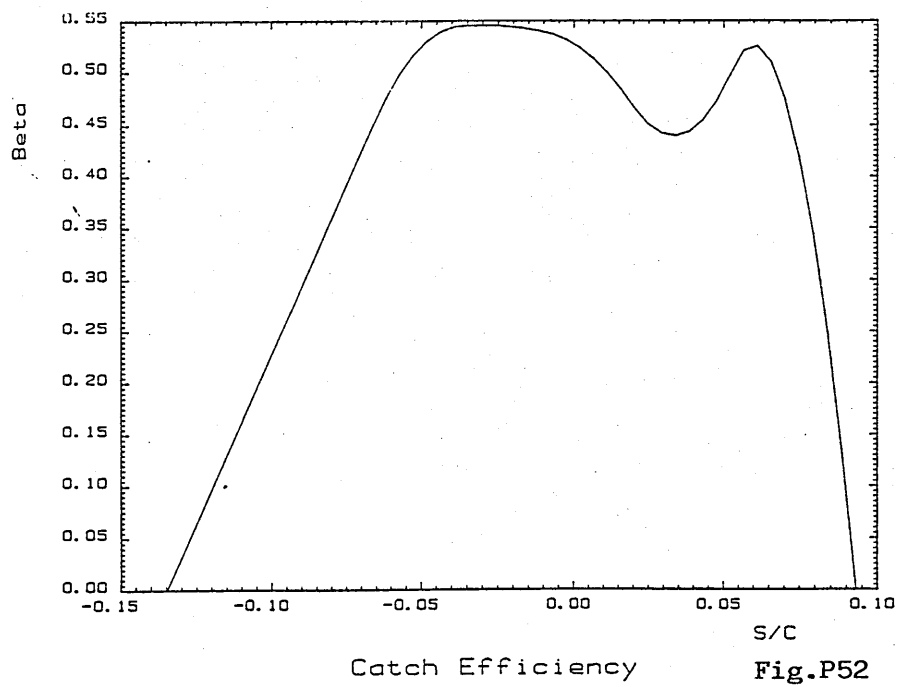


Fig.P53 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 54 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P13
Plot of Scimp and Scsp against s/c	= Fig.P33
Plot of Iced aerofoil	= Fig.P73
TRAJ3 equivalent plot	= Fig.P147

Fig.P54 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P14
Plot of Scimp and Scsp against s/c	= Fig.P34
Plot of Iced aerofoil	= Fig.P74
TRAJ3 equivalent plot	= Fig.P148

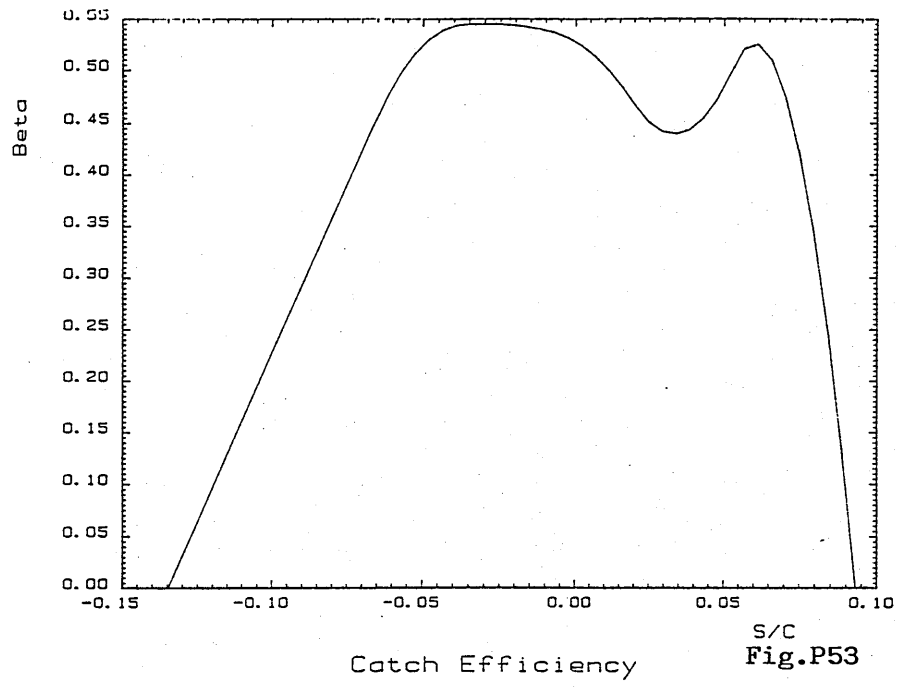
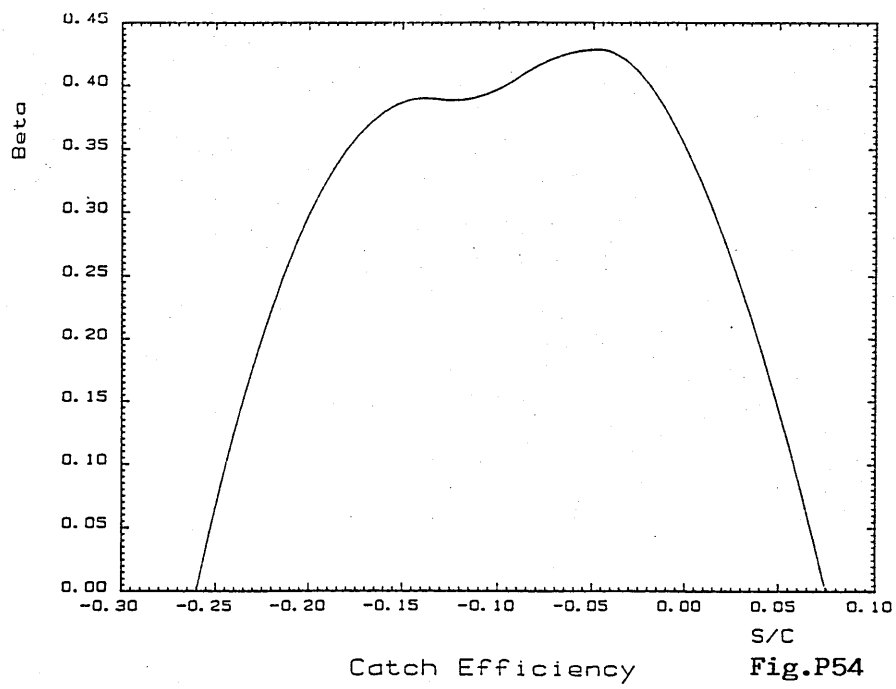


Fig.P55 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 1.4% developed aerofoil chord = 6.5% original lip section chord = 5.5% s/c = 22 mm aft over lip surface
Inner (lower) surface catch limit	= 13.2% developed aerofoil chord = 45.4% original lip section chord = 22.7% s/c = 91 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P15
Plot of Scimp and Scsp against s/c	= Fig.P35
Plot of Iced aerofoil	= Fig.P75
TRAJ3 equivalent plot	= Fig.P149

Fig.P36 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.2% developed aerofoil chord = 23.9% original lip section chord = 5.5% s/c = 19 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 41.3% original lip section chord = 22.7% s/c = 77 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P16
Plot of Beta against s/c	= Fig.P56
Plot of Iced aerofoil	= Fig.P76
TRAJ3 equivalent plot	= Fig.P150

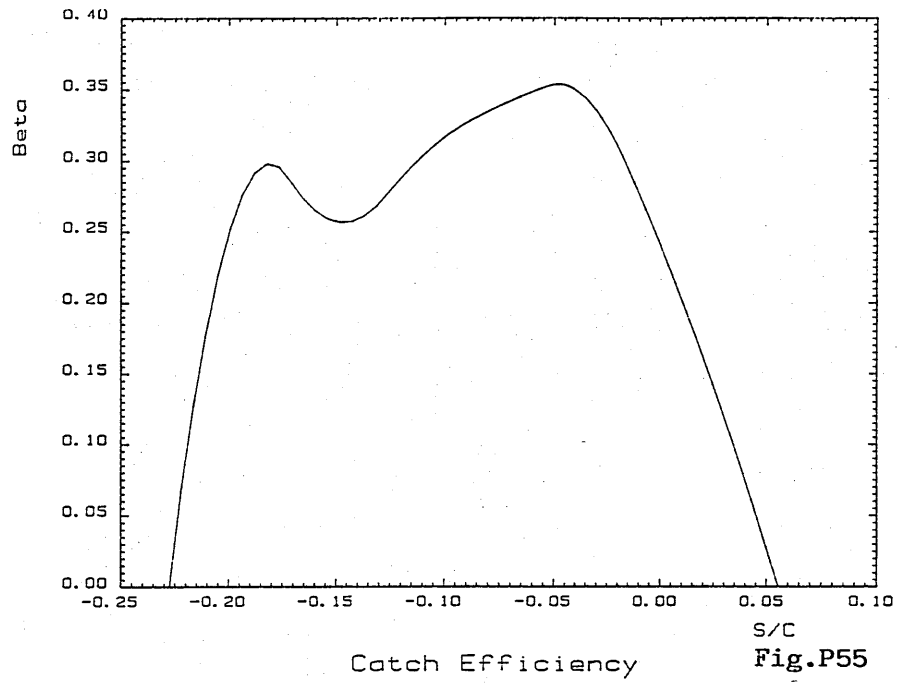
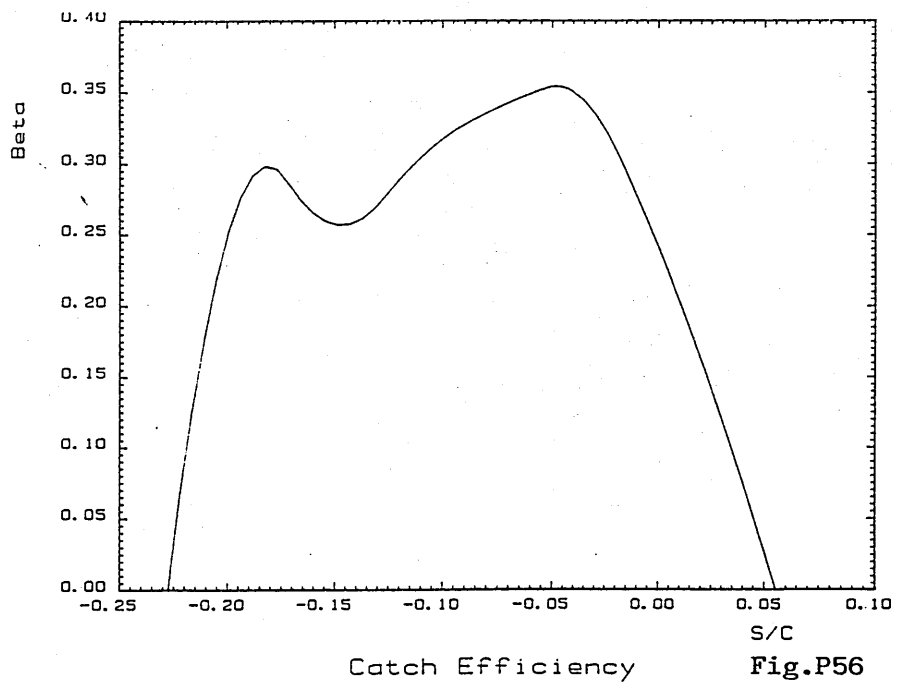


Fig.P57 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 6.7% original lip section chord = 4.0% s/c = 11 mm aft over lip surface
Inner (lower) surface catch limit	= 15.0% developed aerofoil chord = 50.3% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P17
Plot of Scimp and Scsp against s/c	= Fig.P37
Plot of Iced aerofoil	= Fig.P77
TRAJ3 equivalent plot	= Fig.P151

Fig.P58 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.1
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.8% developed aerofoil chord = 29.7% original lip section chord = 8.3% s/c = 26 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 50.1% original lip section chord = 23.3% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P18
Plot of Scimp and Scsp against s/c	= Fig.P38
Plot of Iced aerofoil	= Fig.P78
TRAJ3 equivalent plot	= Fig.P152

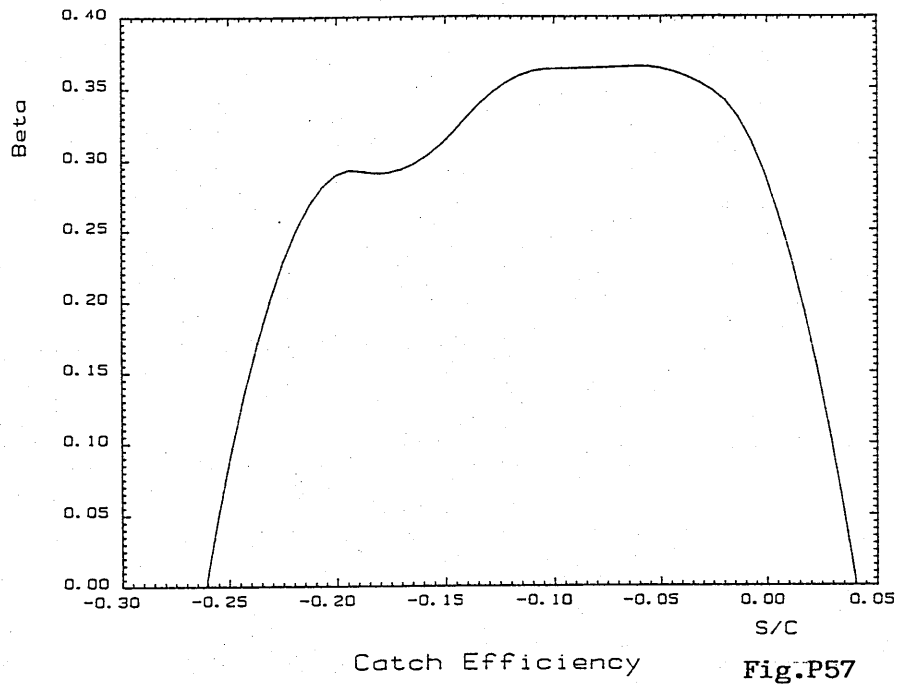
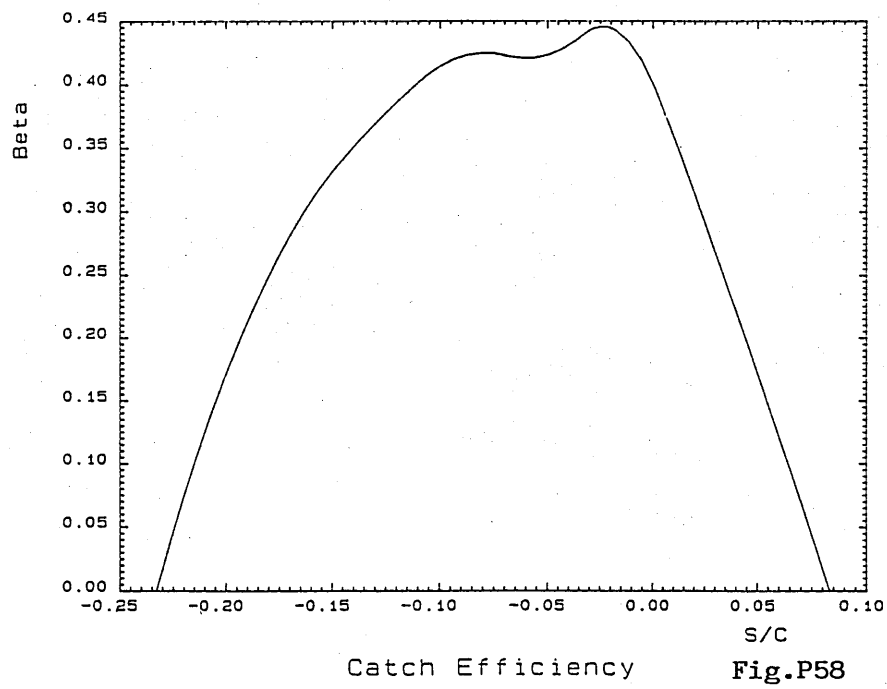


Fig.P59 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.2
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.354 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.1% developed aerofoil chord = 48.4% original lip section chord = 10.2% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 39.6% original lip section chord = 23.0% s/c = 81 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P19
Plot of Scimp and Scsp against s/c	= Fig.P39
Plot of Iced aerofoil	= Fig.P79
TRAJ3 equivalent plot	= Fig.P153

Fig.P60 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.3
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.396 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.8% developed aerofoil chord = 63.4% original lip section chord = 10.5% s/c = 42 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 44.3% original lip section chord = 17.4% s/c = 69 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P20
Plot of Scimp and Scsp against s/c	= Fig.P40
Plot of Iced aerofoil	= Fig.P80
TRAJ3 equivalent plot	= Fig.P154

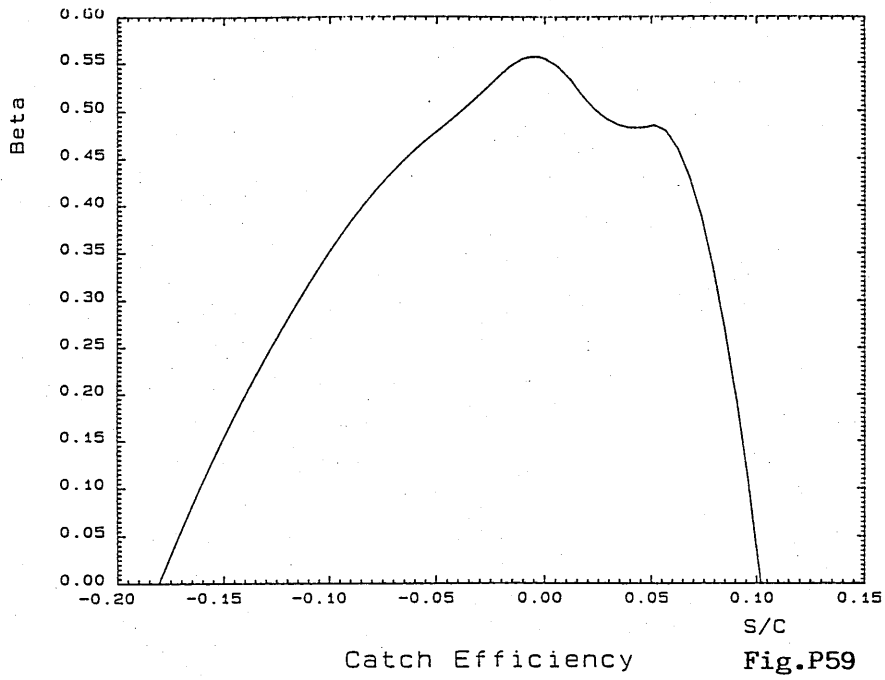
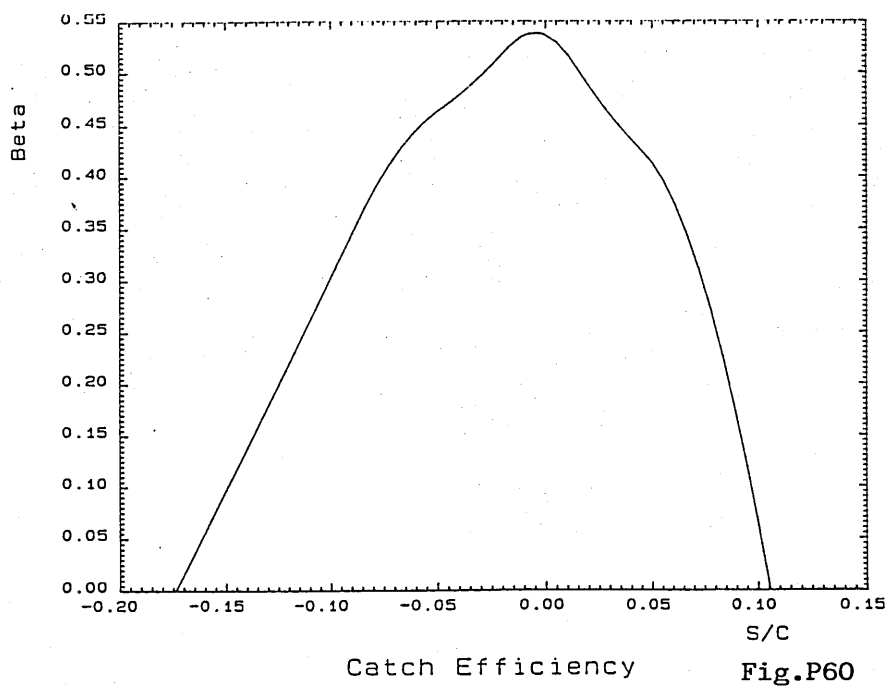


Fig.P61 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.4
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.442 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 76.6% original lip section chord = 10.8% s/c = 48 mm aft over lip surface
Inner (lower) surface catch limit	= 8.1% developed aerofoil chord = 42.1% original lip section chord = 15.2% s/c = 67 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P21
Plot of Scimp and Scsp against s/c	= Fig.P41
Plot of Iced aerofoil	= Fig.P81
TRAJ3 equivalent plot	= Fig.P155

Fig.P62 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.5
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.493 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.8% developed aerofoil chord = 95.3% original lip section chord = 11.0% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 5.1% developed aerofoil chord = 29.6% original lip section chord = 10.9% s/c = 54 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P22
Plot of Scimp and Scsp against s/c	= Fig.P42
Plot of Iced aerofoil	= Fig.P92
TRAJ3 equivalent plot	= Fig.P156

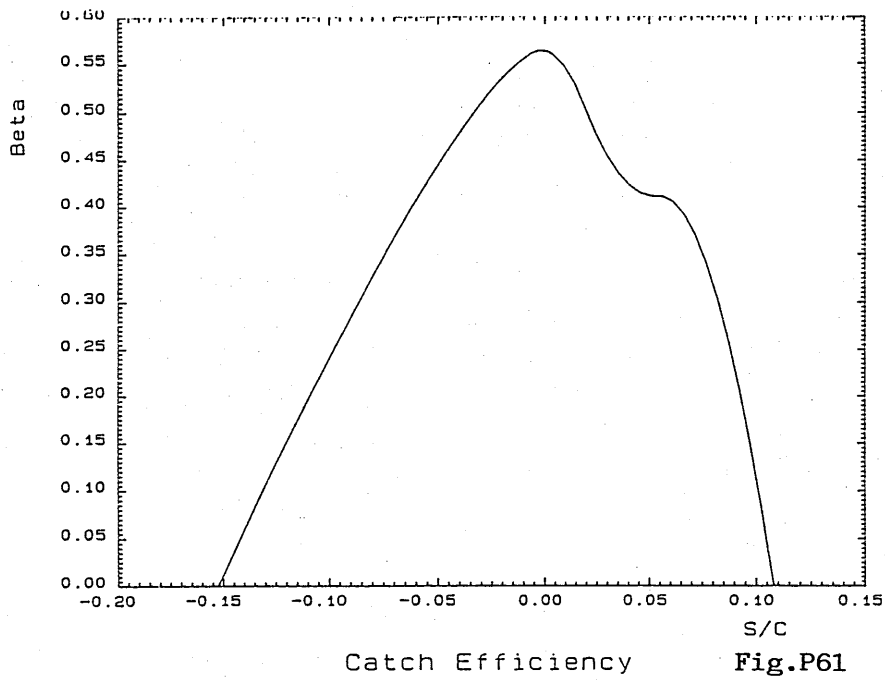
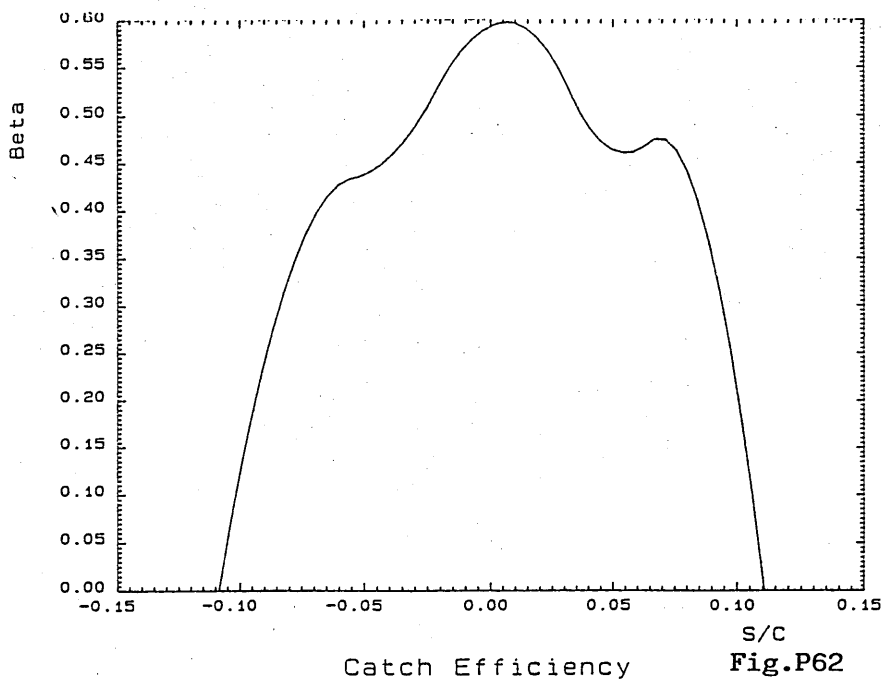


Fig.P63 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P23
Plot of Scimp and Scsp against s/c	= Fig.P43
Plot of Iced aerofoil	= Fig.P83
TRAJ3 equivalent plot	= Fig.P157

Fig.P64 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.1% developed aerofoil chord = 24.4% original lip section chord = 13.6% s/c = 55 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P24
Plot of Scimp and Scsp against s/c	= Fig.P44
Plot of Iced aerofoil	= Fig.P84
TRAJ3 equivalent plot	= Fig.P158

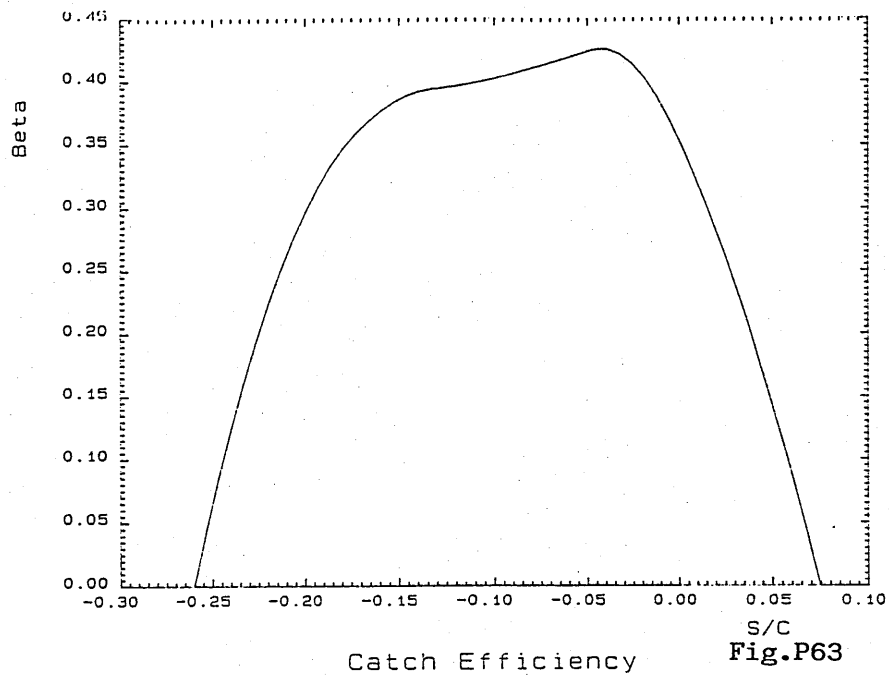
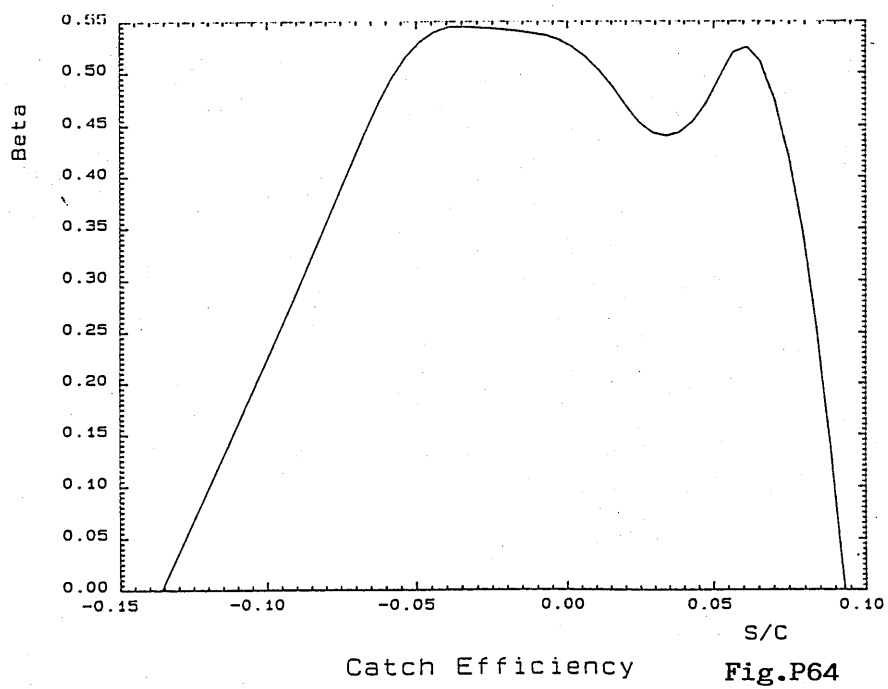


Fig.P65 (case 17)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.2% developed aerofoil chord = 22.2% original lip section chord = 13.7% s/c = 46 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P25
Plot of Scimp and Scsp against s/c	= Fig.P45
Plot of Iced aerofoil	= Fig.P85
TRAJ3 equivalent plot	= Fig.P159

Fig.P66 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.9% developed aerofoil chord = 20.1% original lip section chord = 7.5% s/c = 24 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 55.7% original lip section chord = 26.0% s/c = 83 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P26
Plot of Scimp and Scsp against s/c	= Fig.P46
Plot of Iced aerofoil	= Fig.P86
TRAJ3 equivalent plot	= Fig.P160

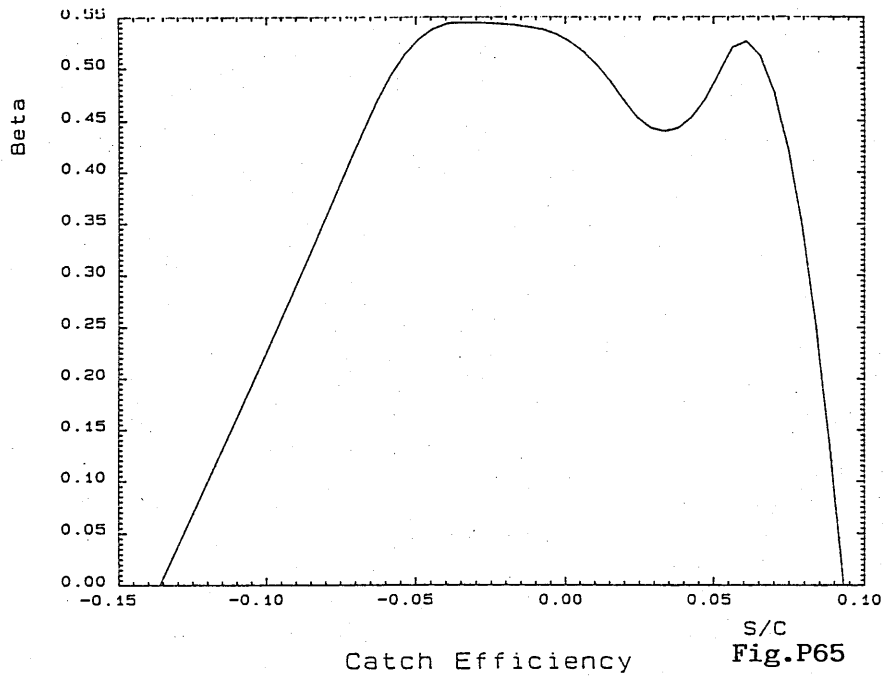
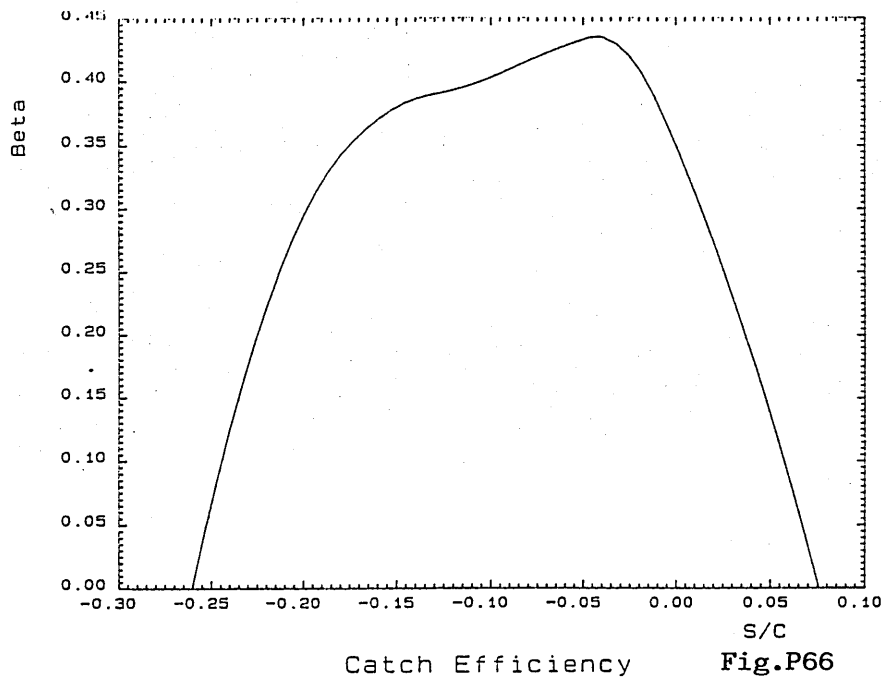


Fig.P67 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.1% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P27
Plot of Scimp and Scsp against s/c	= Fig.P47
Plot of Iced aerofoil	= Fig.P87
TRAJ3 equivalent plot	= Fig.P161

Fig.P68 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.2% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P28
Plot of Scimp and Scsp against s/c	= Fig.P48
Plot of Iced aerofoil	= Fig.P88
TRAJ3 equivalent plot	= Fig.P162

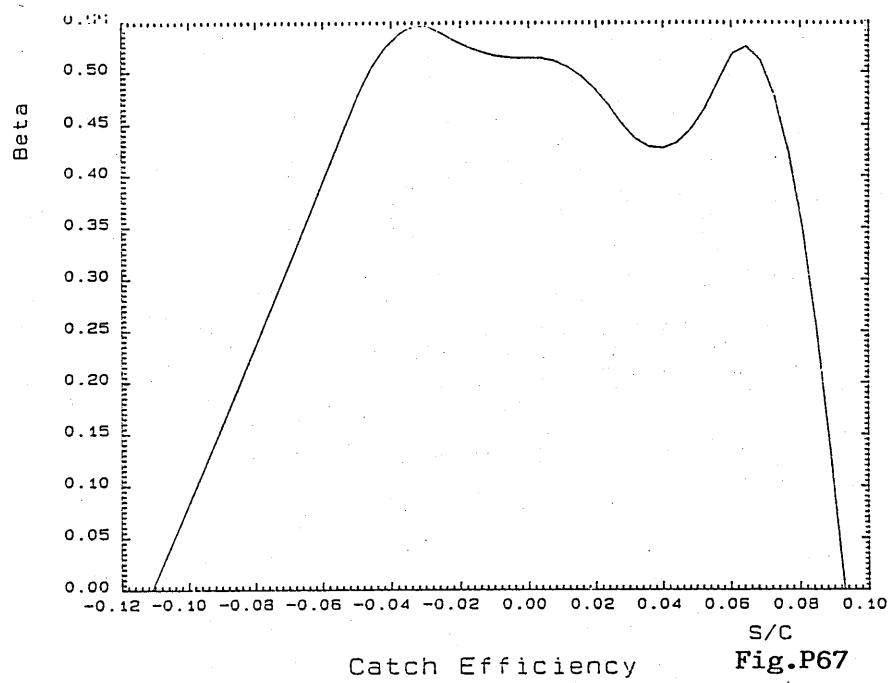
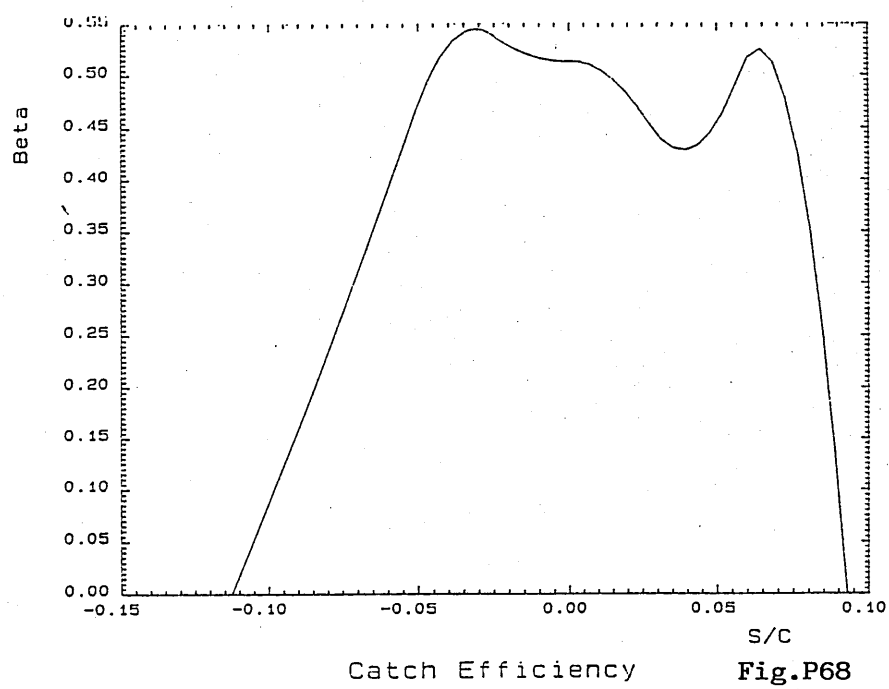
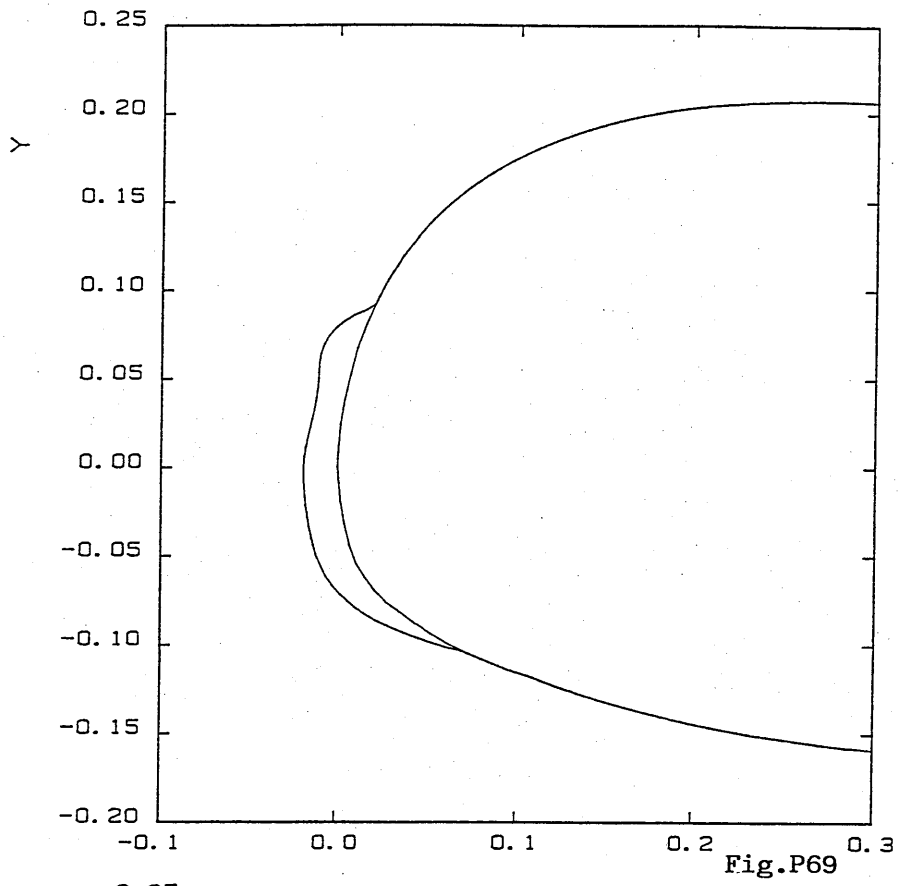
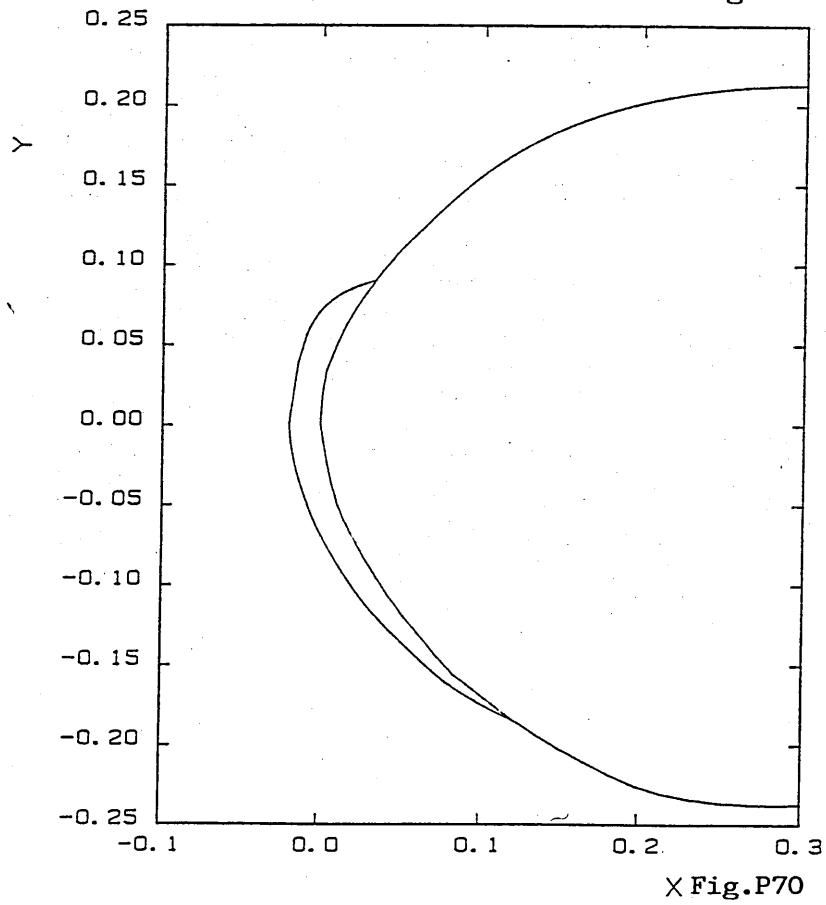


Fig.P69 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 μm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P9
Plot of Scimp and Scsp against s/c	= Fig.P29
Plot of Beta against s/c	= Fig.P49
TRAJ3 equivalent plot	= Fig.P163

Fig.P70 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 μm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.2% developed aerofoil chord = 9.3% original lip section chord = 9.8% s/c = 28 mm aft over lip surface
Inner (lower) surface catch limit	= 12.1% developed aerofoil chord = 40.6% original lip section chord = 22.8% s/c = 65 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P10
Plot of Scimp and Scsp against s/c	= Fig.P30
Plot of Beta against s/c	= Fig.P50
TRAJ3 equivalent plot	= Fig.P164



Ice Shape

Fig.P71 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.1% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 17.8% developed aerofoil chord = 61.2% original lip section chord = 24.7% s/c = 99 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P11
Plot of Scimp and Scsp against s/c	= Fig.P31
Plot of Beta against s/c	= Fig.P51
TRAJ3 equivalent plot	= Fig.P165

Fig.P72 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 21.6% original lip section chord = 13.5% s/c = 46 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P12
Plot of Scimp and Scsp against s/c	= Fig.P32
Plot of Beta against s/c	= Fig.P52
TRAJ3 equivalent plot	= Fig.P166

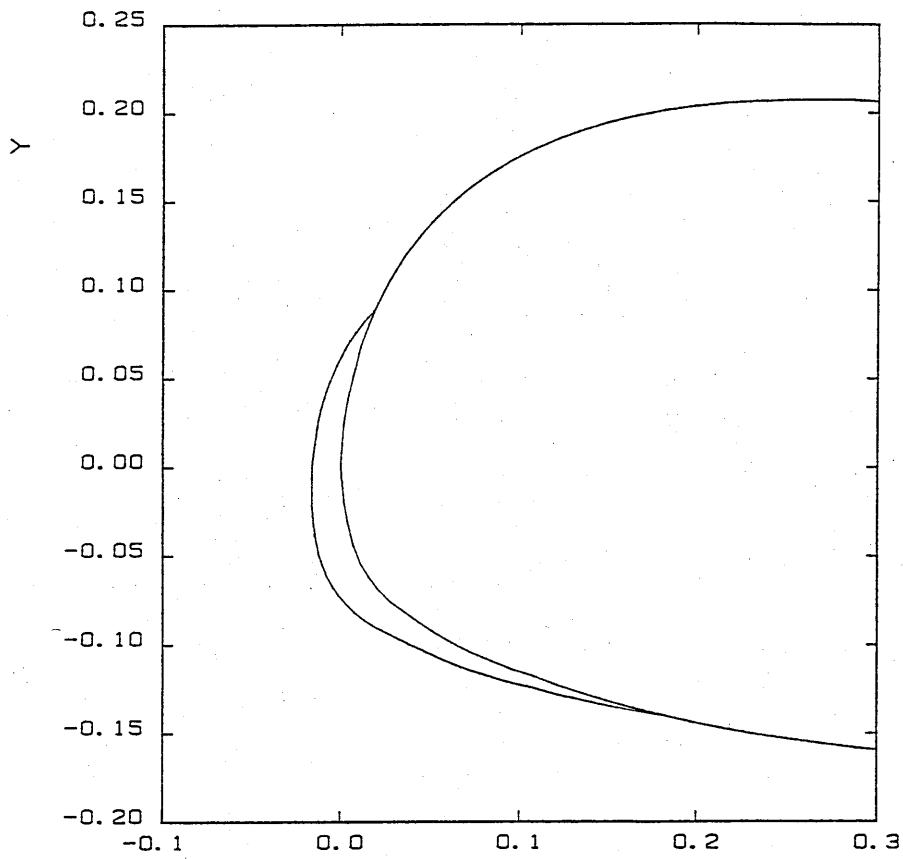
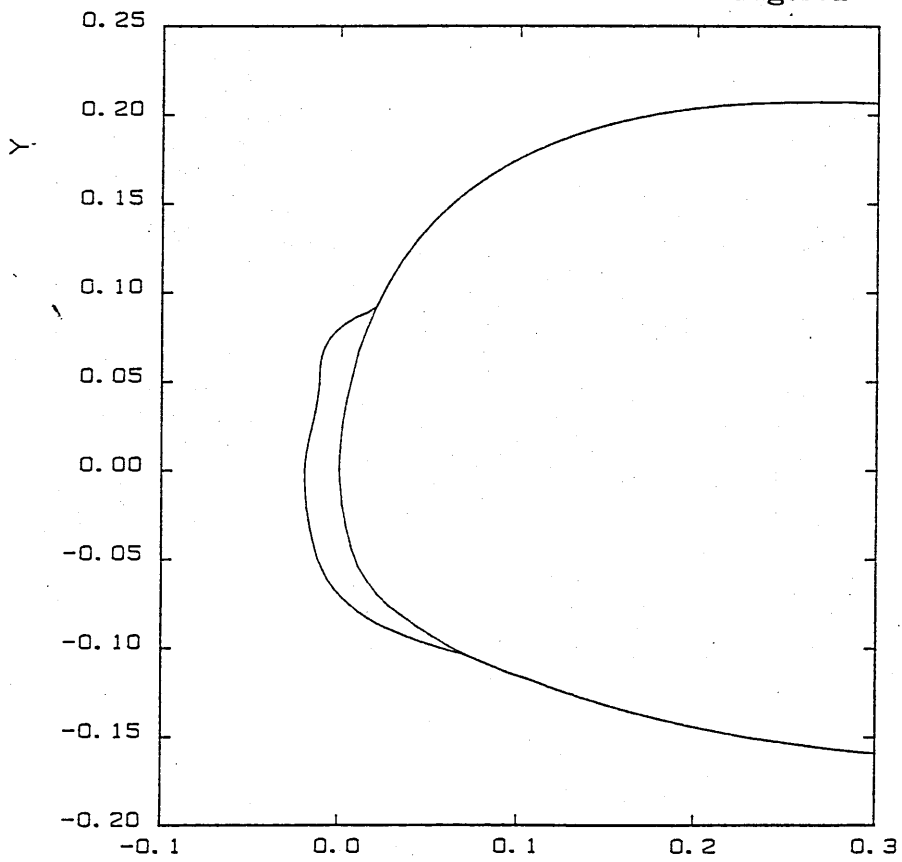


Fig.P71



X Fig.P72

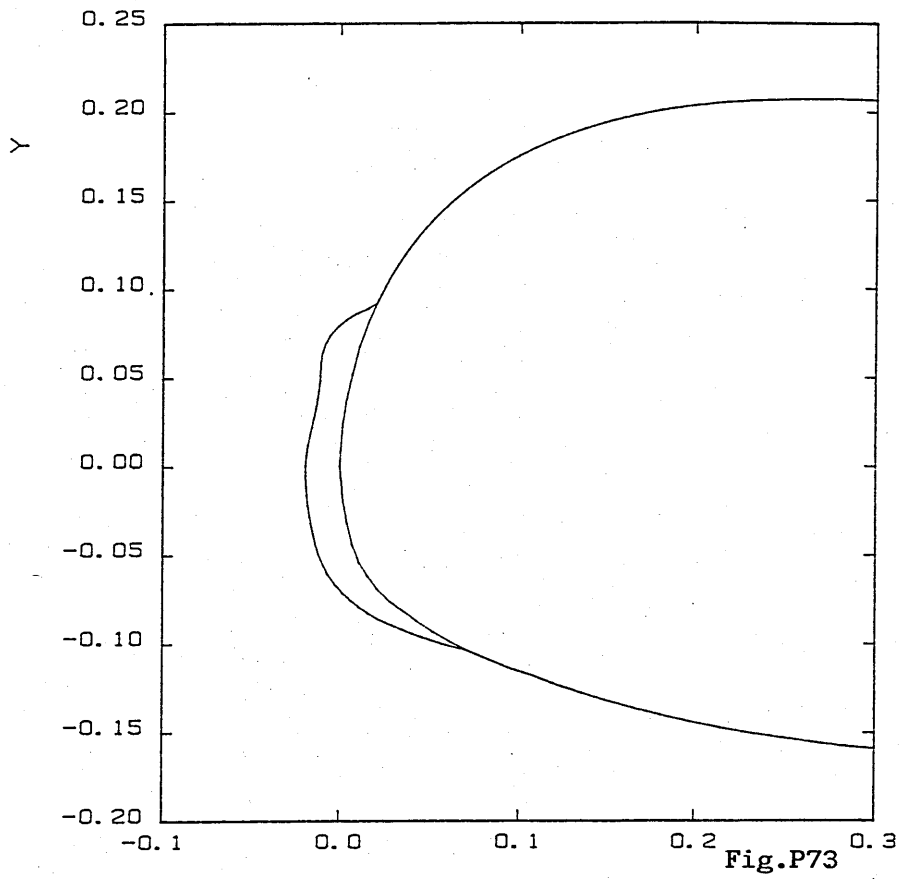
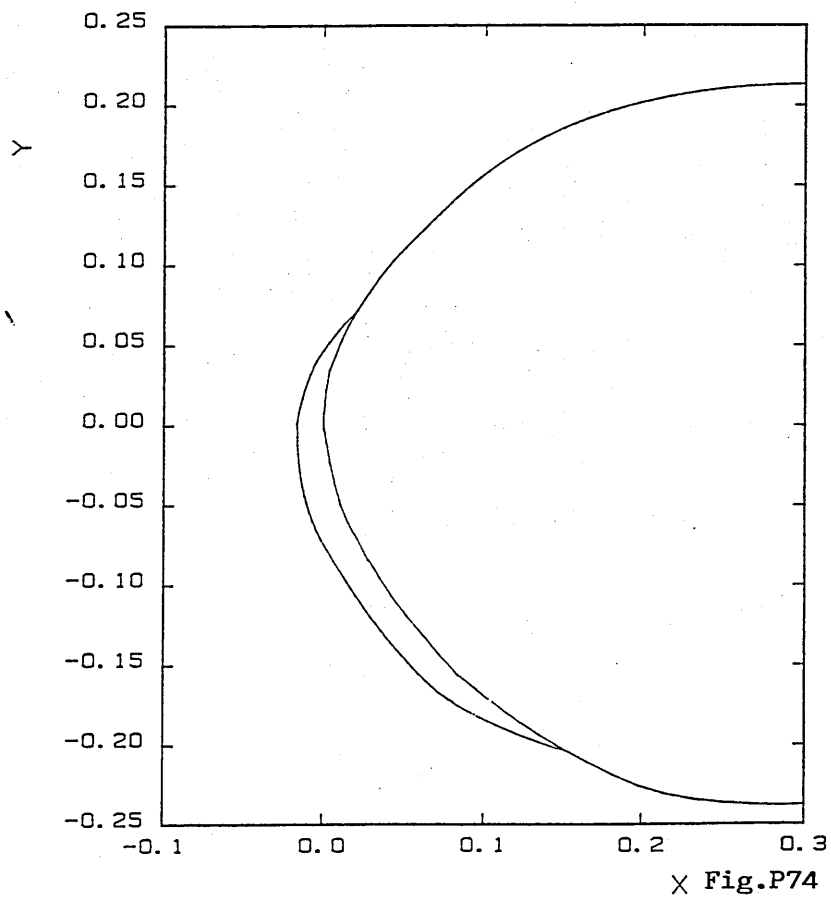
Ice Shape

Fig.P73 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.0% developed aerofoil chord = 24.1% original lip section chord = 13.5% s/c = 54 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P13
Plot of Scimp and Scsp against s/c	= Fig.P33
Plot of Beta against s/c	= Fig.P53
TRAJ3 equivalent plot	= Fig.P167

Fig.P74 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P14
Plot of Scimp and Scsp against s/c	= Fig.P34
Plot of Beta against s/c	= Fig.P54
TRAJ3 equivalent plot	= Fig.P168



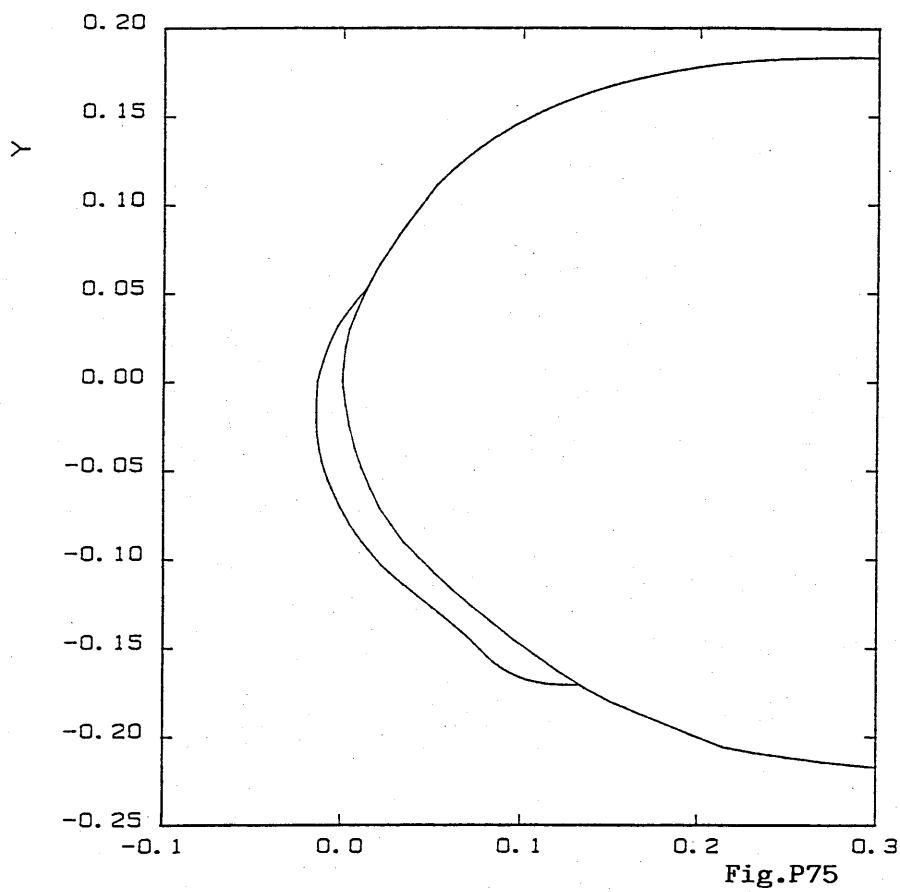
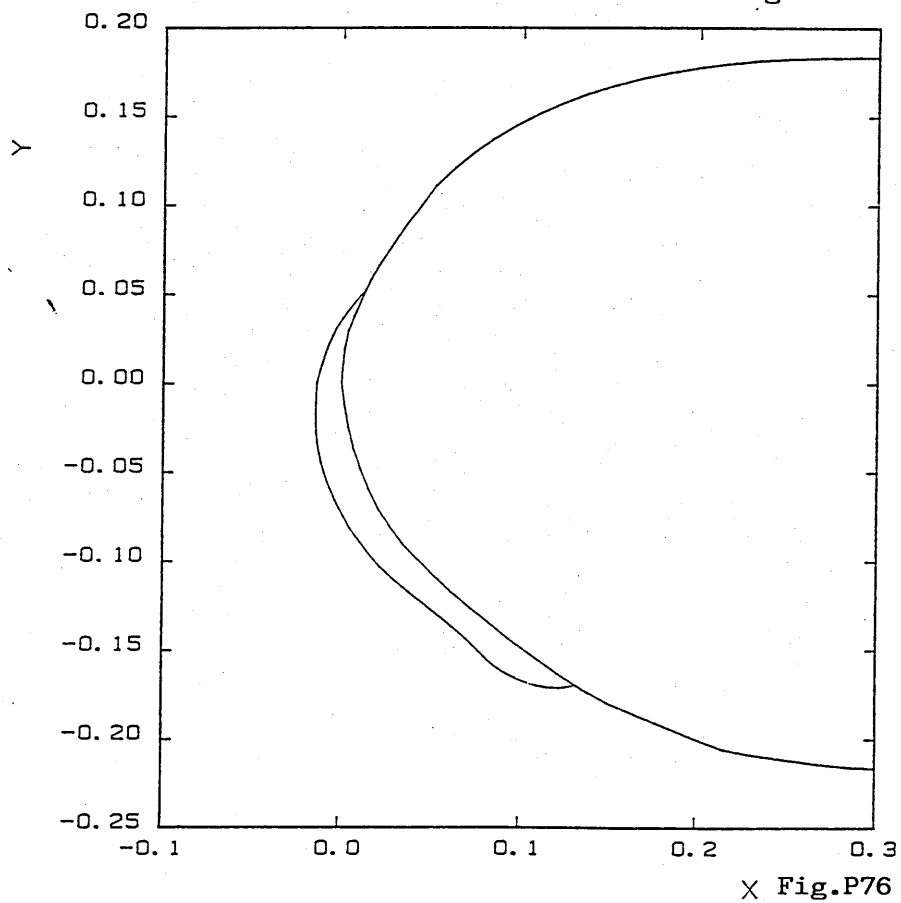
Ice Shape

Fig.P75 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 1.4% developed aerofoil chord = 6.5% original lip section chord = 5.5% s/c = 22 mm aft over lip surface
Inner (lower) surface catch limit	= 13.2% developed aerofoil chord = 45.4% original lip section chord = 22.7% s/c = 91 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P15
Plot of Scimp and Scsp against s/c	= Fig.P35
Plot of Beta against s/c	= Fig.P55
TRAJ3 equivalent plot	= Fig.P169

Fig.P76 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.2% developed aerofoil chord = 23.9% original lip section chord = 5.5% s/c = 19 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 41.3% original lip section chord = 22.7% s/c = 77 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P16
Plot of Scimp and Scsp against s/c	= Fig.P36
Plot of Beta against s/c	= Fig.P56
TRAJ3 equivalent plot	= Fig.P170



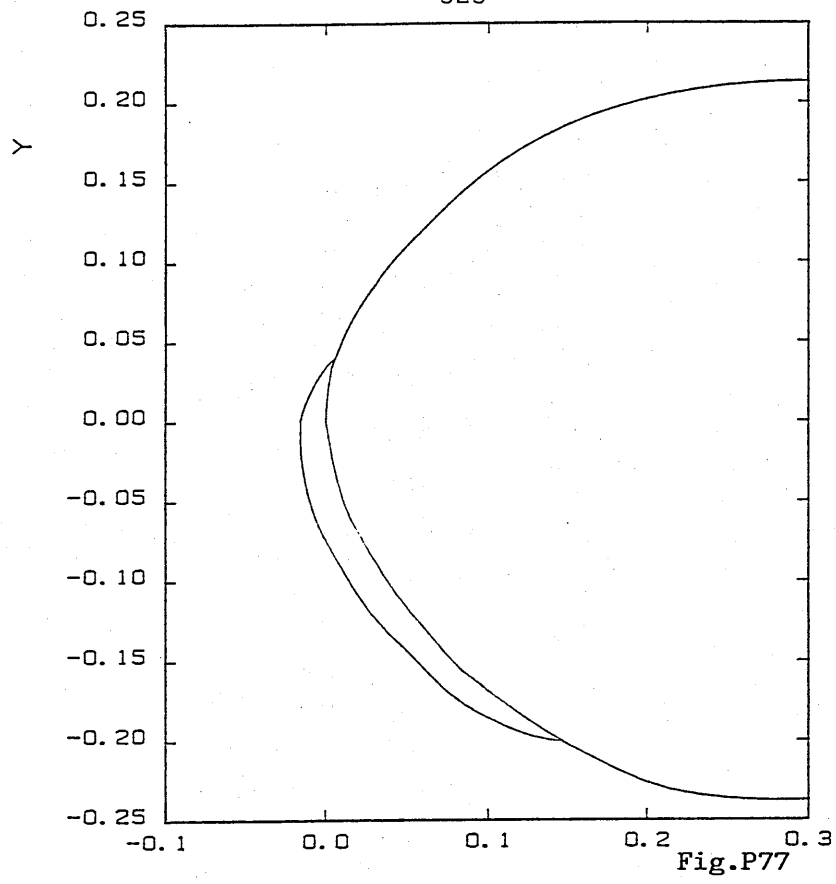
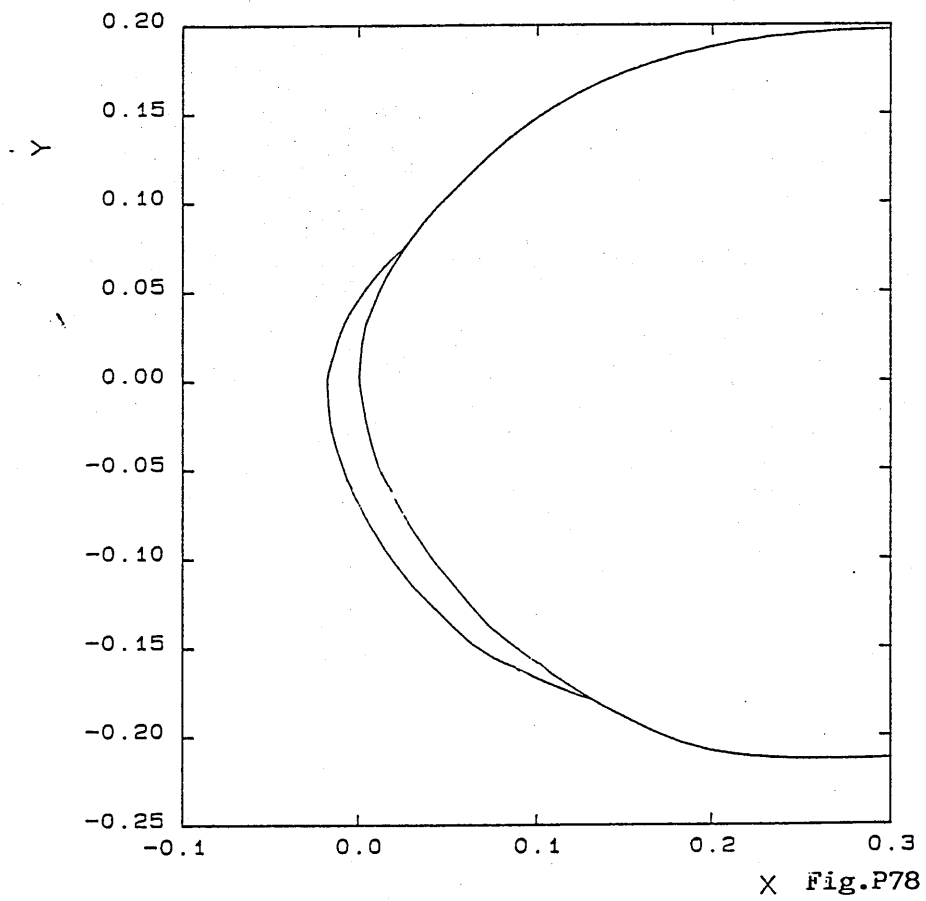
Ice Shape

Fig.P77 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 6.7% original lip section chord = 4.0% s/c = 11 mm aft over lip surface
Inner (lower) surface catch limit	= 15.0% developed aerofoil chord = 50.3% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P17
Plot of Scimp and Scsp against s/c	= Fig.P37
Plot of Beta against s/c	= Fig.P57
TRAJ3 equivalent plot	= Fig.P171

Fig.P78 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.1
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.8% developed aerofoil chord = 29.7% original lip section chord = 8.3% s/c = 26 mm aft over lip surface
Inner (lower) surface catch limit	= 13.4% developed aerofoil chord = 50.1% original lip section chord = 23.3% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P18
Plot of Scimp and Scsp against s/c	= Fig.P38
Plot of Beta against s/c	= Fig.P58
TRAJ3 equivalent plot	= Fig.P172



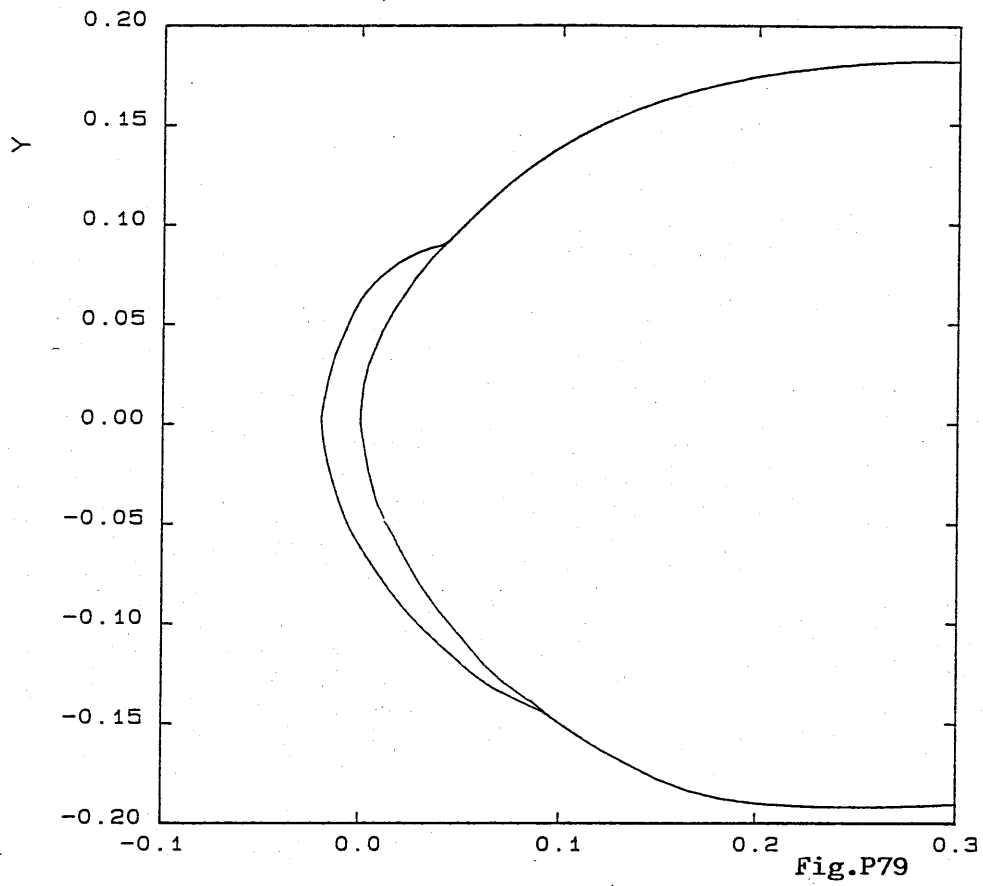
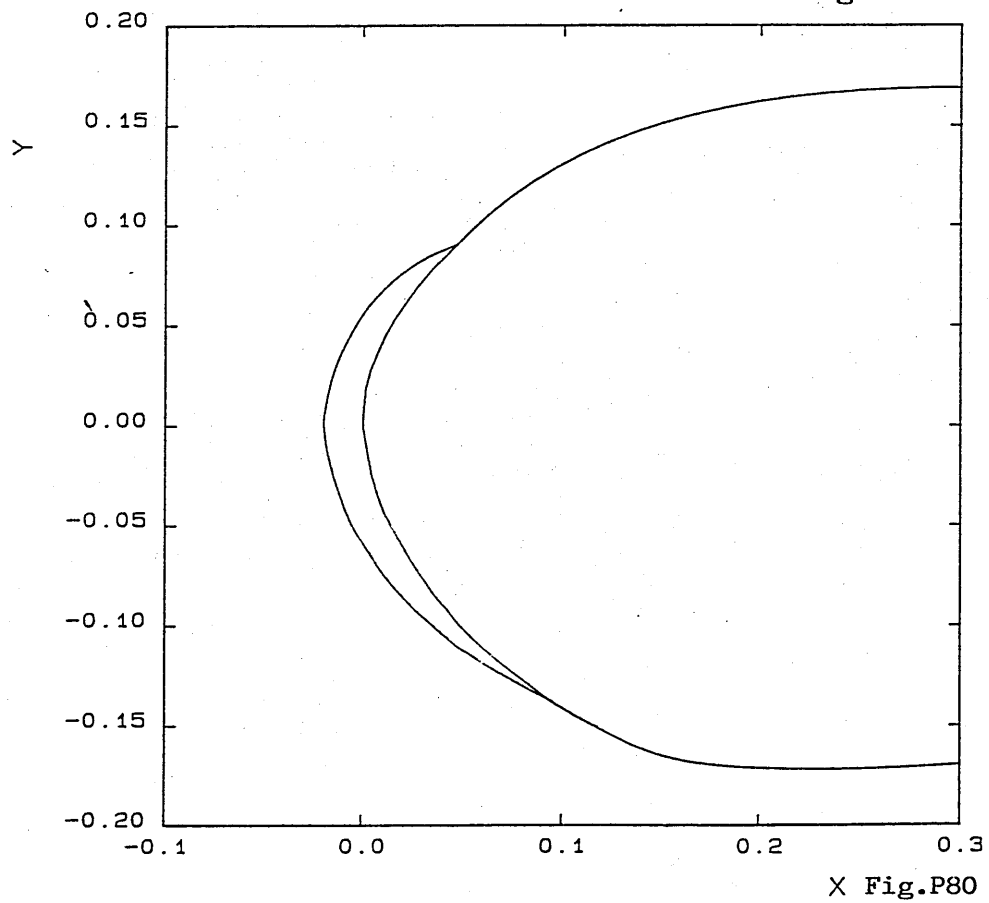
Ice Shape

Fig.P79 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.2
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.354 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.1% developed aerofoil chord = 48.4% original lip section chord = 10.2% s/c = 36 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 39.6% original lip section chord = 23.0% s/c = 81 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P19
Plot of Scimp and Scsp against s/c	= Fig.P39
Plot of Beta against s/c	= Fig.P59
TRAJ3 equivalent plot	= Fig.P173

Fig.P80 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.3
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.396 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.8% developed aerofoil chord = 63.4% original lip section chord = 10.5% s/c = 42 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 44.3% original lip section chord = 17.4% s/c = 69 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P20
Plot of Scimp and Scsp against s/c	= Fig.P40
Plot of Beta against s/c	= Fig.P60
TRAJ3 equivalent plot	= Fig.P174



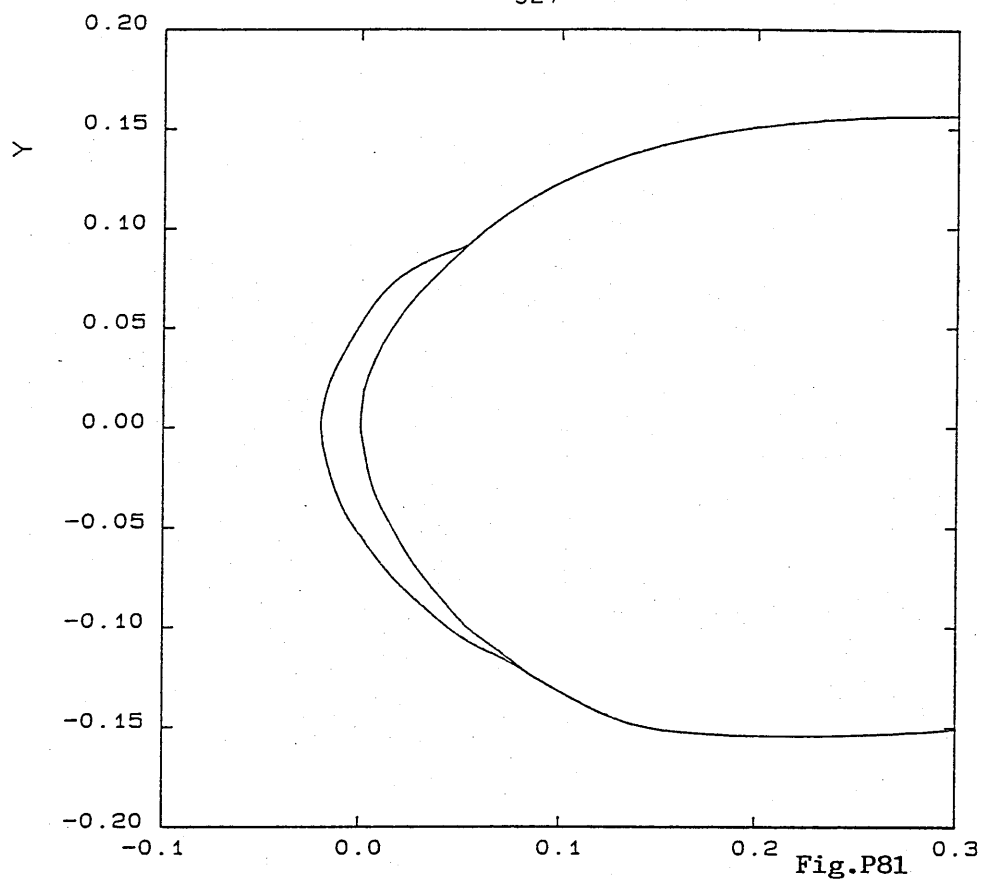
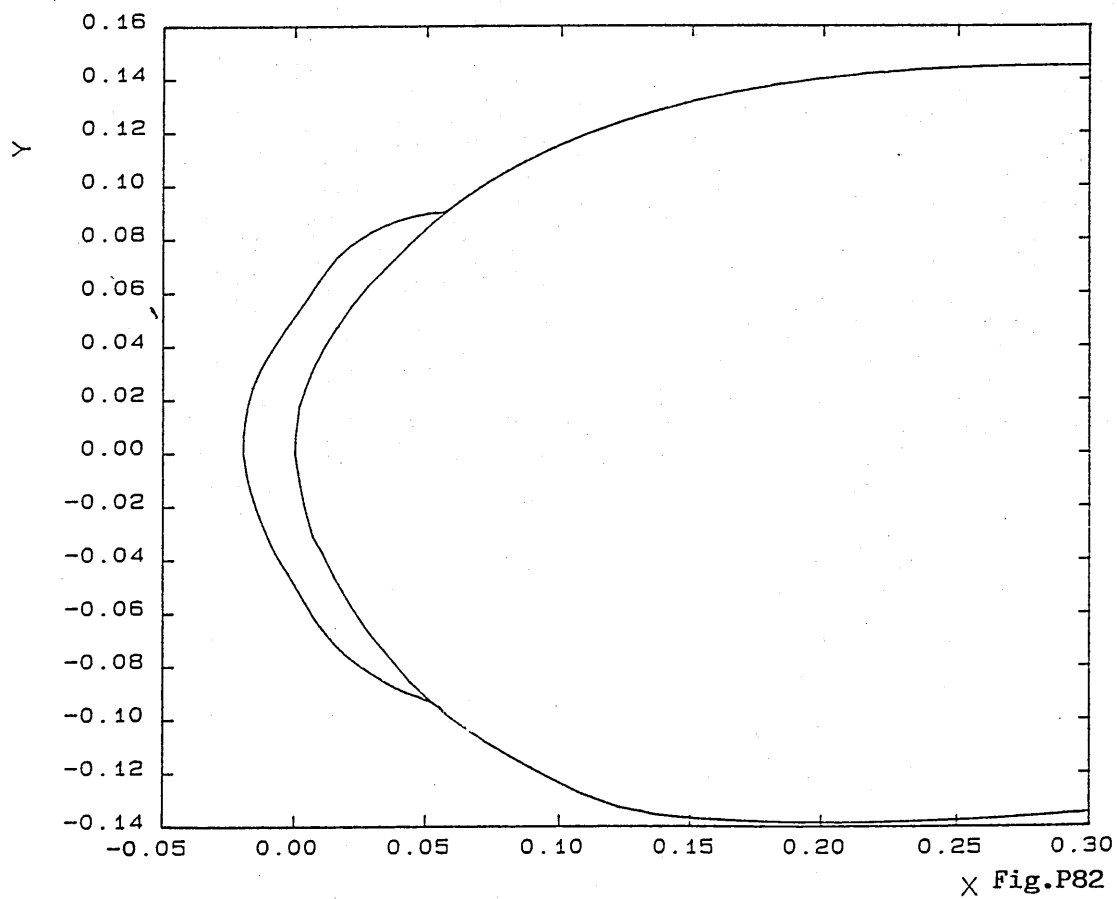
Ice Shape

Fig.P81 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.4
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.442 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 76.6% original lip section chord = 10.8% s/c = 48 mm aft over lip surface
Inner (lower) surface catch limit	= 8.1% developed aerofoil chord = 42.1% original lip section chord = 15.2% s/c = 67 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P21
Plot of Scimp and Scsp against s/c	= Fig.P41
Plot of Beta against s/c	= Fig.P61
TRAJ3 equivalent plot	= Fig.P175

Fig.P82 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.5
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.493 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.8% developed aerofoil chord = 95.3% original lip section chord = 11.0% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 5.1% developed aerofoil chord = 29.6% original lip section chord = 10.9% s/c = 54 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P22
Plot of Scimp and Scsp against s/c	= Fig.P42
Plot of Beta against s/c	= Fig.P62
TRAJ3 equivalent plot	= Fig.P176



Ice Shape

Fig.P83 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.285 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 19.0% original lip section chord = 7.5% s/c = 21 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 50.0% original lip section chord = 26.0% s/c = 74 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P23
Plot of Scimp and Scsp against s/c	= Fig.P43
Plot of Beta against s/c	= Fig.P63
TRAJ3 equivalent plot	= Fig.P177

Fig.P84 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.402 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 9.3% original lip section chord = 9.3% s/c = 37 mm aft over lip surface
Inner (lower) surface catch limit	= 7.1% developed aerofoil chord = 24.4% original lip section chord = 13.6% s/c = 55 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P24
Plot of Scimp and Scsp against s/c	= Fig.P44
Plot of Beta against s/c	= Fig.P64
TRAJ3 equivalent plot	= Fig.P178

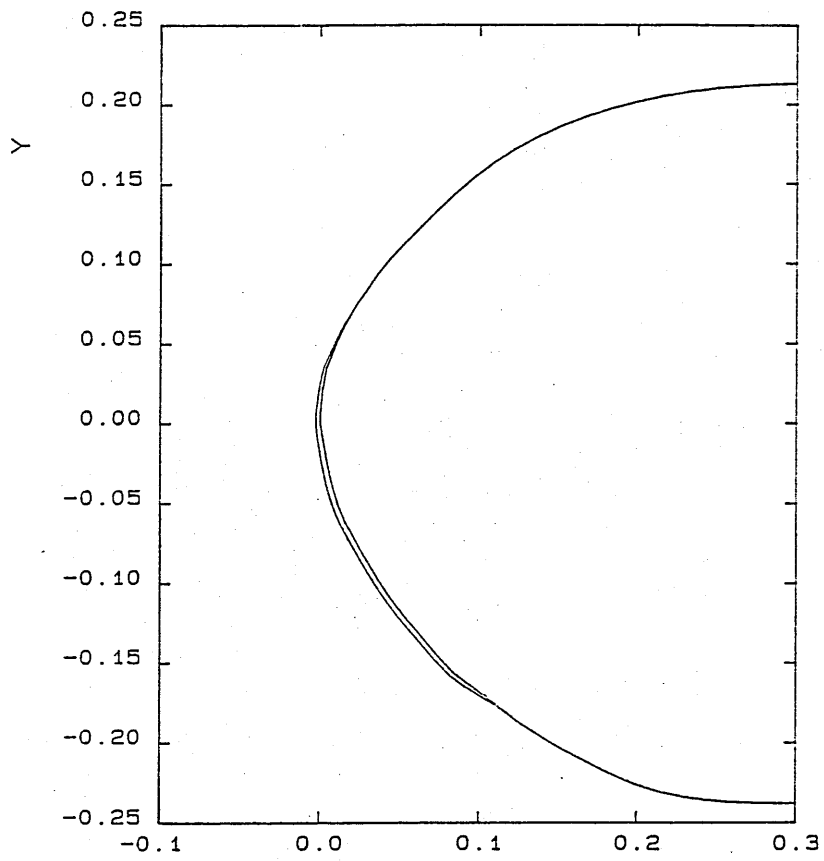
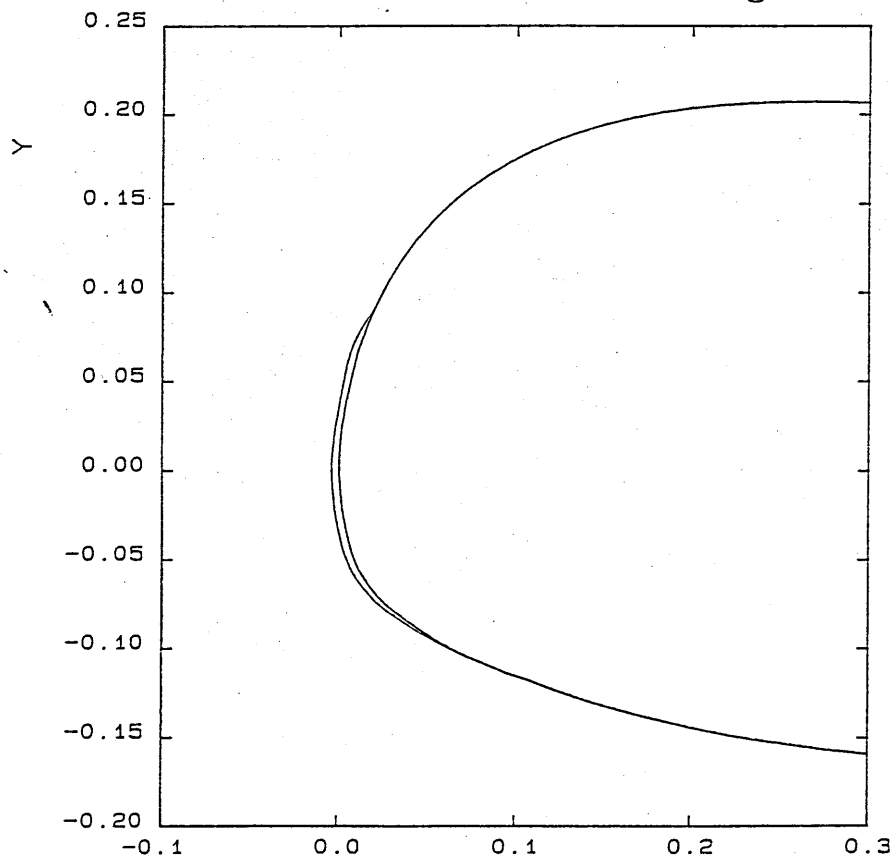


Fig.P83



X Fig.P84

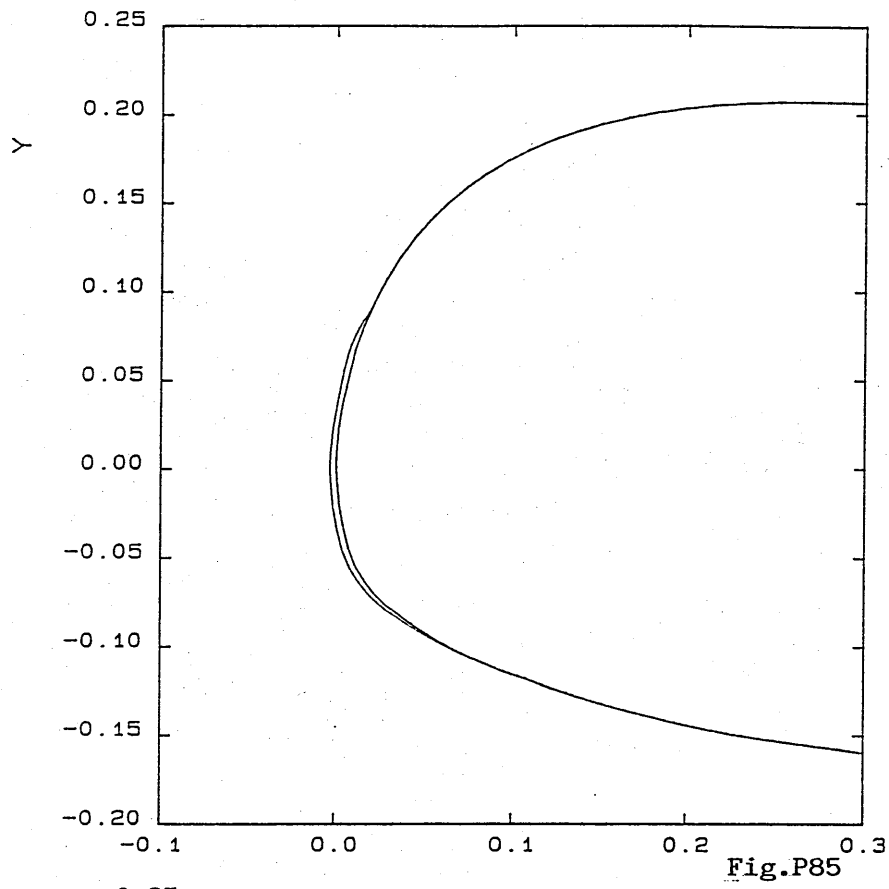
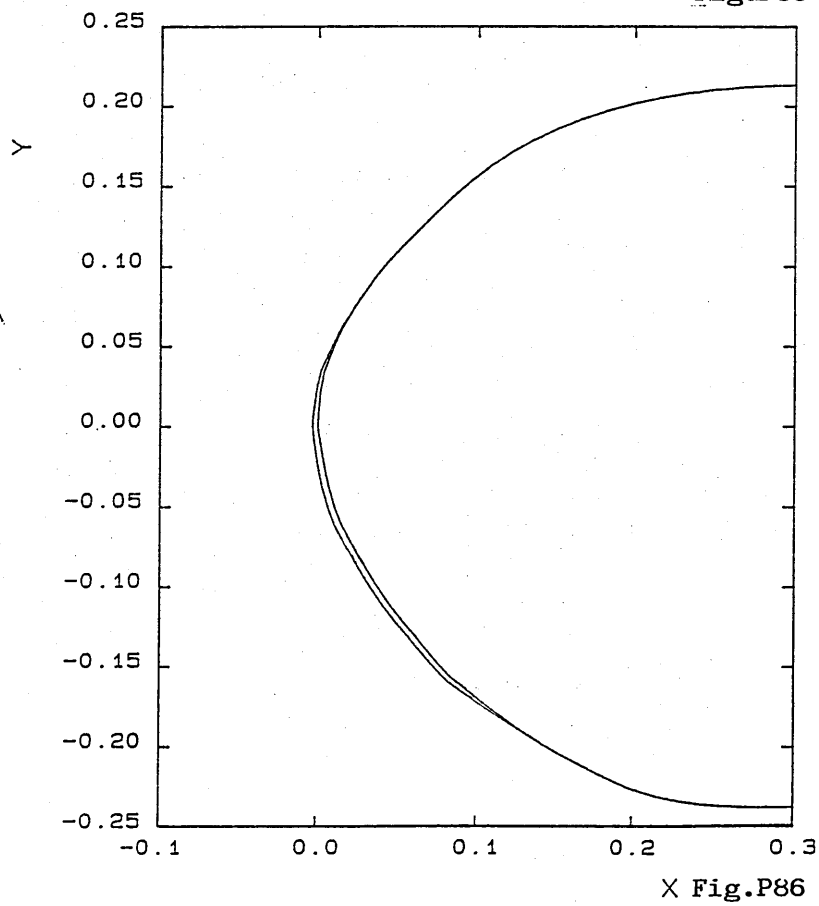
Ice Shape

Fig.P85 (Case 17)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 7.2% developed aerofoil chord = 22.2% original lip section chord = 13.7% s/c = 46 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P25
Plot of Scimp and Scsp against s/c	= Fig.P45
Plot of Beta against s/c	= Fig.P65
TRAJ3 equivalent plot	= Fig.P179

Fig.P86 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.318 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 1.9% developed aerofoil chord = 20.1% original lip section chord = 7.5% s/c = 24 mm aft over lip surface
Inner (lower) surface catch limit	= 14.9% developed aerofoil chord = 55.7% original lip section chord = 26.0% s/c = 83 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P26
Plot of Scimp and Scsp against s/c	= Fig.P46
Plot of Beta against s/c	= Fig.P66
TRAJ3 equivalent plot	= Fig.P180



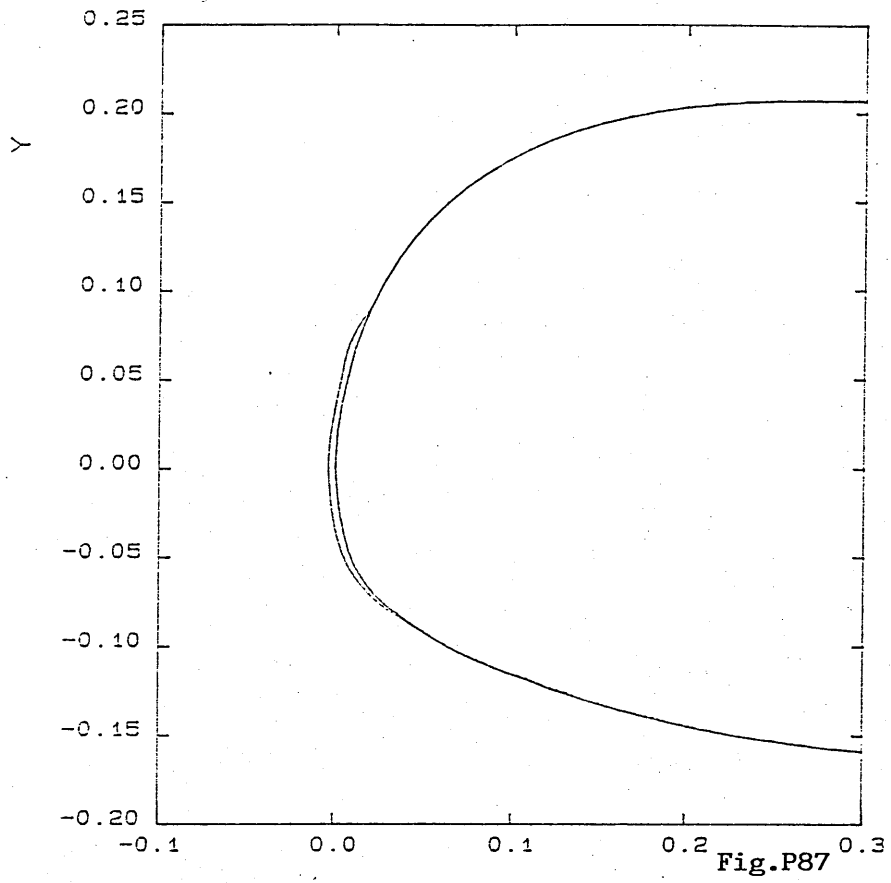
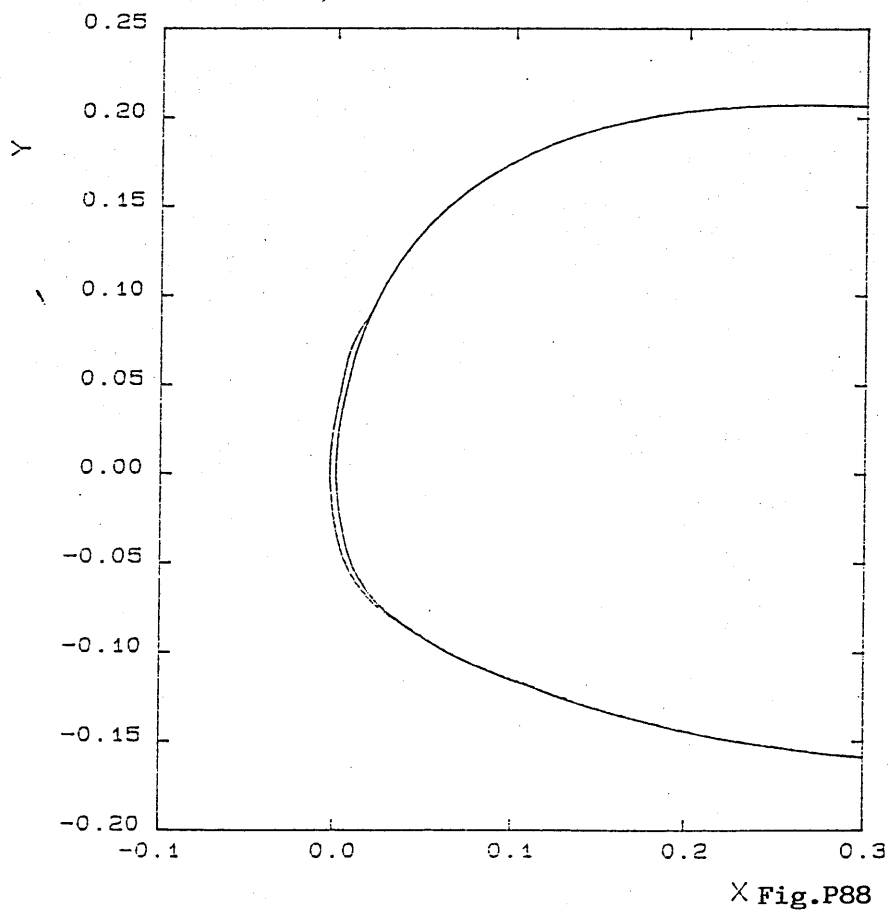
Ice Shape

Fig.P87 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.1% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P27
Plot of Scimp and Scsp against s/c	= Fig.P47
Plot of Beta against s/c	= Fig.P67
TRAJ3 equivalent plot	= Fig.P181

Fig.P88 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ2
Main ice prediction program	TRAJ2
CLE	= 1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.339 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.0% developed aerofoil chord = 39.9% original lip section chord = 9.3% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 5.0% developed aerofoil chord = 15.4% original lip section chord = 11.2% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P28
Plot of Scimp and Scsp against s/c	= Fig.P48
Plot of Beta against s/c	= Fig.P68
TRAJ3 equivalent plot	= Fig.P182



Ice Shape

Fig.P89

Lip Section	180°
Program	PTRAJ3
CLE	= 1.0
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.270 m

Fig.P90

Lip Section	180°
Program	PTRAJ3
CLE	= 1.1
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.302 m

Fig.P91

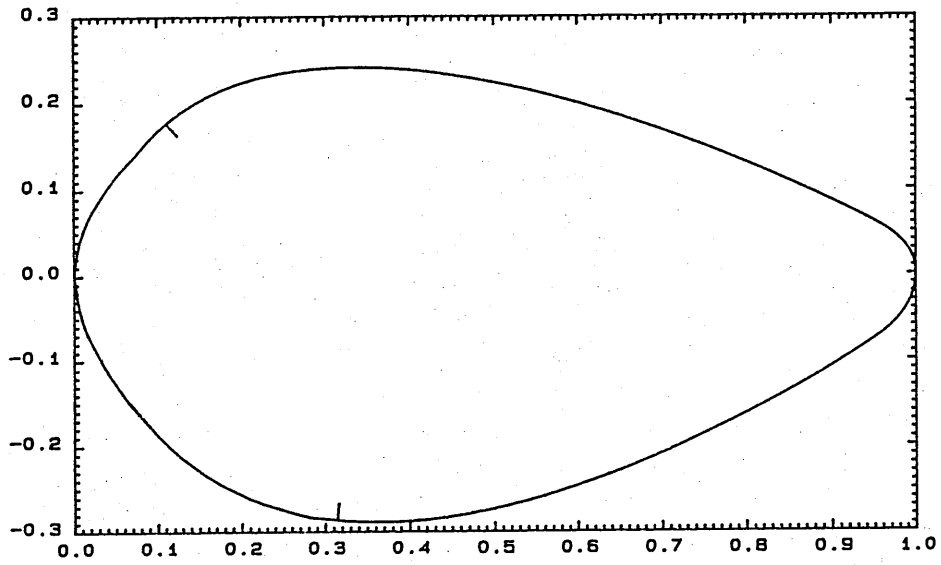
Lip Section	180°
Program	PTRAJ3
CLE	= 1.2
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.337 m

Fig.P92

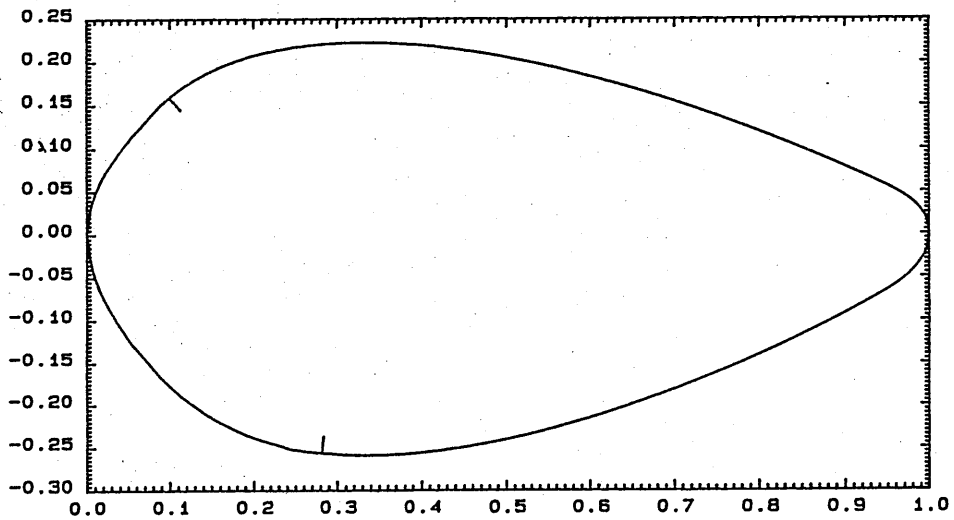
Lip Section	180°
Program	PTRAJ3
CLE	= 1.3
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.376 m

Fig.P93

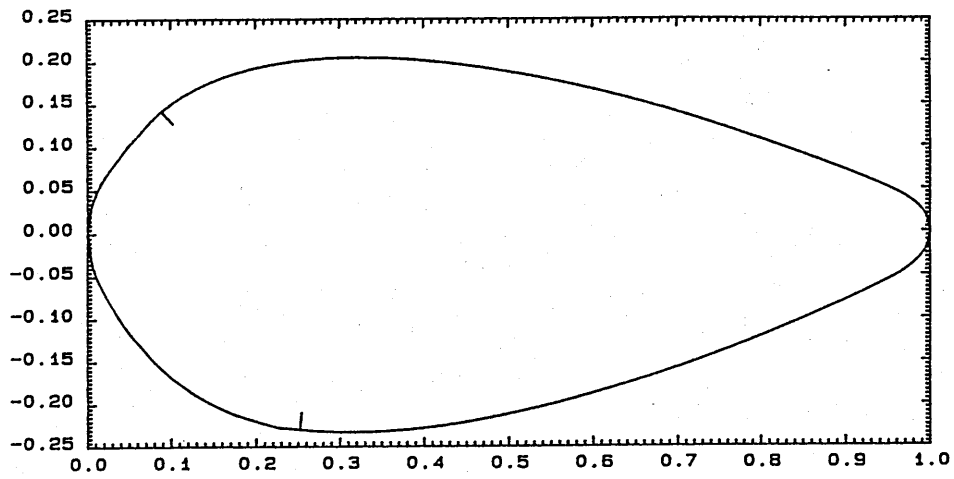
Lip Section	180°
Program	PTRAJ3
CLE	= 1.4
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.420 m



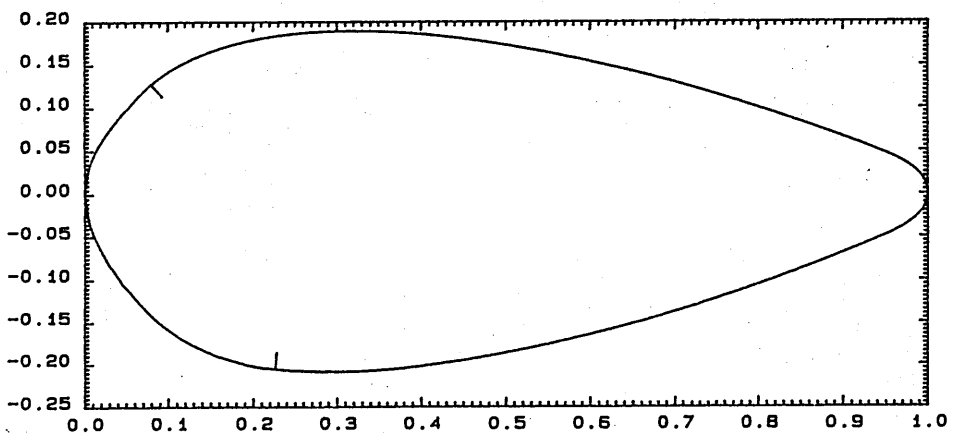
Chord 0.270381 m Fig.P89



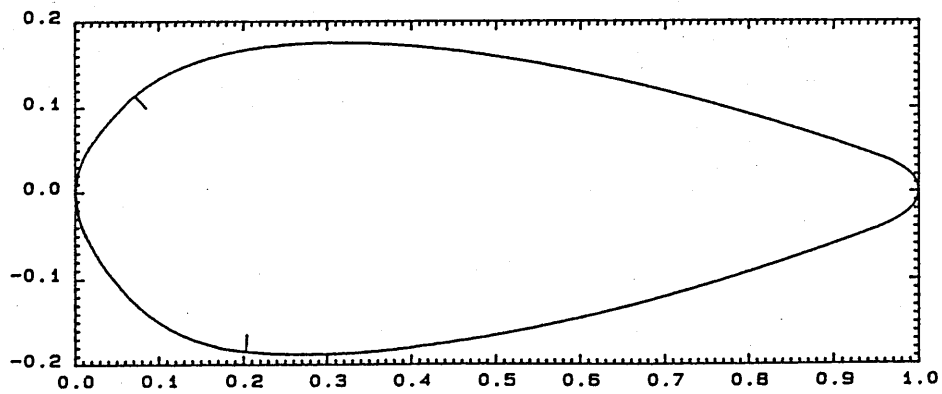
Chord 0.301778 m Fig.P90



Chord 0.336822 m Fig.P91



Chord 0.375935 m Fig.P92



Chord 0.419589 m Fig.P93

Fig.P94

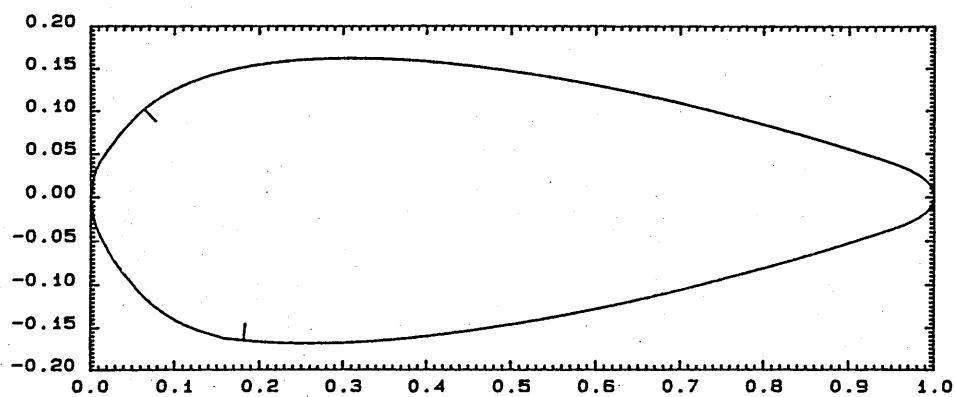
Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.468 m

Fig.P95

Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 0.8
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.439 m

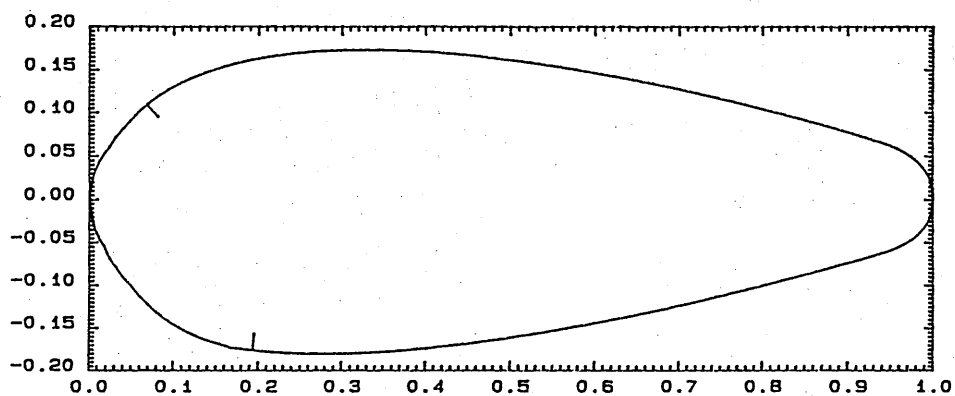
Fig.P96

Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 0.6
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.409 m



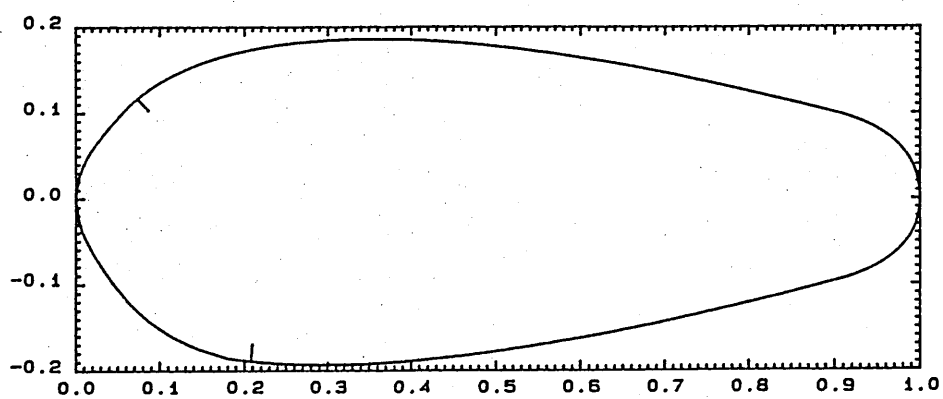
Chord 0.468313 m

Fig.P94



Chord 0.438736 m

Fig.P95



Chord 0.409158 m

Fig.P96

Fig.P97

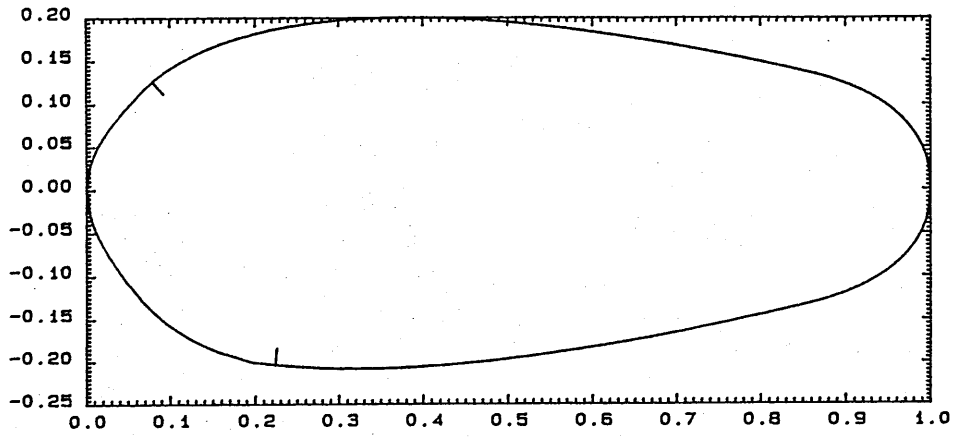
Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 0.4
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.380 m

Fig.P98

Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 0.2
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.350 m

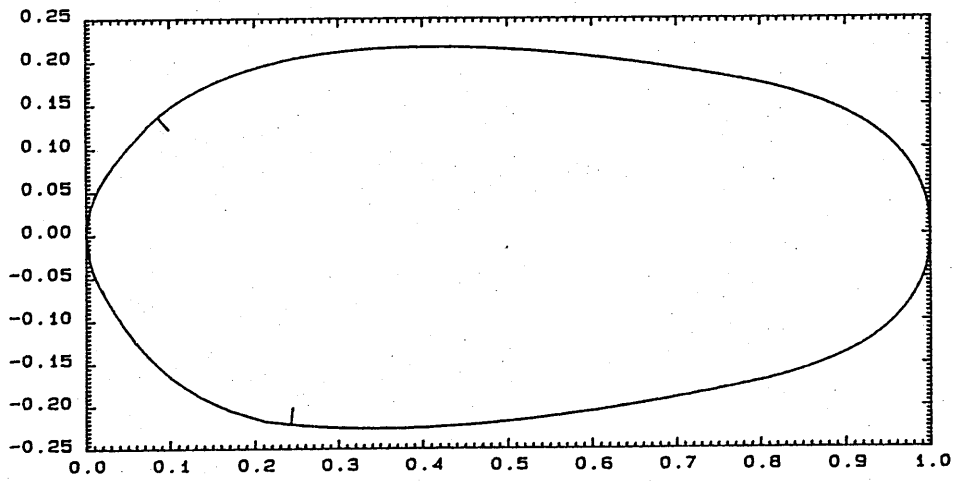
Fig.P99

Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 0.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.350 m



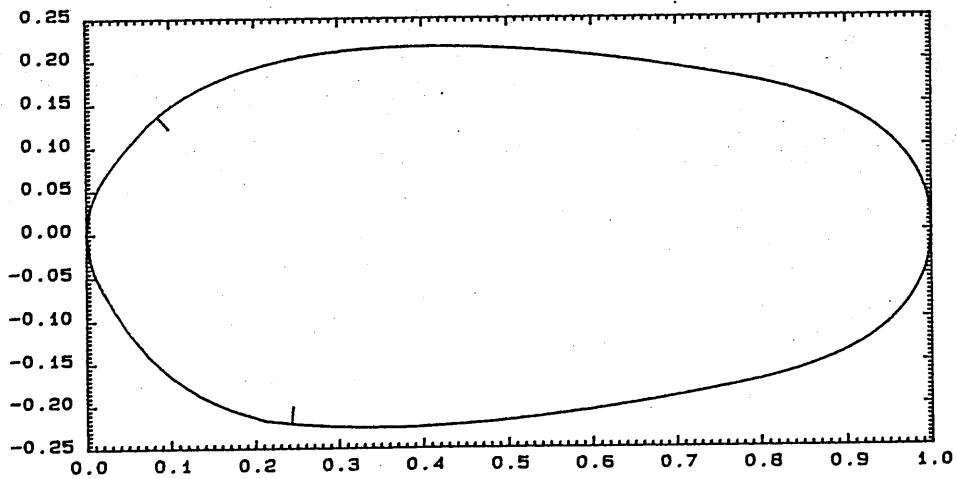
Chord 0.379580 m

Fig.P97



Chord 0.350003 m

Fig.P98



Chord 0.350003 m

Fig.P99

Fig.P100

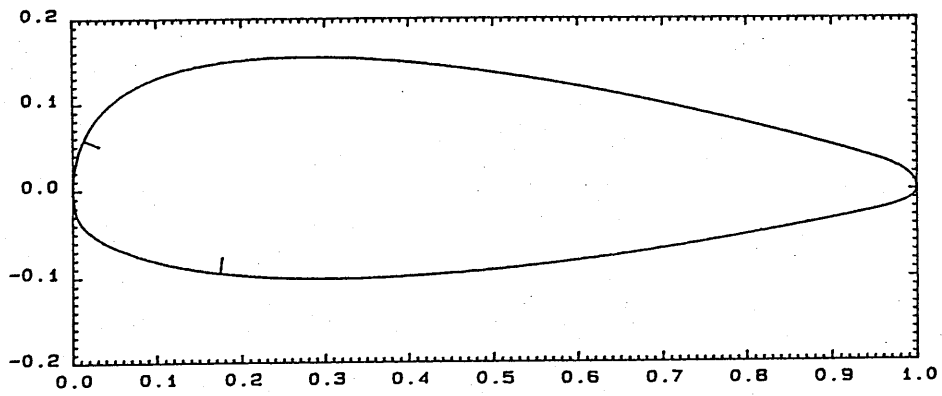
Lip Section	90°
Program	PTRAJ3
CLE	= 1.5
BLF	= 1.0
Lip chord (upper surface)	= 0.086 m
(lower surface)	= 0.117 m
Developed aerofoil chord	= 0.662 m

Fig.P101

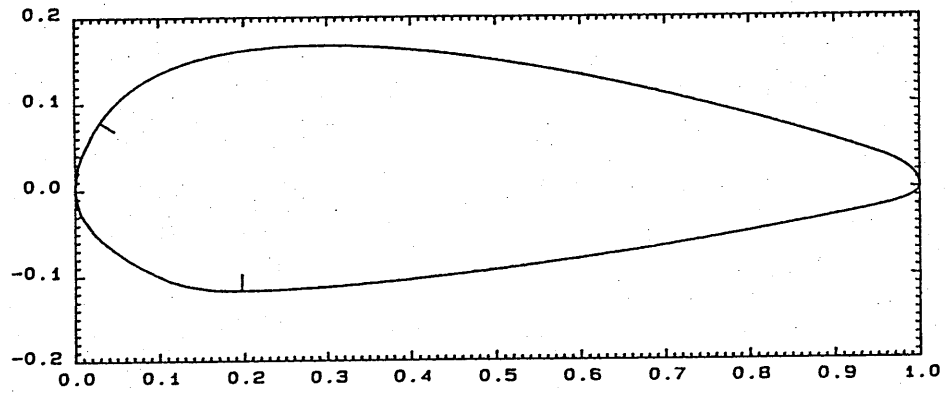
Lip Section	135°
Program	PTRAJ3
CLE	= 1.5
BLF	= 1.0
Lip chord (upper surface)	= 0.017 m
(lower surface)	= 0.110 m
Developed aerofoil chord	= 0.558 m

Fig.P102

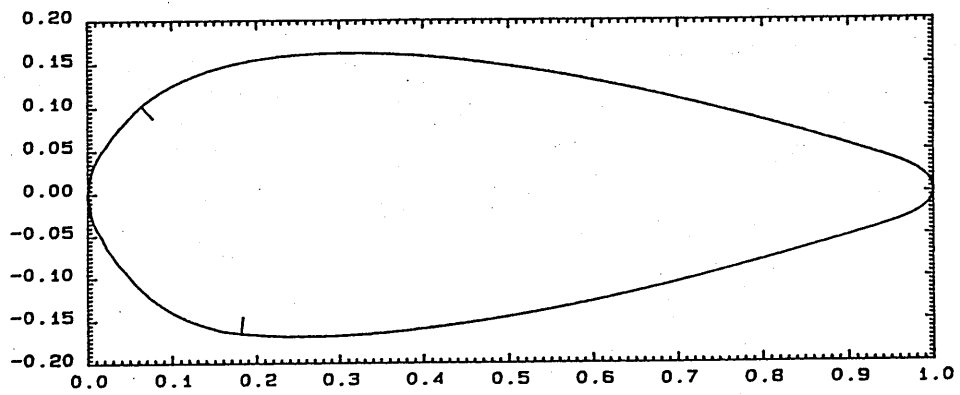
Lip Section	180°
Program	PTRAJ3
CLE	= 1.5
BLF	= 1.0
Lip chord (upper surface)	= 0.030 m
(lower surface)	= 0.085 m
Developed aerofoil chord	= 0.468 m



Chord 0.662065 m Fig.P100



Chord 0.558118 m Fig.P101



Chord 0.468313 m Fig.P102

Fig.P103 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P123
Plot of Beta against s/c	= Fig.P143
Plot of Iced aerofoil	= Fig.P163
TRAJ2 equivalent plot	= Fig.P9

Fig.P104 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P124
Plot of Beta against s/c	= Fig.P144
Plot of Iced aerofoil	= Fig.P164
TRAJ2 equivalent plot	= Fig.P10

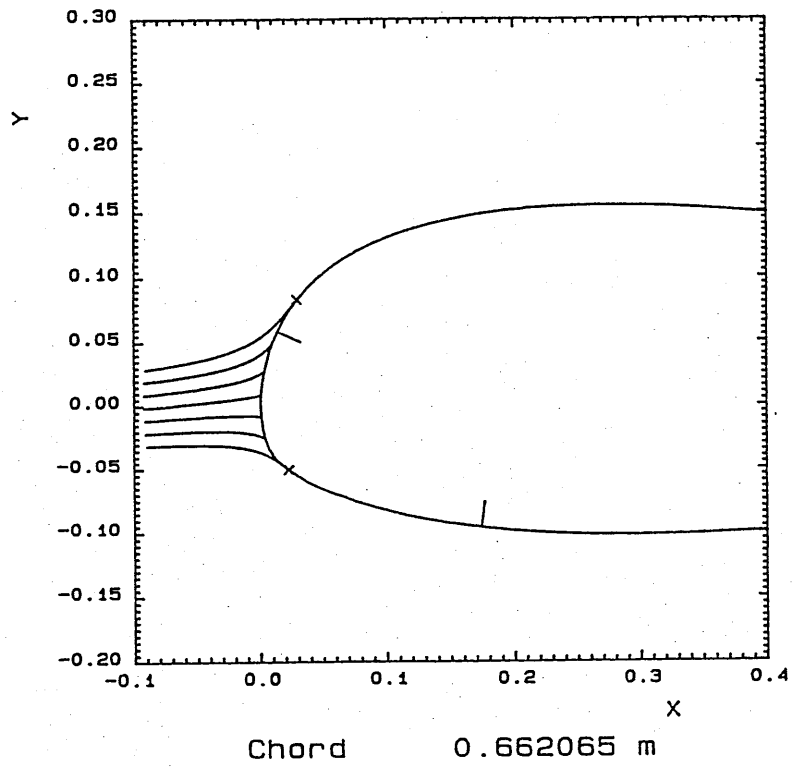


Fig.P103

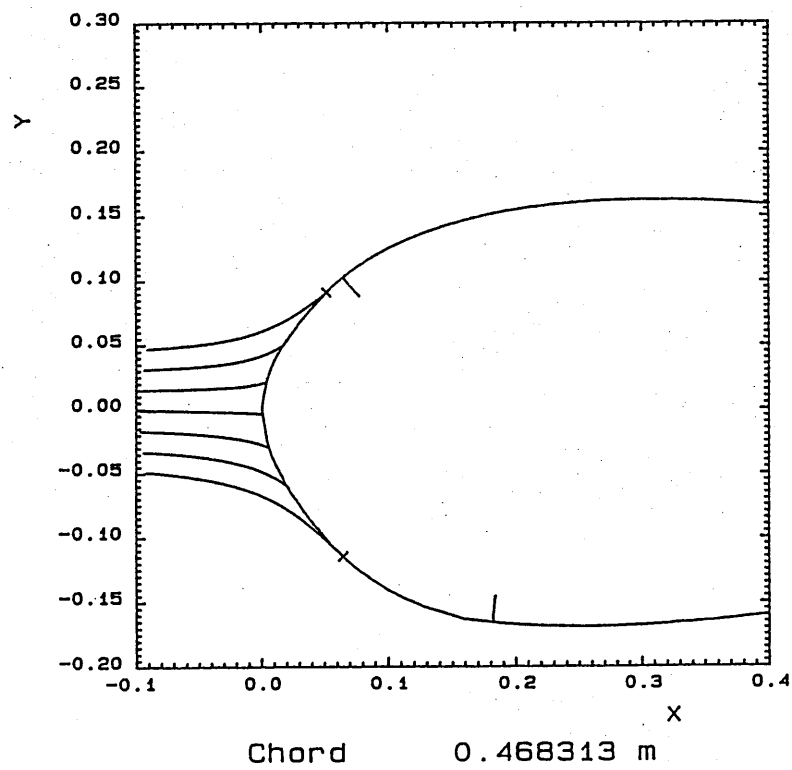


Fig.P104

Fig.P105 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P125
Plot of Beta against s/c	= Fig.P145
Plot of Iced aerofoil	= Fig.P165
TRAJ2 equivalent plot	= Fig.P11

Fig.P106 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P126
Plot of Beta against s/c	= Fig.P146
Plot of Iced aerofoil	= Fig.P166
TRAJ2 equivalent plot	= Fig.P12

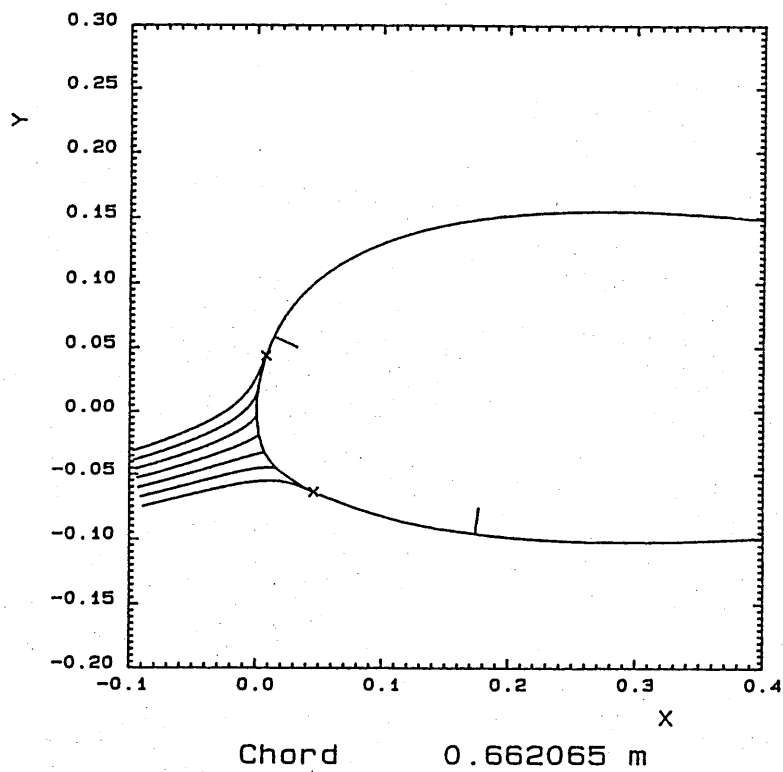


Fig.P105

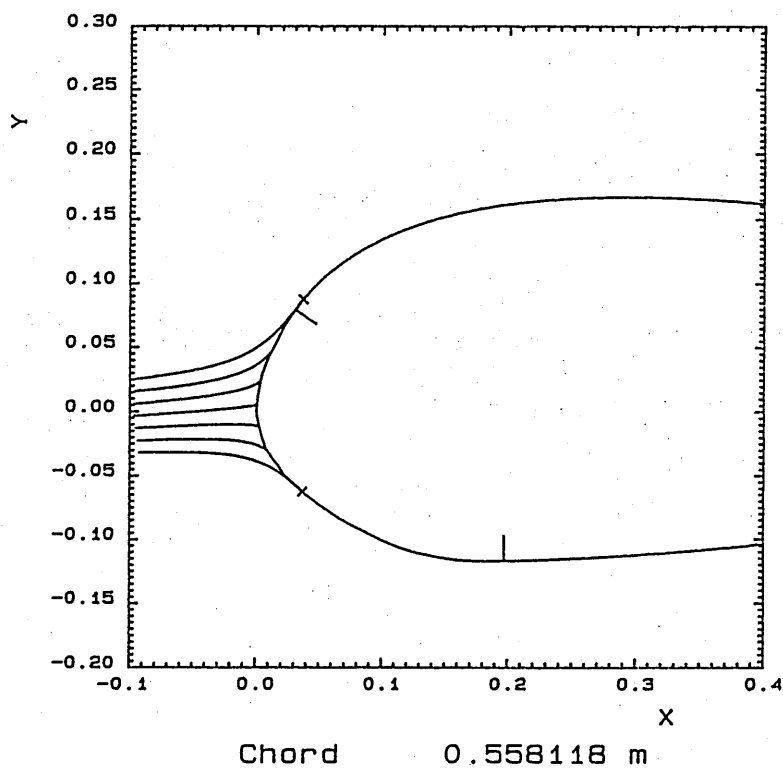


Fig.P106

Fig.P107 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/B;F	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P127
Plot of Beta against s/c	= Fig.P147
Plot of Iced aerofoil	= Fig.P167
TRAJ2 equivalent plot	= Fig.P13

Fig.P108 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P128
Plot of Beta against s/c	= Fig.P148
Plot of Iced aerofoil	= Fig.P168
TRAJ2 equivalent plot	= Fig.P14

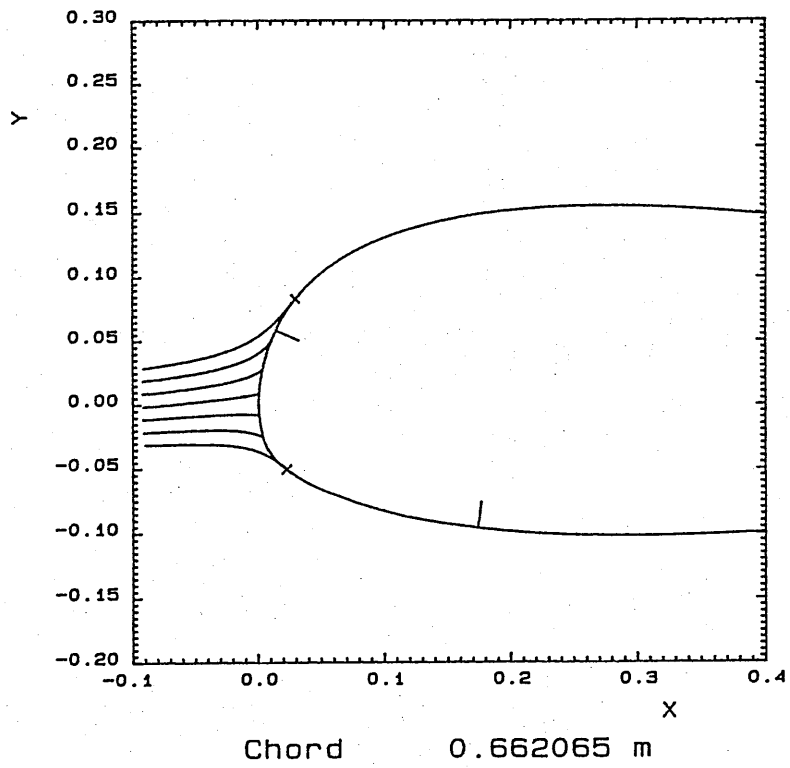


Fig.P107

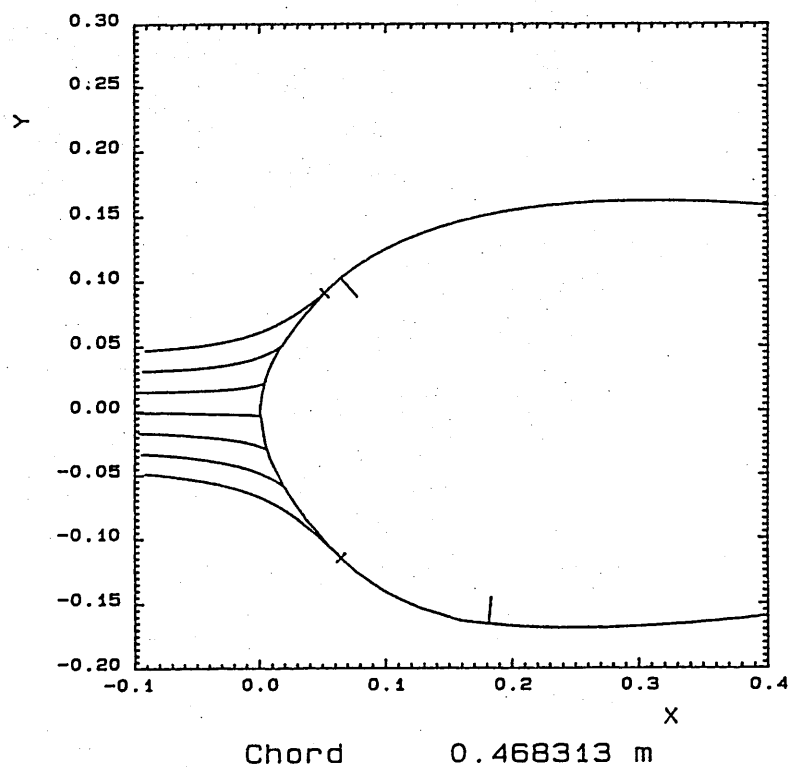


Fig.P108

Fig.P109 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P129
Plot of Beta against s/c	= Fig.P149
Plot of Iced aerofoil	= Fig.P169
TRAJ2 equivalent plot	= Fig.P15

Fig.P110 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P130
Plot of Beta against s/c	= Fig.P150
Plot of Iced aerofoil	= Fig.P170
TRAJ2 equivalent plot	= Fig.P16

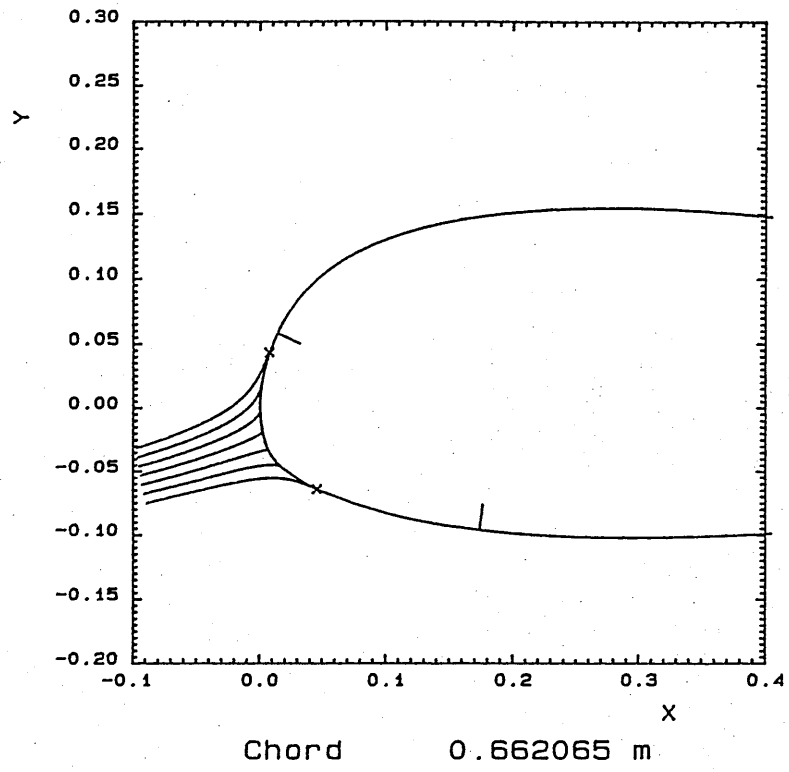


Fig.P109

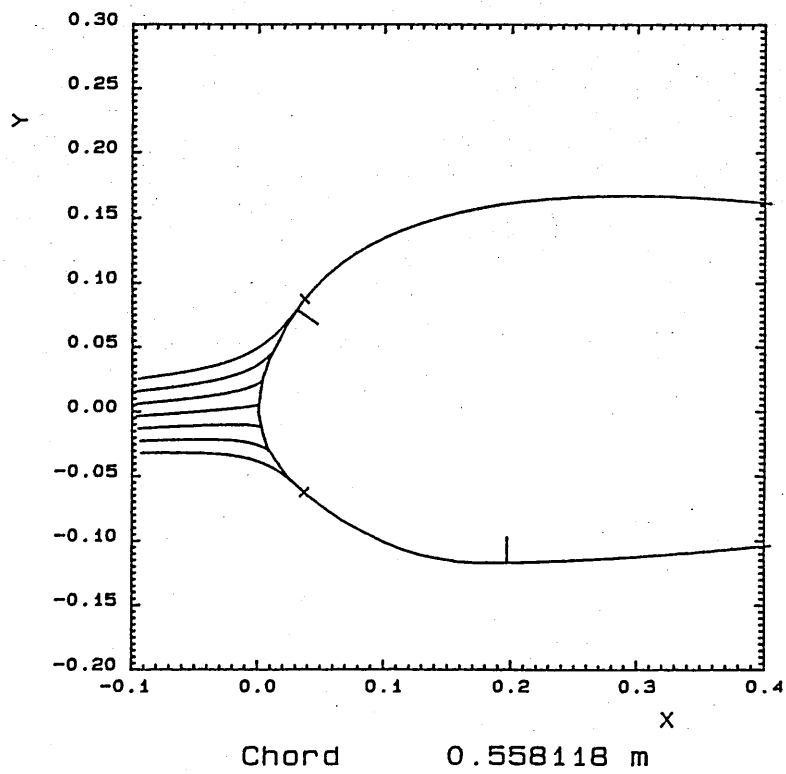


Fig.P110

Fig.P111 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 57.7% original lip section chord = 8.6% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P131
Plot of Beta against s/c	= Fig.P151
Plot of Iced aerofoil	= Fig.P171
TRAJ2 equivalent plot	= Fig.P17

Fig.P112 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.1/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.302 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 37.2% original lip section chord = 10.0% s/c = 30 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 35.5% original lip section chord = 21.0% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P132
Plot of Beta against s/c	= Fig.P152
Plot of Iced aerofoil	= Fig.P172
TRAJ2 equivalent plot	= Fig.P18

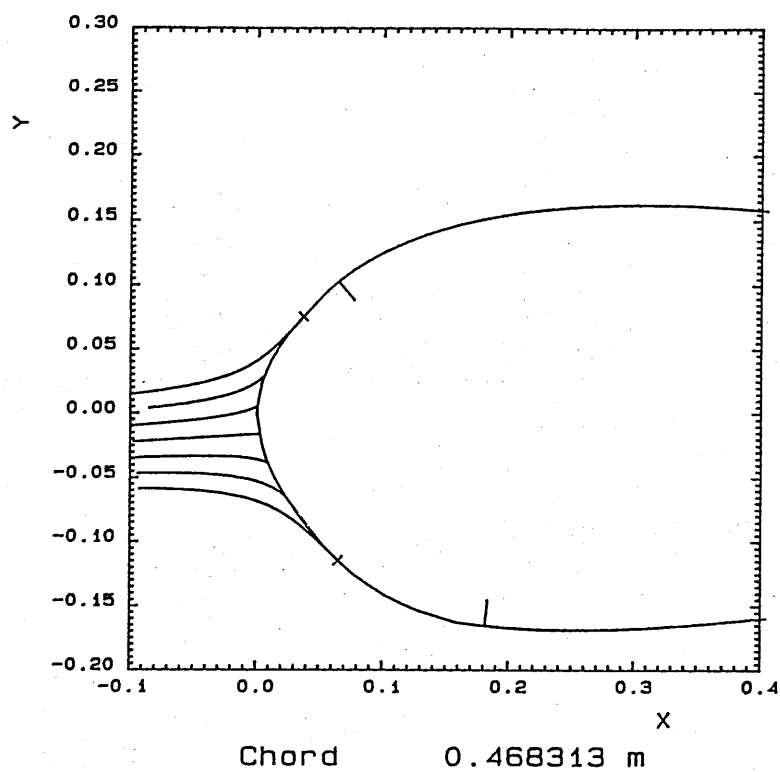


Fig.P111

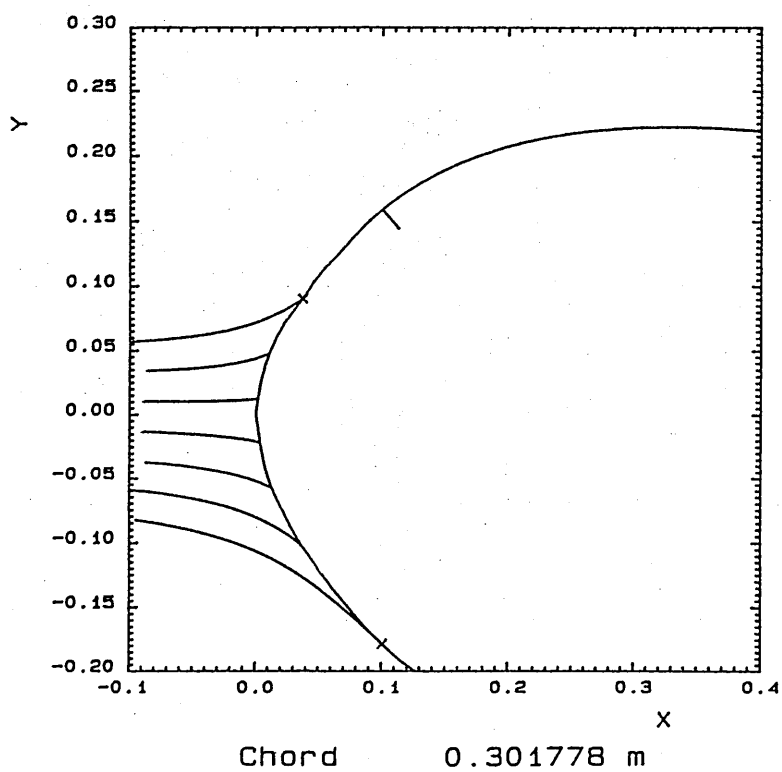


Fig.P112

Fig.P113 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.2/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P133
Plot of Beta against s/c	= Fig.P153
Plot of Iced aerofoil	= Fig.P173
TRAJ2 equivalent plot	= Fig.P19

Fig.P114 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.3/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P134
Plot of Beta against s/c	= Fig.P154
Plot of Iced aerofoil	= Fig.P174
TRAJ2 equivalent plot	= Fig.P20

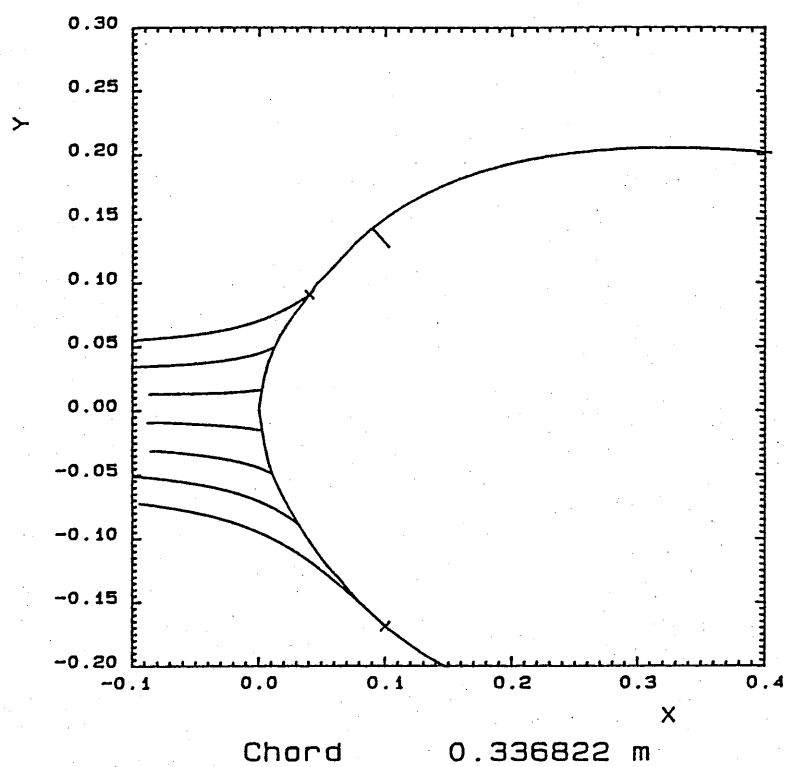


Fig.P113

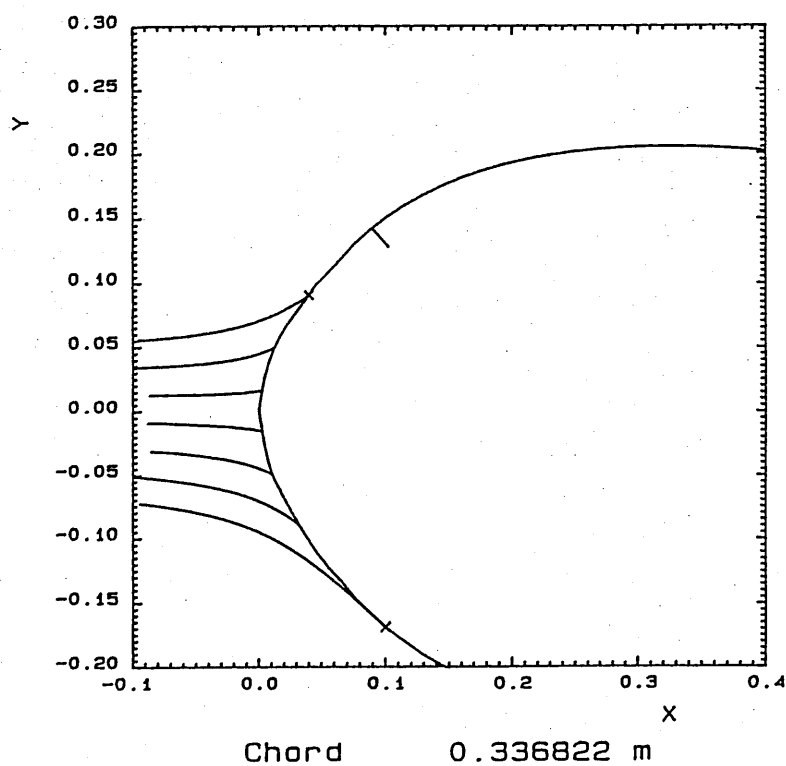


Fig.P114

Fig.P115 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.4/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.420 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.7% developed aerofoil chord = 65.8% original lip section chord = 10.4% s/c = 44 mm aft over lip surface
Inner (lower) surface catch limit	= 7.5% developed aerofoil chord = 37.1% original lip section chord = 15.5% s/c = 65 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P135
Plot of Beta against s/c	= Fig.P155
Plot of Iced aerofoil	= Fig.P175
TRAJ2 equivalent plot	= Fig.P21

Fig.P116 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P136
Plot of Beta against s/c	= Fig.P156
Plot of Iced aerofoil	= Fig.P176
TRAJ2 equivalent plot	= Fig.P22

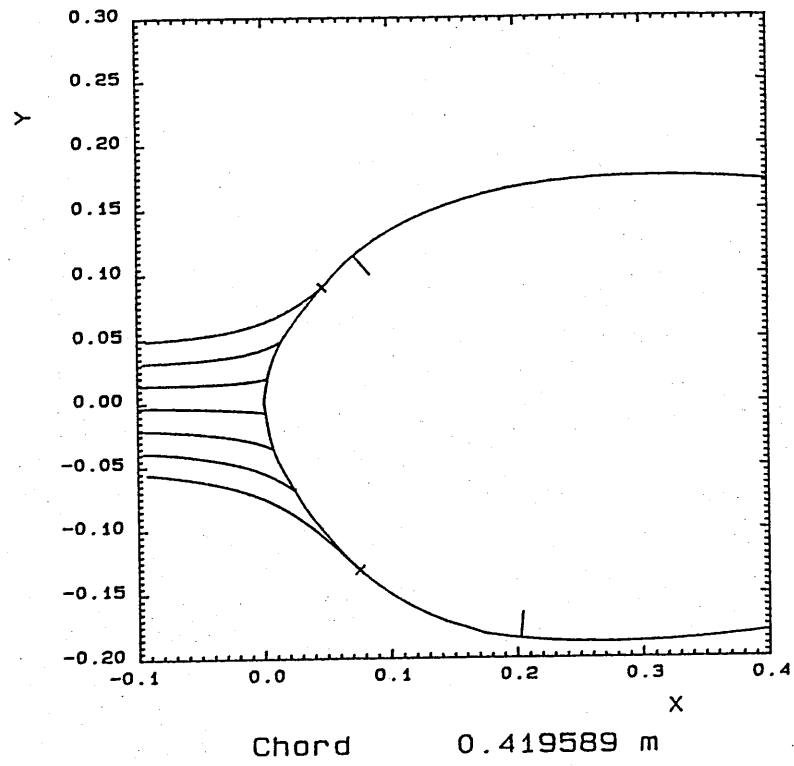


Fig.P115

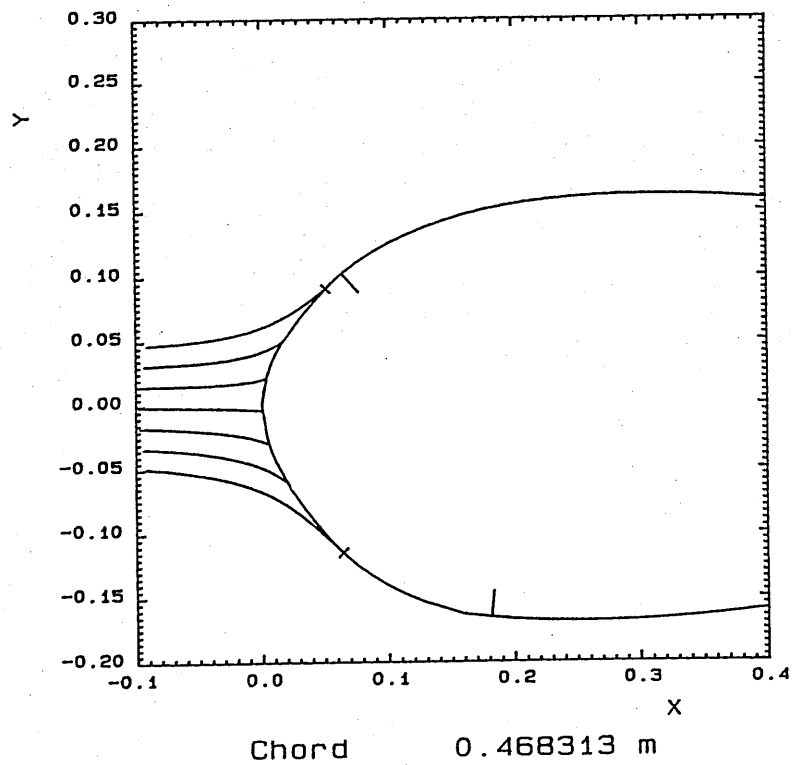


Fig.P116

Fig.P117 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P137
Plot of Beta against s/c	= Fig.P157
Plot of Iced aerofoil	= Fig.P177
TRAJ2 equivalent plot	= Fig.P23

Fig.P118 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.7% s/c = 38 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P138
Plot of Beta against s/c	= Fig.P158
Plot of Iced aerofoil	= Fig.P178
TRAJ2 equivalent plot	= Fig.P24

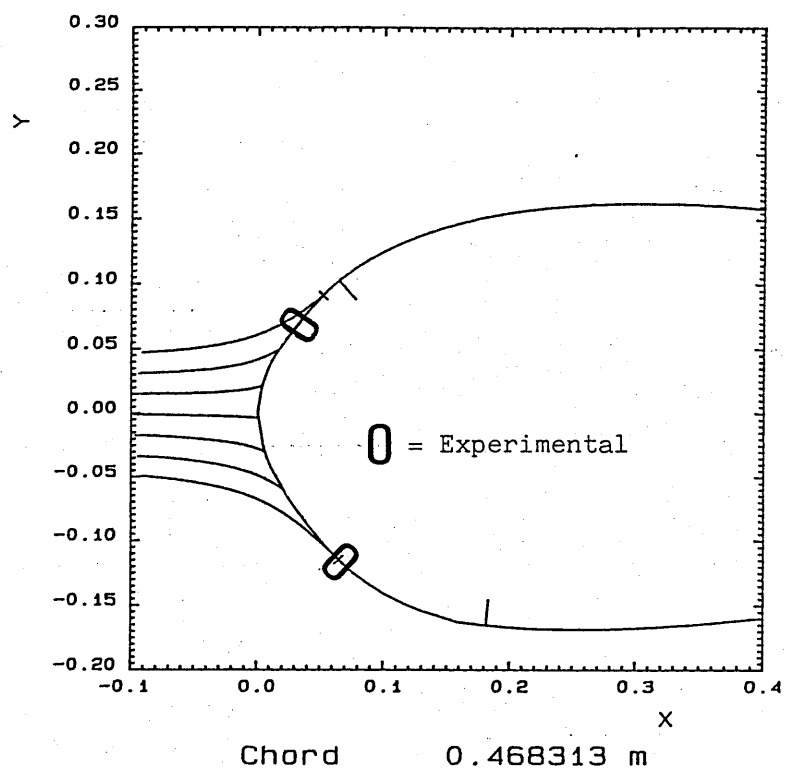


Fig.P117

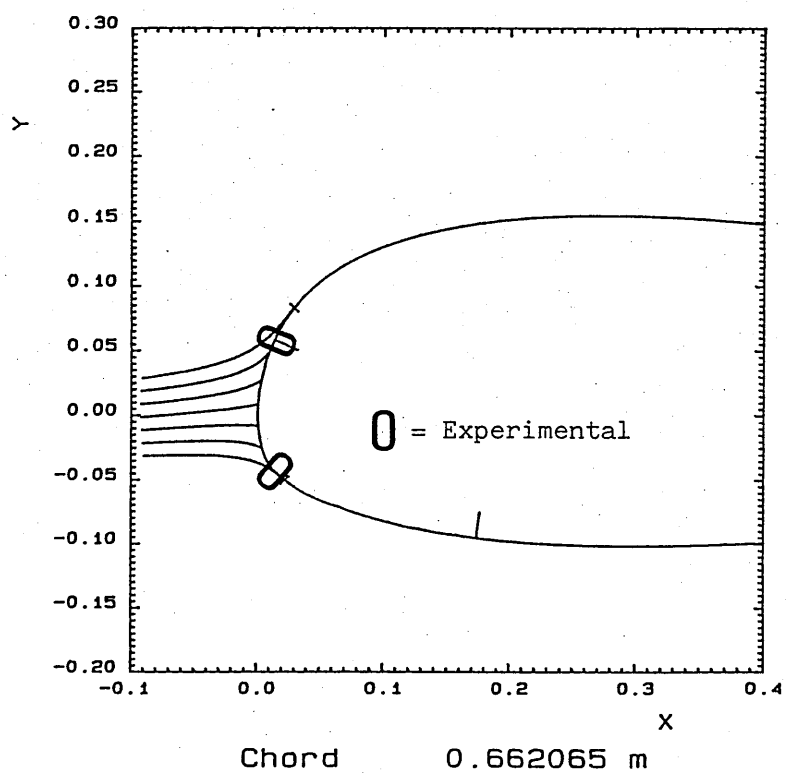


Fig.P118

Fig.P119 (Case 17)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.2% developed aerofoil chord = 72.2% original lip section chord = 7.2% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 50.7% original lip section chord = 14.9% s/c = 83 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P139
Plot of Beta against s/c	= Fig.P159
Plot of Iced aerofoil	= Fig.P179
TRAJ2 equivalent plot	= Fig.P25

Fig.P120 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P140
Plot of Beta against s/c	= Fig.P160
Plot of Iced aerofoil	= Fig.P180
TRAJ2 equivalent plot	= Fig.P26

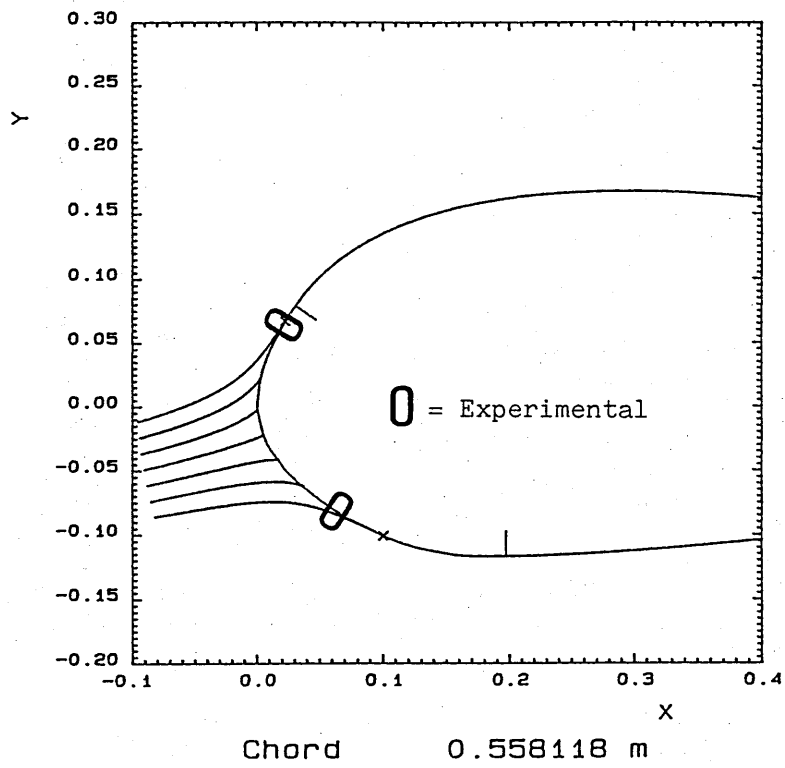


Fig.P119

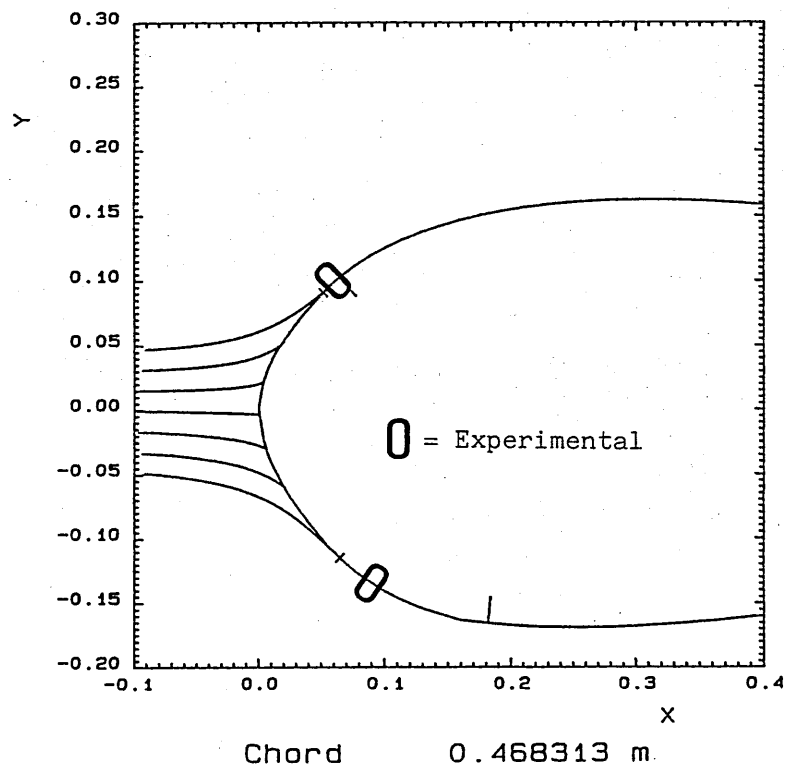


Fig.P120

Fig.P121 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord =131.3% original lip section chord = 10.0% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P141
Plot of Beta against s/c	= Fig.P161
Plot of Iced aerofoil	= Fig.P181
TRAJ2 equivalent plot	= Fig.P27

Fig.P122 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord =131.3% original lip section chord = 10.1% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P142
Plot of Beta against s/c	= Fig.P162
Plot of Iced aerofoil	= Fig.P182
TRAJ2 equivalent plot	= Fig.P28

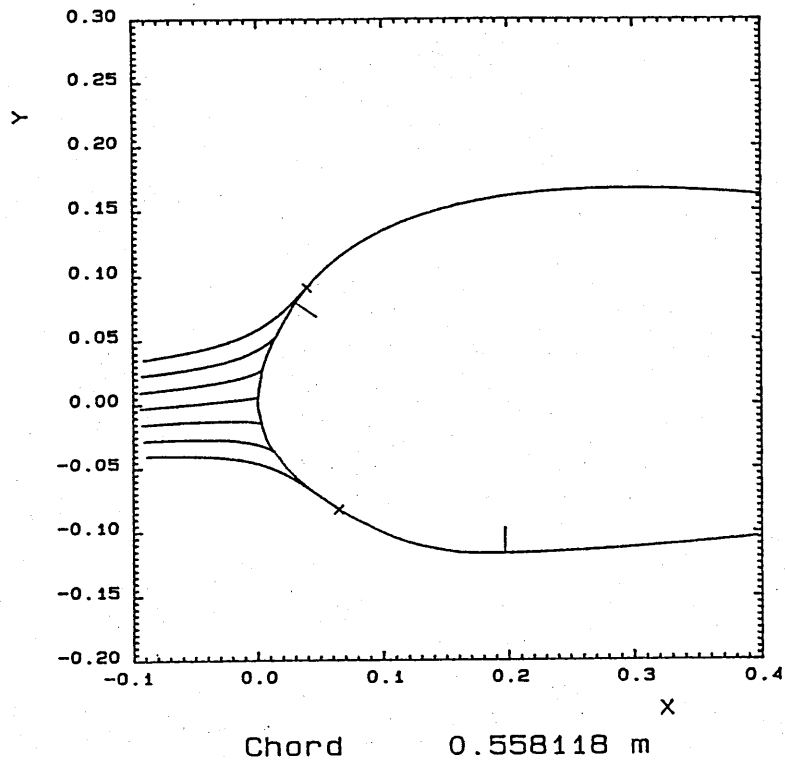


Fig.P121

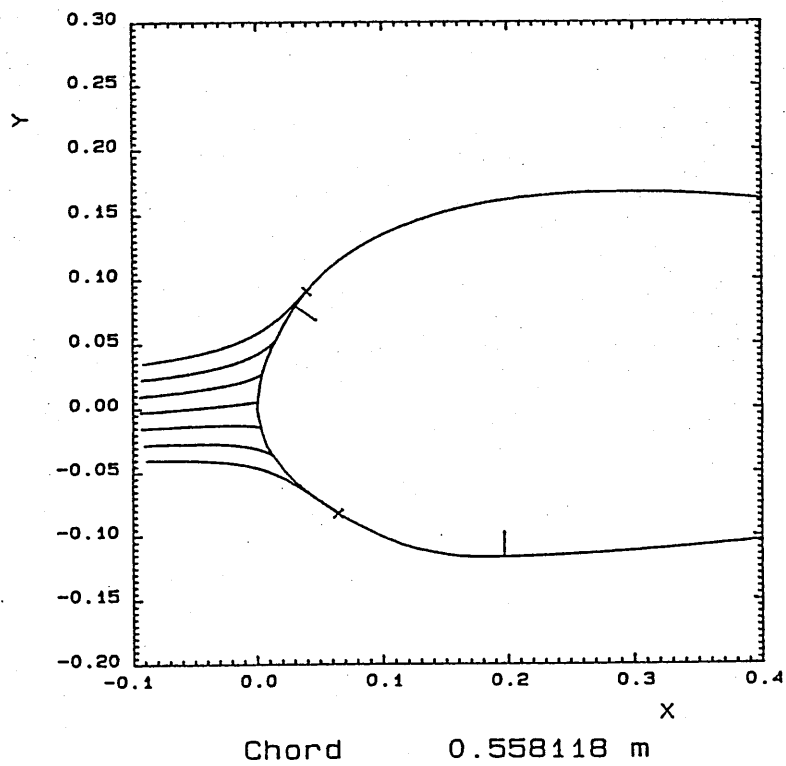


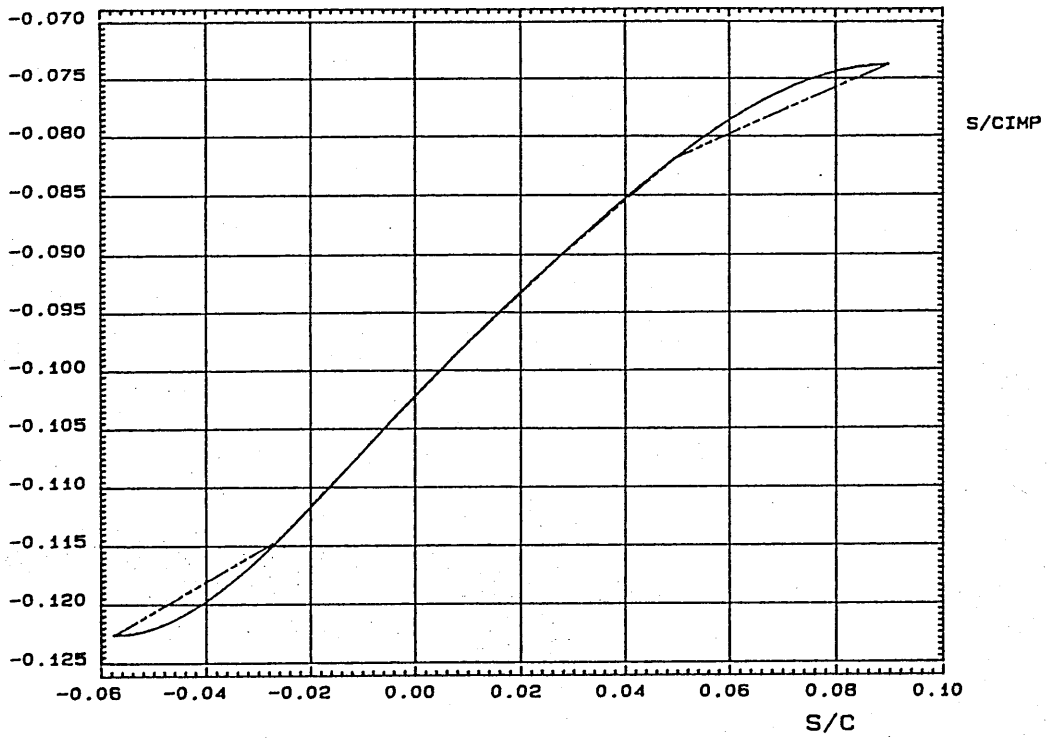
Fig.P122

Fig.P123 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P103
Plot of Beta against s/c	= Fig.P143
Plot of Iced aerofoil	= Fig.P163
TRAJ2 equivalent plot	= Fig.P29

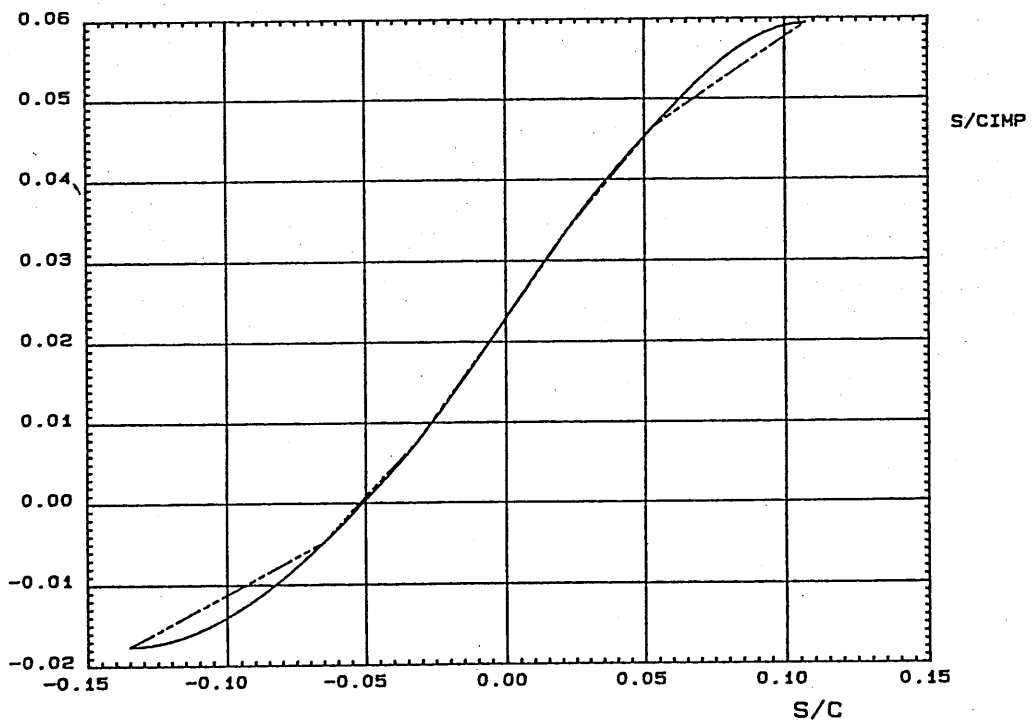
Fig.P124 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P104
Plot of Beta against s/c	= Fig.P144
Plot of Iced aerofoil	= Fig.P164
TRAJ2 equivalent plot	= Fig.P30



CATCH

Fig. P123



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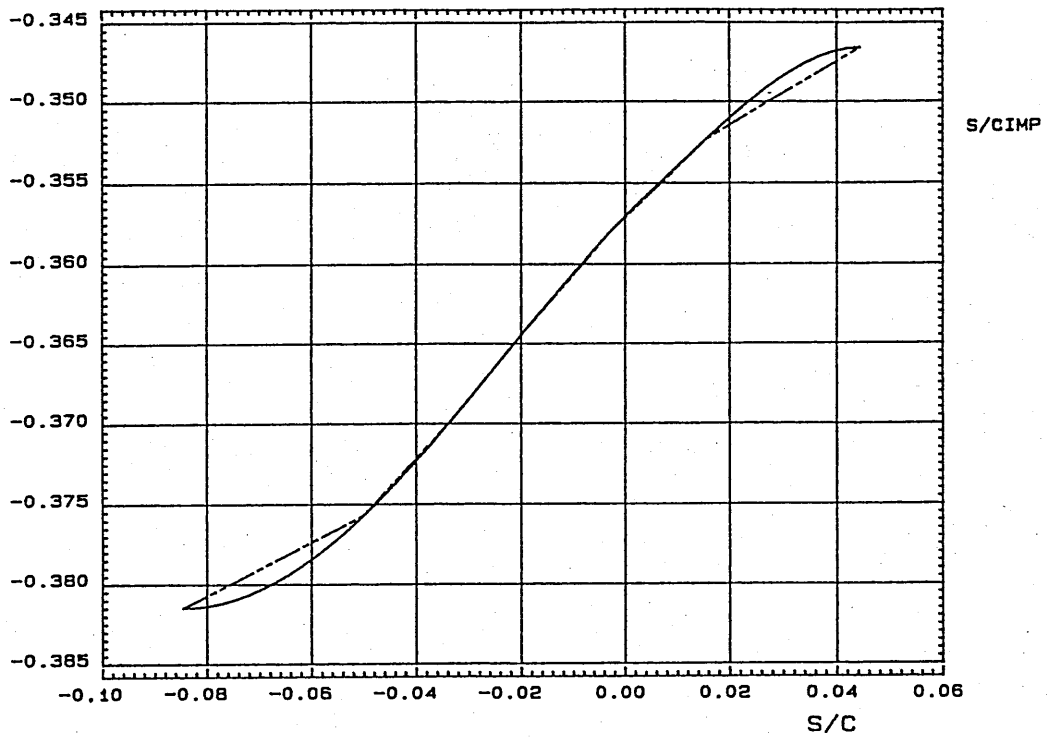
Fig. P124

Fig.P125 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P105
Plot of Beta against s/c	= Fig.P145
Plot of Iced aerofoil	= Fig.P165
TRAJ2 equivalent plot	= Fig.P31

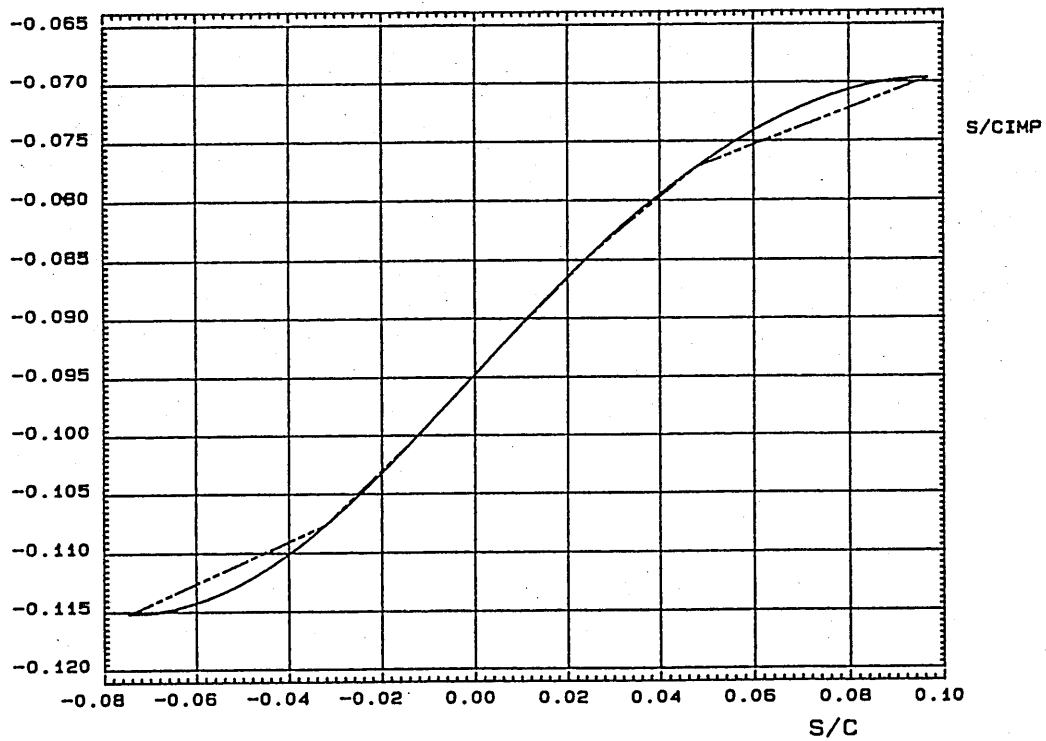
Fig.P126 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P106
Plot of Beta against s/c	= Fig.P146
Plot of Iced aerofoil	= Fig.P166
TRAJ2 equivalent plot	= Fig.P32



CATCH

Fig.P125



CATCH

Fig.P126

Fig.P127 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/B;F	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P107
Plot of Beta against s/c	= Fig.P147
Plot of Iced aerofoil	= Fig.P167
TRAJ2 equivalent plot	= Fig.P33

Fig.P128 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P108
Plot of Beta against s/c	= Fig.P148
Plot of Iced aerofoil	= Fig.P168
TRAJ2 equivalent plot	= Fig.P34

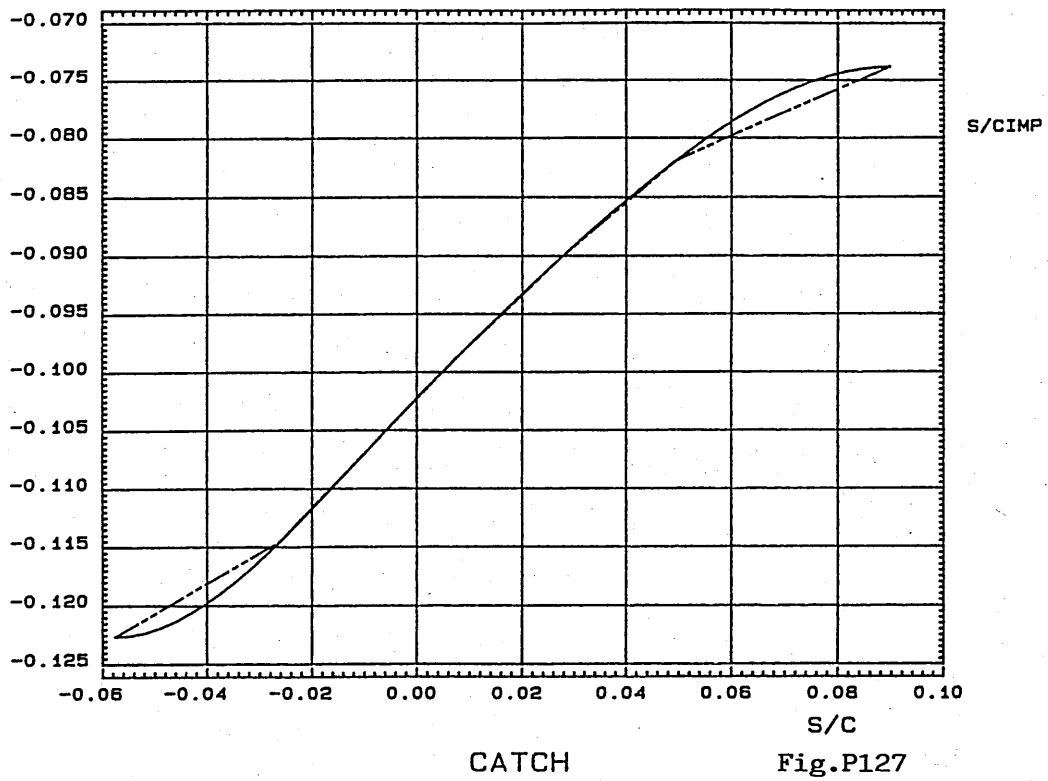
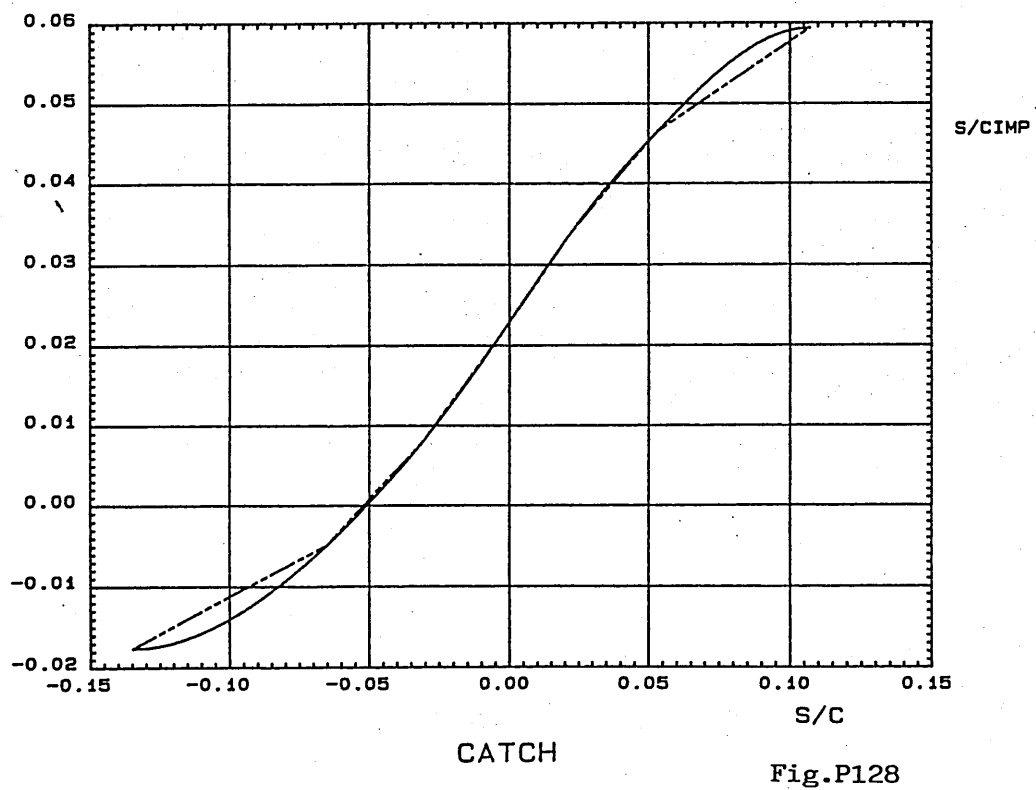
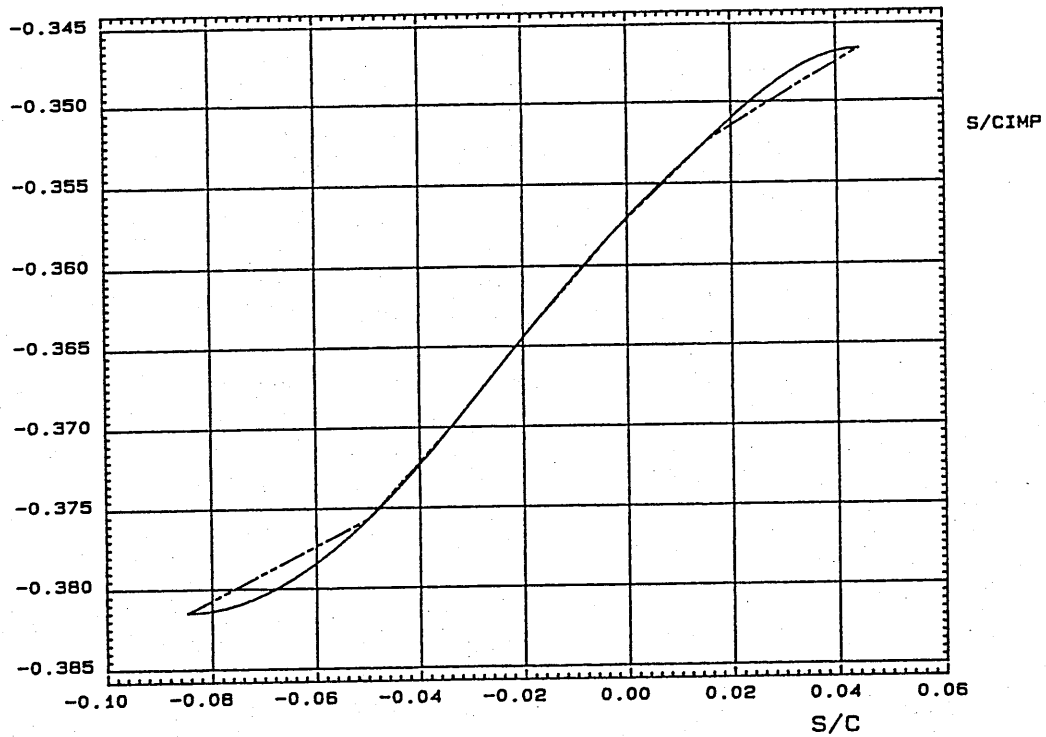


Fig.P129 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P109
Plot of Beta against s/c	= Fig.P149
Plot of Iced aerofoil	= Fig.P169
TRAJ2 equivalent plot	= Fig.P35

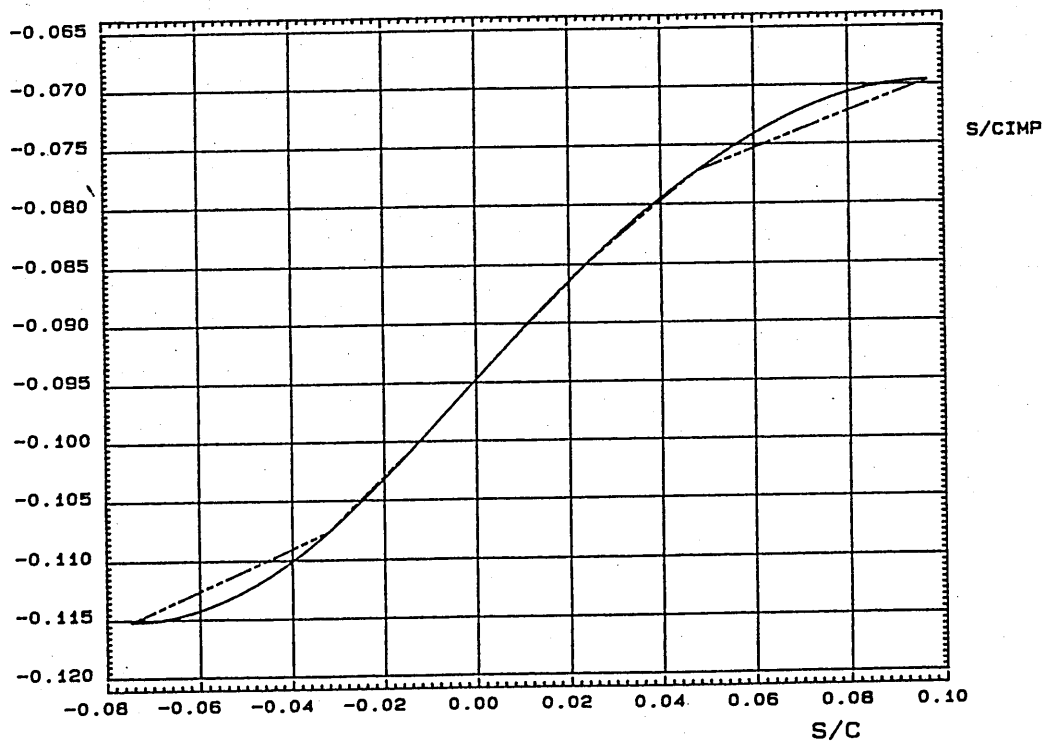
Fig.P130 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P110
Plot of Beta against s/c	= Fig.P150
Plot of Iced aerofoil	= Fig.P170
TRAJ2 equivalent plot	= Fig.P36



CATCH

Fig.P129



CATCH

Fig.P130

Fig.P131 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 57.7% original lip section chord = 8.6% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P111
Plot of Beta against s/c	= Fig.P151
Plot of Iced aerofoil	= Fig.P171
TRAJ2 equivalent plot	= Fig.P37

Fig.P132 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.1/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.302 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 37.2% original lip section chord = 10.0% s/c = 30 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 35.5% original lip section chord = 21.0% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P112
Plot of Beta against s/c	= Fig.P152
Plot of Iced aerofoil	= Fig.P172
TRAJ2 equivalent plot	= Fig.P38

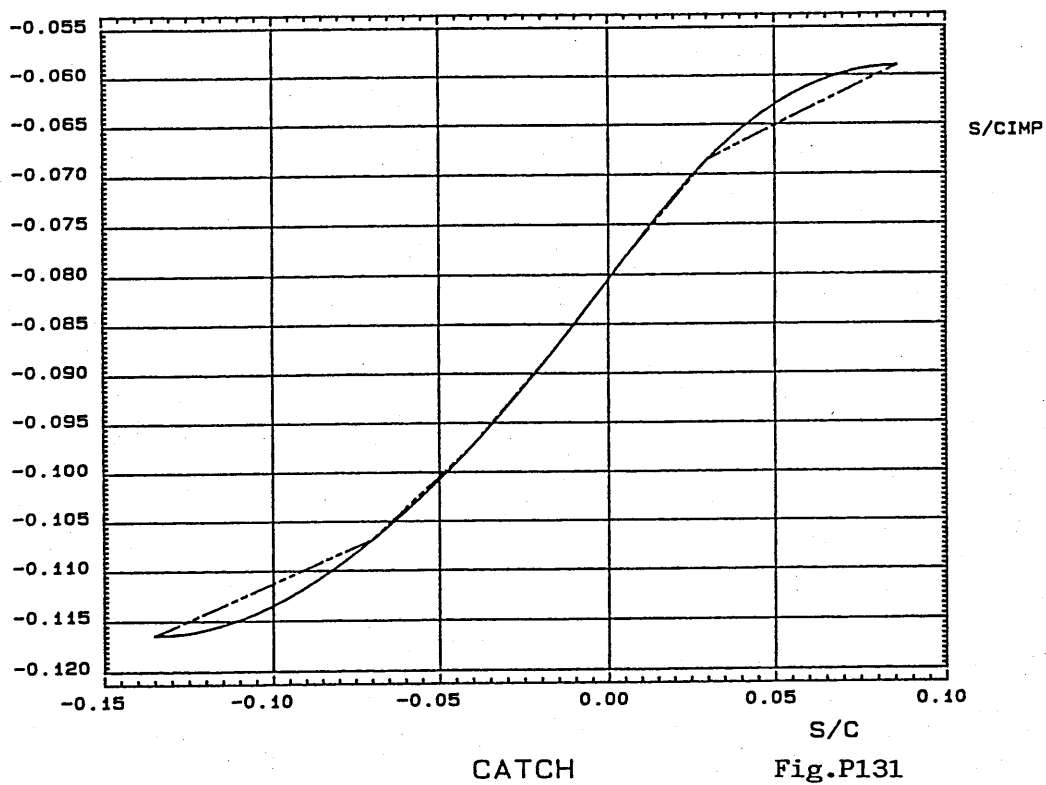
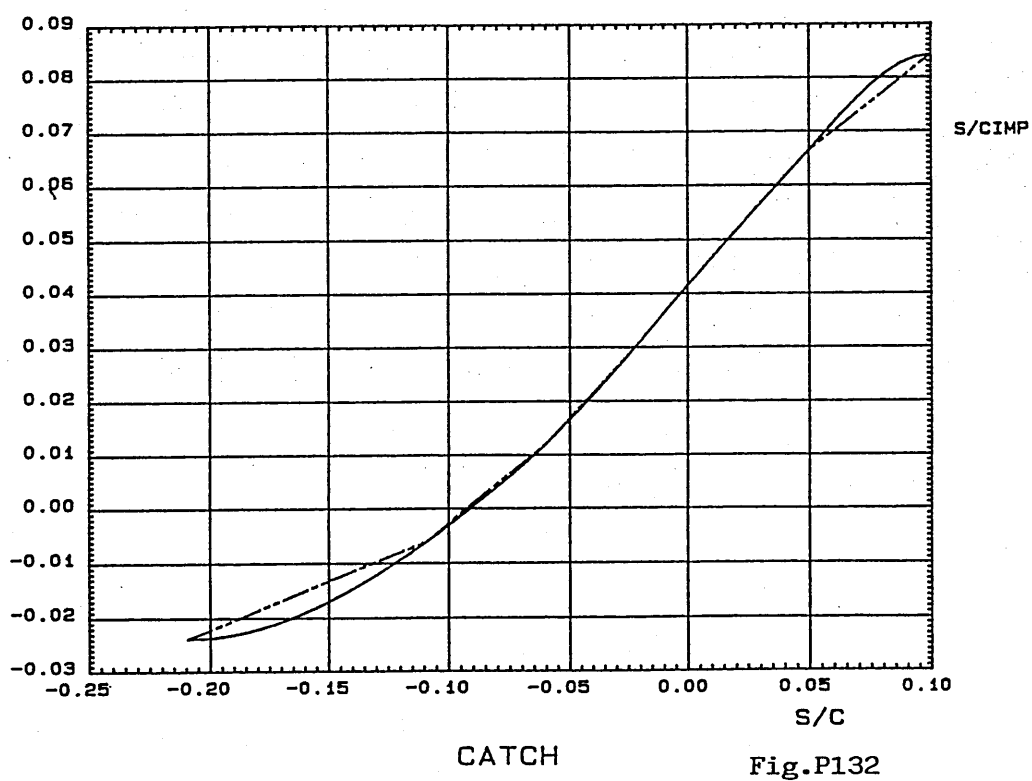
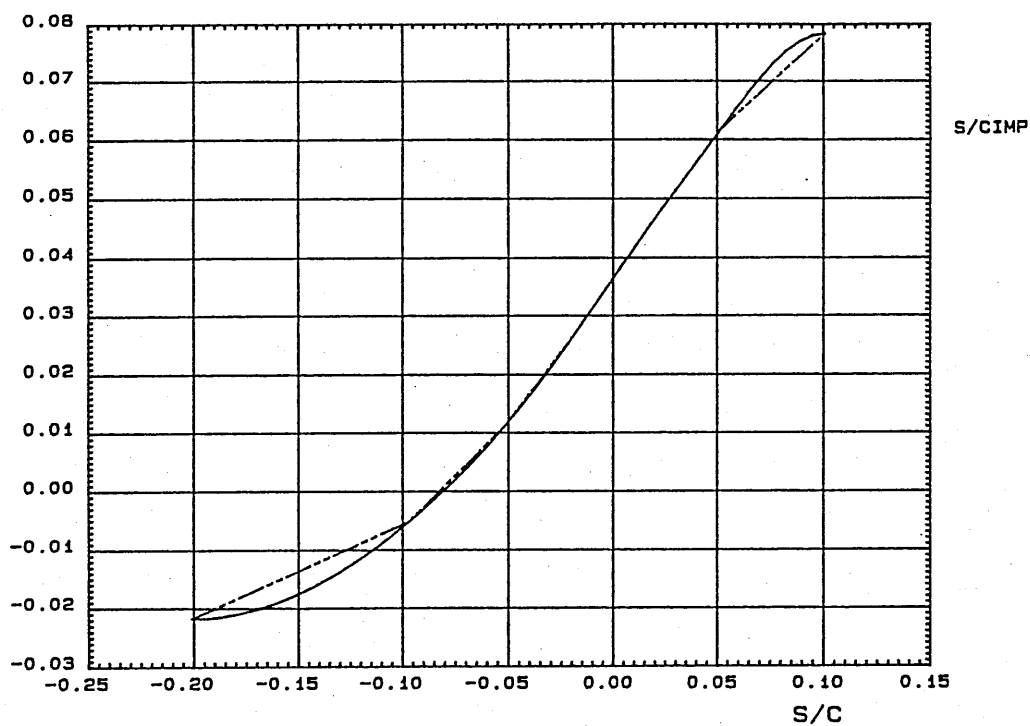


Fig.P133 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.2/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P113
Plot of Beta against s/c	= Fig.P153
Plot of Iced aerofoil	= Fig.P173
TRAJ2 equivalent plot	= Fig.P39

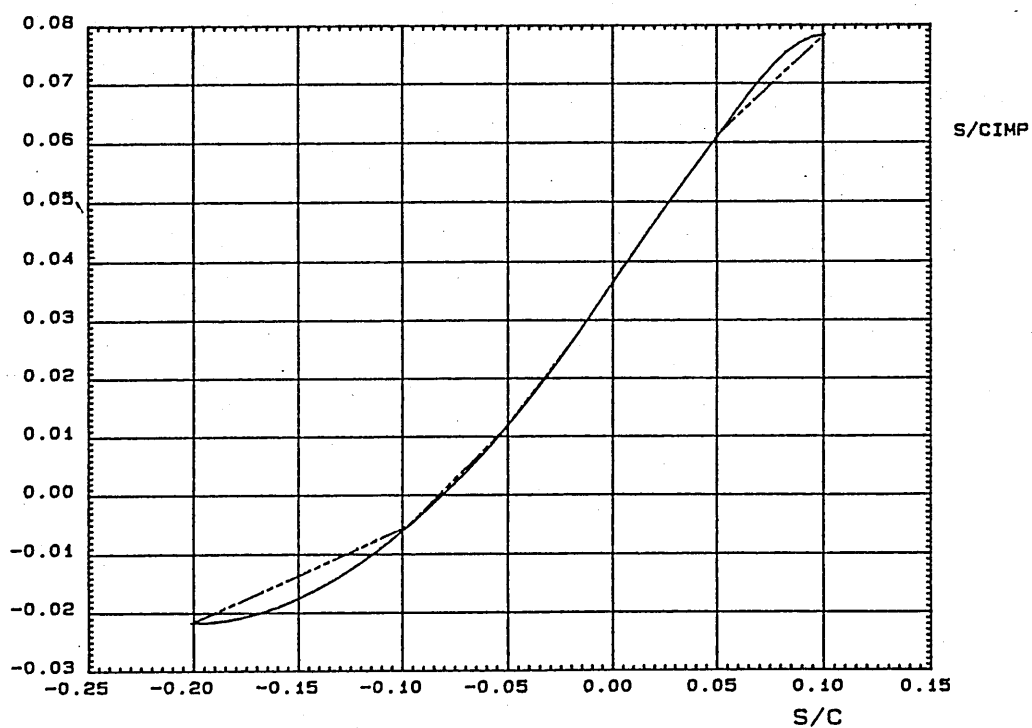
Fig.P134 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.3/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P134
Plot of Beta against s/c	= Fig.P154
Plot of Iced aerofoil	= Fig.P174
TRAJ2 equivalent plot	= Fig.P40



CATCH

Fig.P133



CATCH

Fig.P134

Fig.P135 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.4/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.420 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.7% developed aerofoil chord = 65.8% original lip section chord = 10.4% s/c = 44 mm aft over lip surface
Inner (lower) surface catch limit	= 7.5% developed aerofoil chord = 37.1% original lip section chord = 15.5% s/c = 65 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P115
Plot of Beta against s/c	= Fig.P155
Plot of Iced aerofoil	= Fig.P175
TRAJ2 equivalent plot	= Fig.P41

Fig.P136 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P116
Plot of Beta against s/c	= Fig.P156
Plot of Iced aerofoil	= Fig.P176
TRAJ2 equivalent plot	= Fig.P42

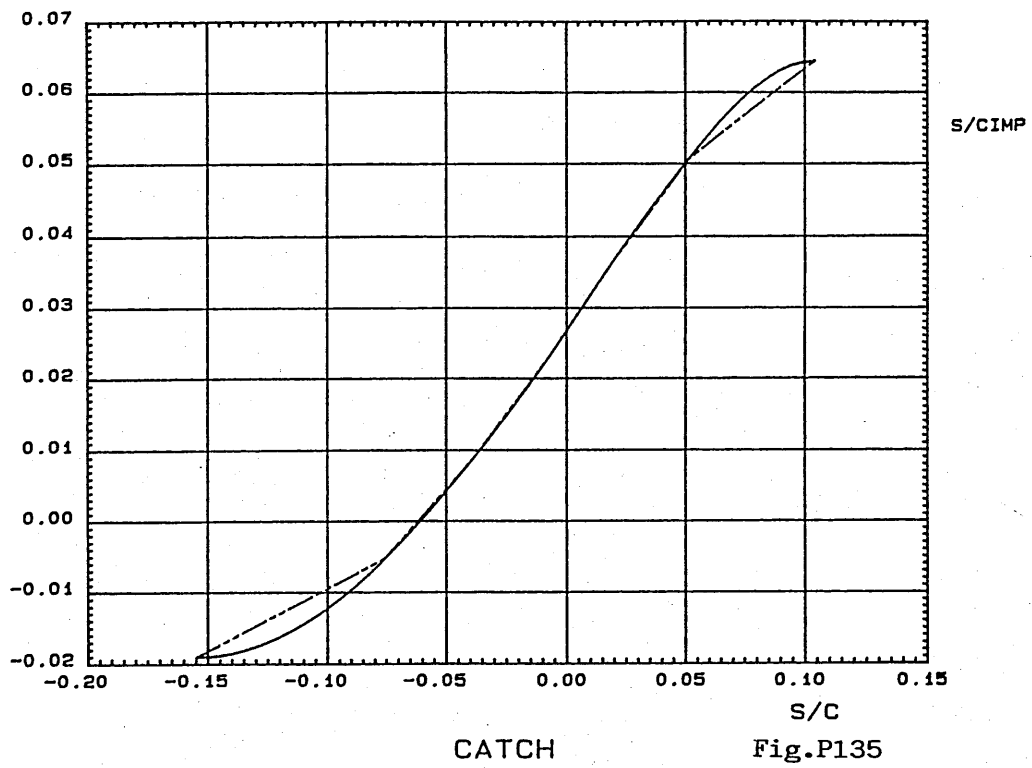
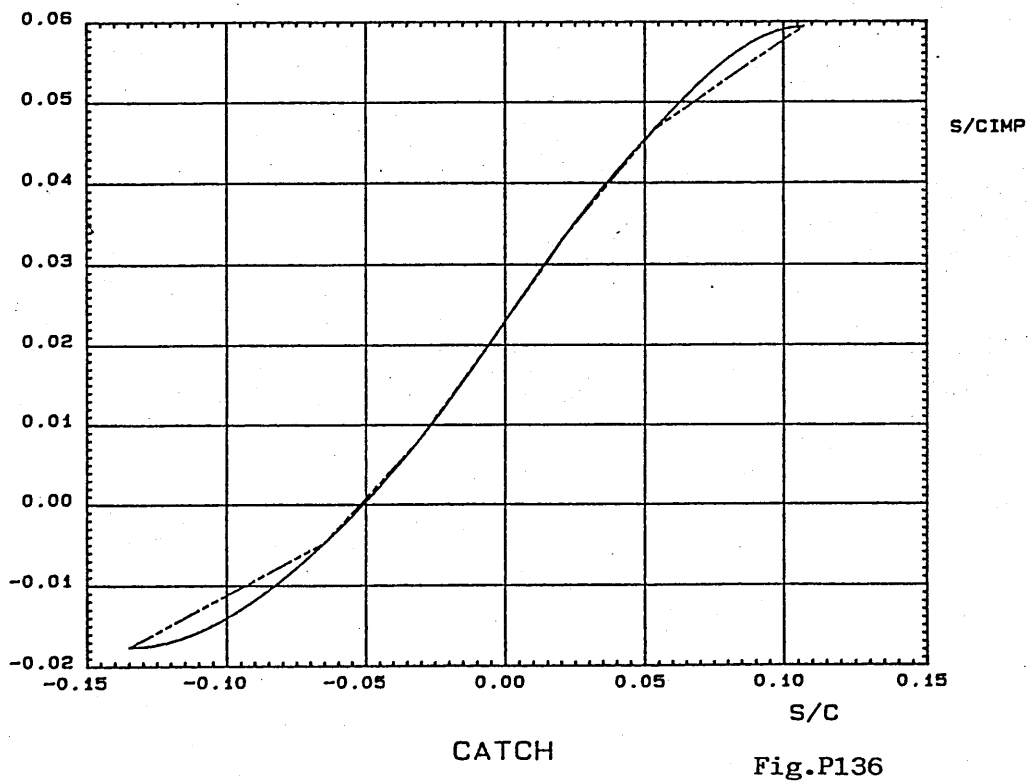
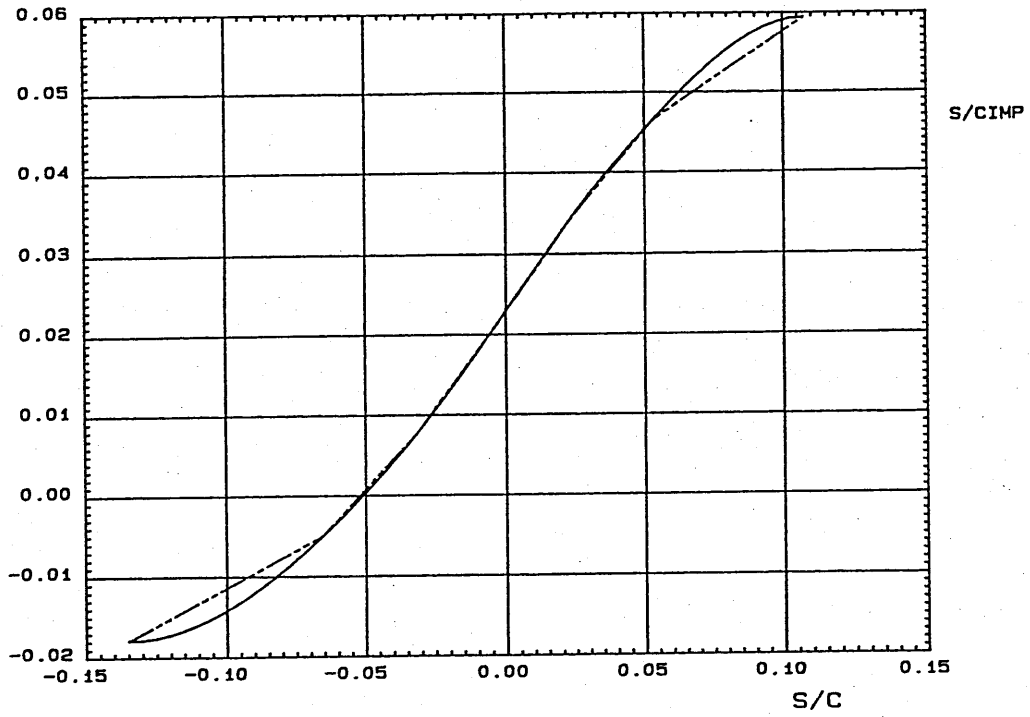


Fig.P137 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P117
Plot of Beta against s/c	= Fig.P157
Plot of Iced aerofoil	= Fig.P177
TRAJ2 equivalent plot	= Fig.P43

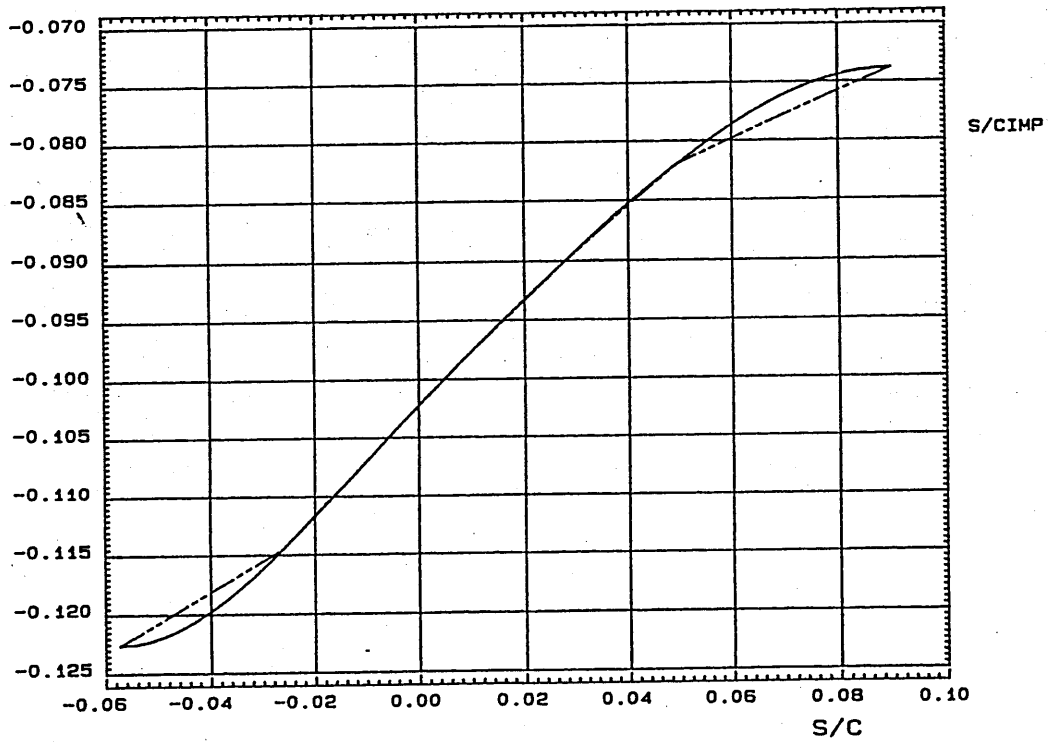
Fig.P138 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.7% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P118
Plot of Beta against s/c	= Fig.P158
Plot of Iced aerofoil	= Fig.P178
TRAJ2 equivalent plot	= Fig.P44



CATCH

Fig.P137



CATCH

Fig.P138

Fig.P139 (Case 17)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.2% developed aerofoil chord = 72.2% original lip section chord = 7.2% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 50.7% original lip section chord = 14.9% s/c = 83 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P119
Plot of Beta against s/c	= Fig.P159
Plot of Iced aerofoil	= Fig.P179
TRAJ2 equivalent plot	= Fig.P45

Fig.P140 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P120
Plot of Beta against s/c	= Fig.P160
Plot of Iced aerofoil	= Fig.P180
TRAJ2 equivalent plot	= Fig.P46

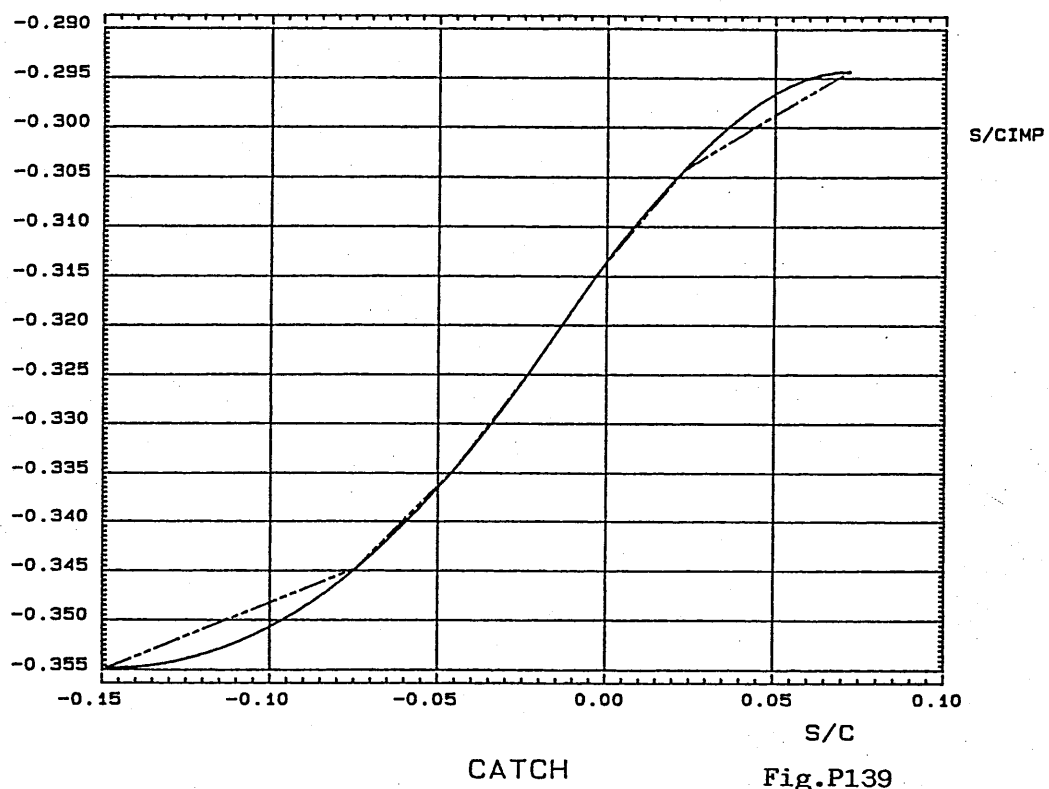
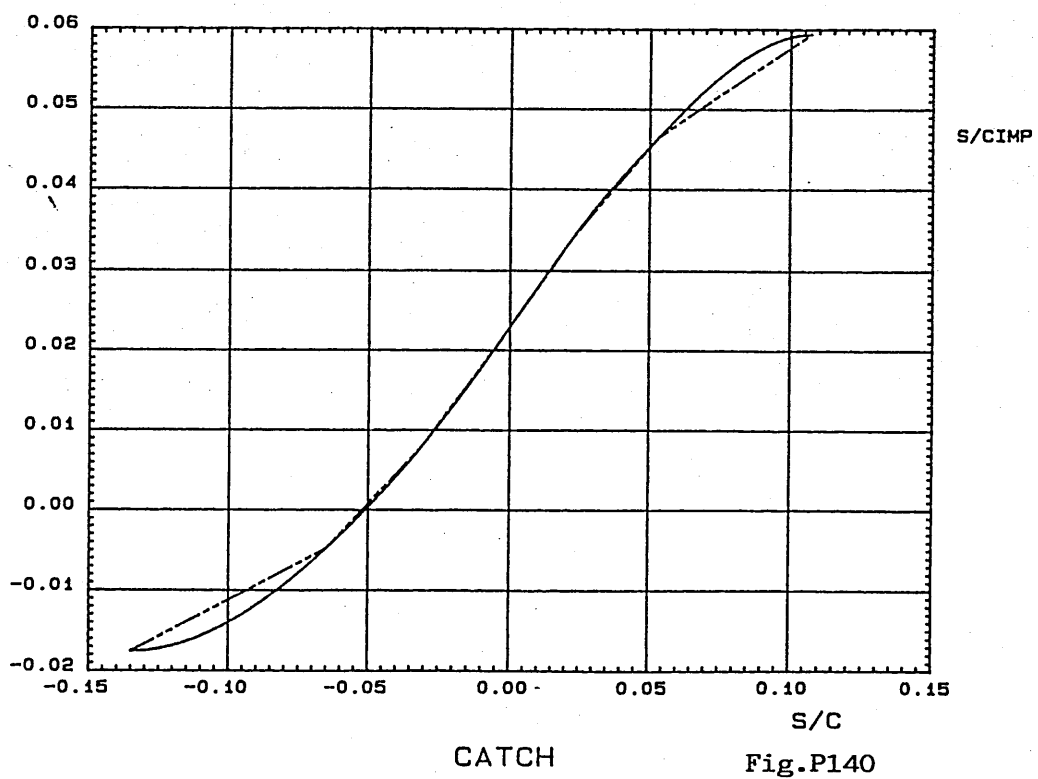


Fig.P141 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 131.3% original lip section chord = 10.0% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P121
Plot of Beta against s/c	= Fig.P161
Plot of Iced aerofoil	= Fig.P181
TRAJ2 equivalent plot	= Fig.P47

Fig.P142 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 131.3% original lip section chord = 10.1% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P122
Plot of Beta against s/c	= Fig.P162
Plot of Iced aerofoil	= Fig.P182
TRAJ2 equivalent plot	= Fig.P48

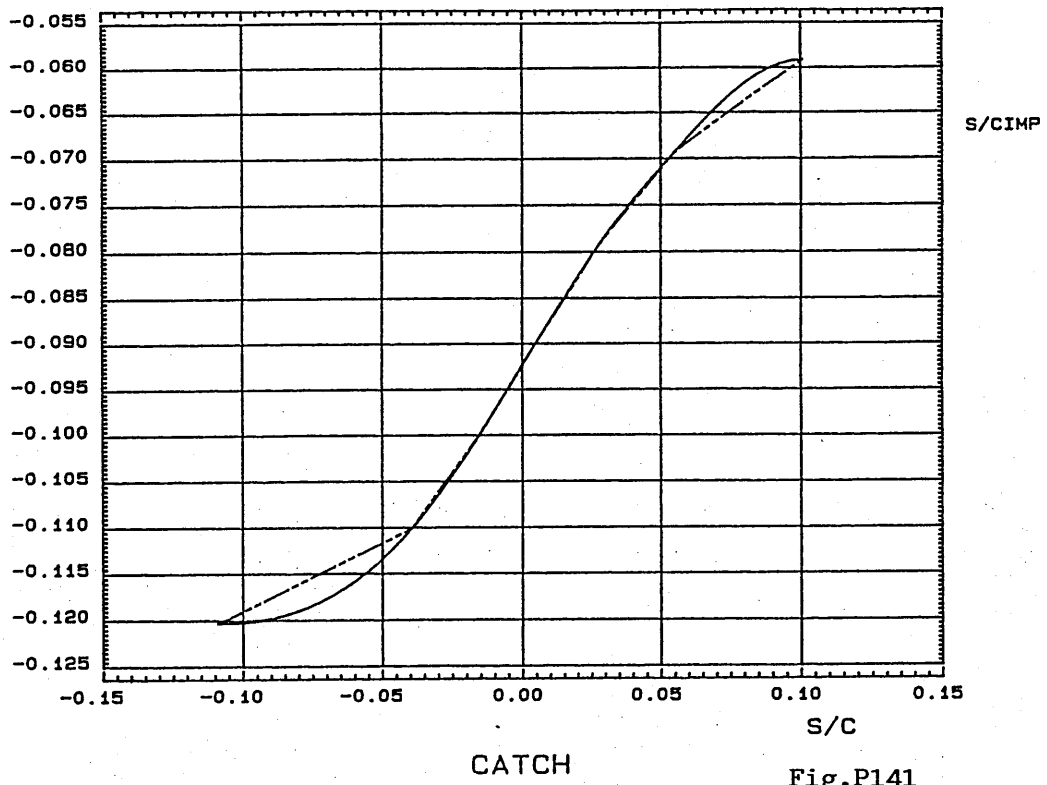
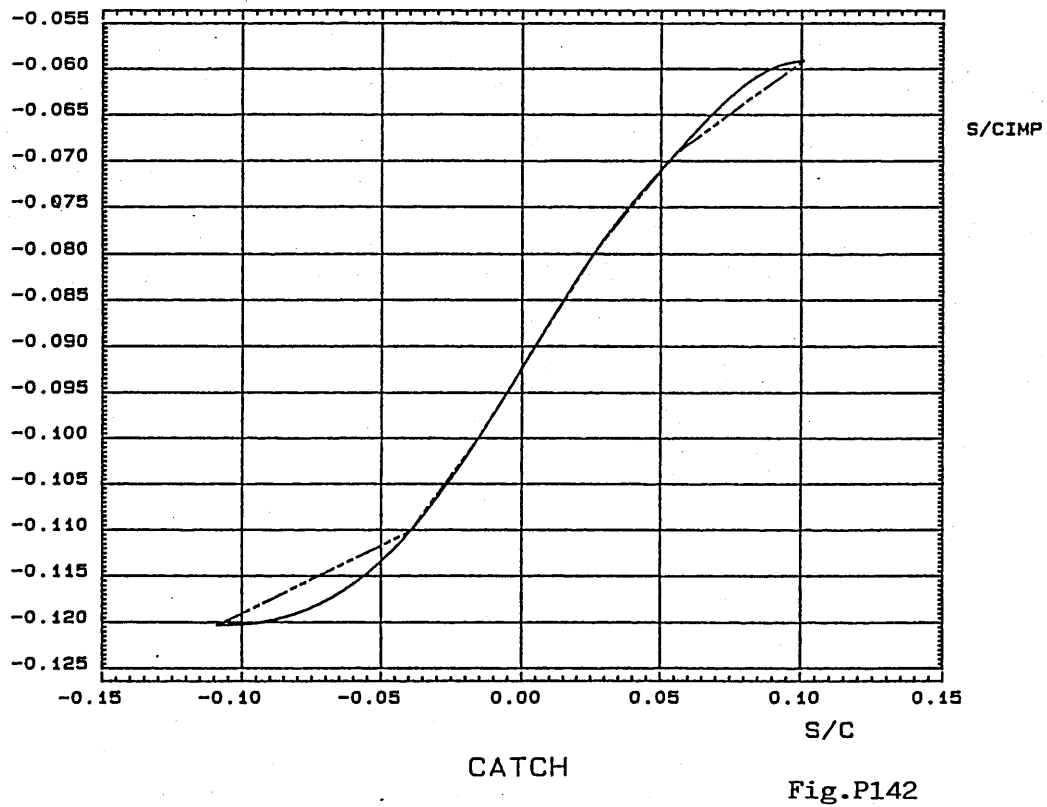
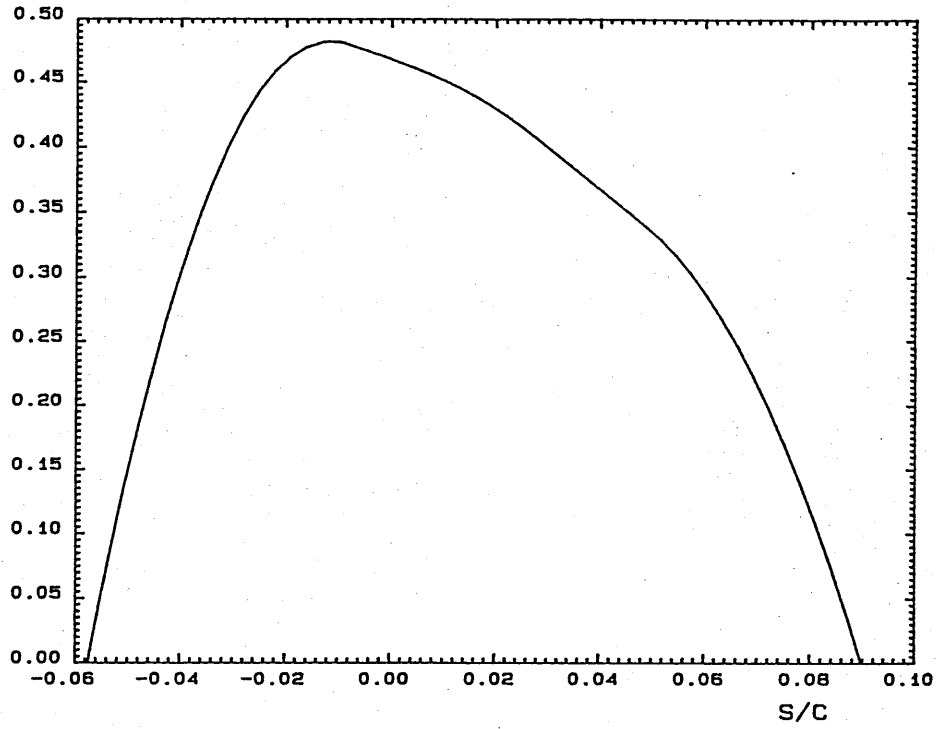


Fig.P143 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P103
Plot of Scimp and Scsp against s/c	= Fig.P123
Plot of Iced aerofoil	= Fig.P163
TRAJ2 equivalent plot	= Fig.P49

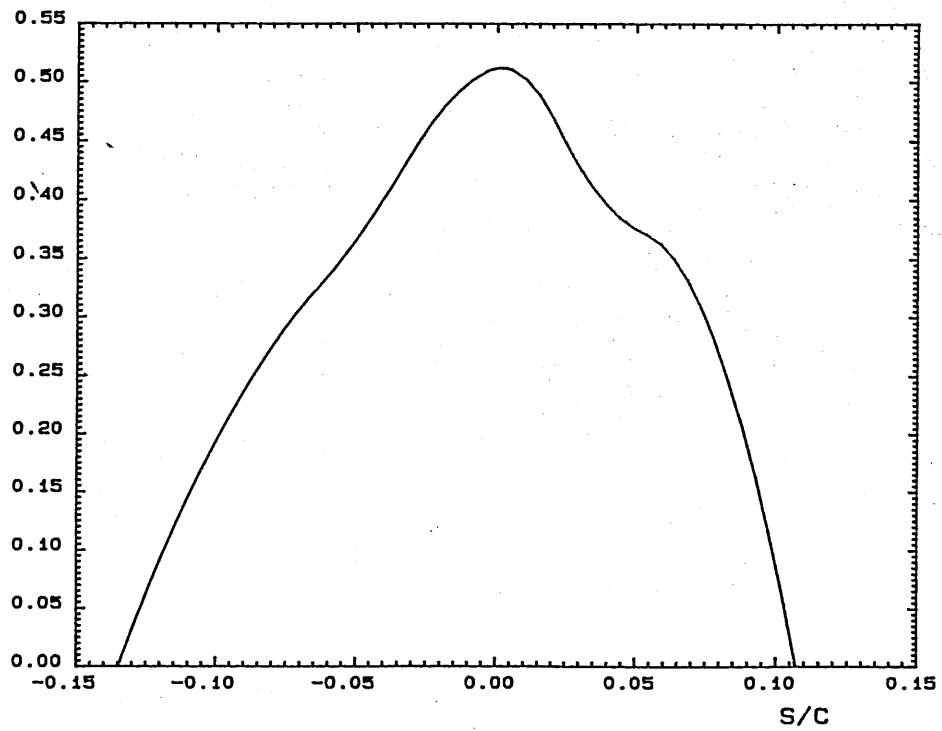
Fig.P144 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P104
Plot of Scimp and Scsp against s/c	= Fig.P124
Plot of Iced aerofoil	= Fig.P164
TRAJ2 equivalent plot	= Fig.P50



Catch Efficiency

Fig.P143



Catch Efficiency

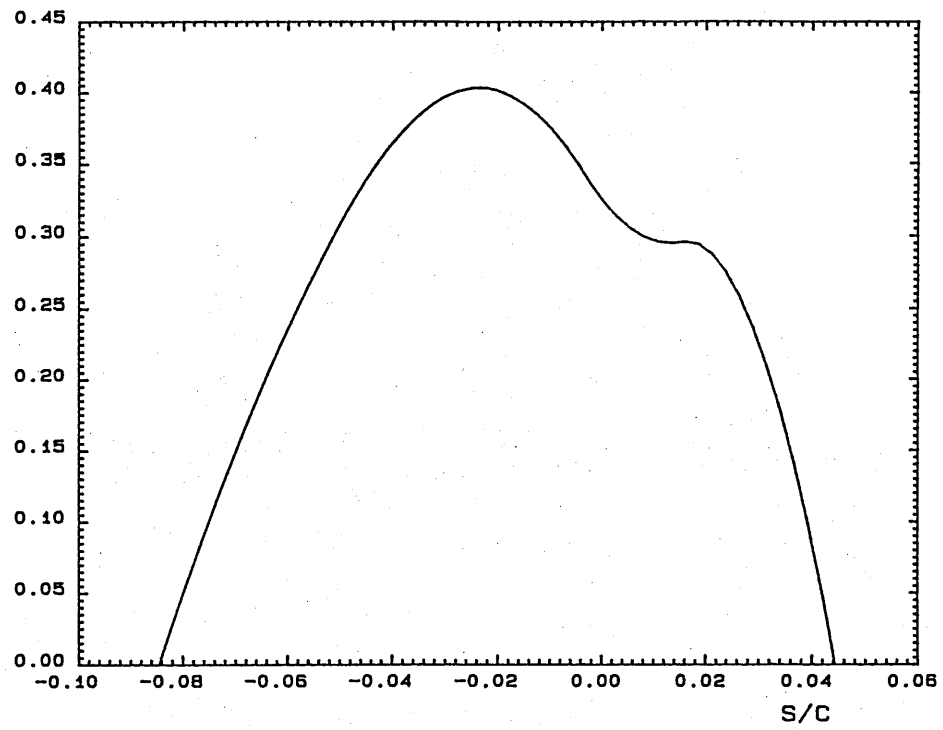
Fig.P144

Fig.P145 (Case 3)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P105
Plot of Scimp and Scsp against s/c	= Fig.P125
Plot of Iced aerofoil	= Fig.P165
TRAJ2 equivalent plot	= Fig.P51

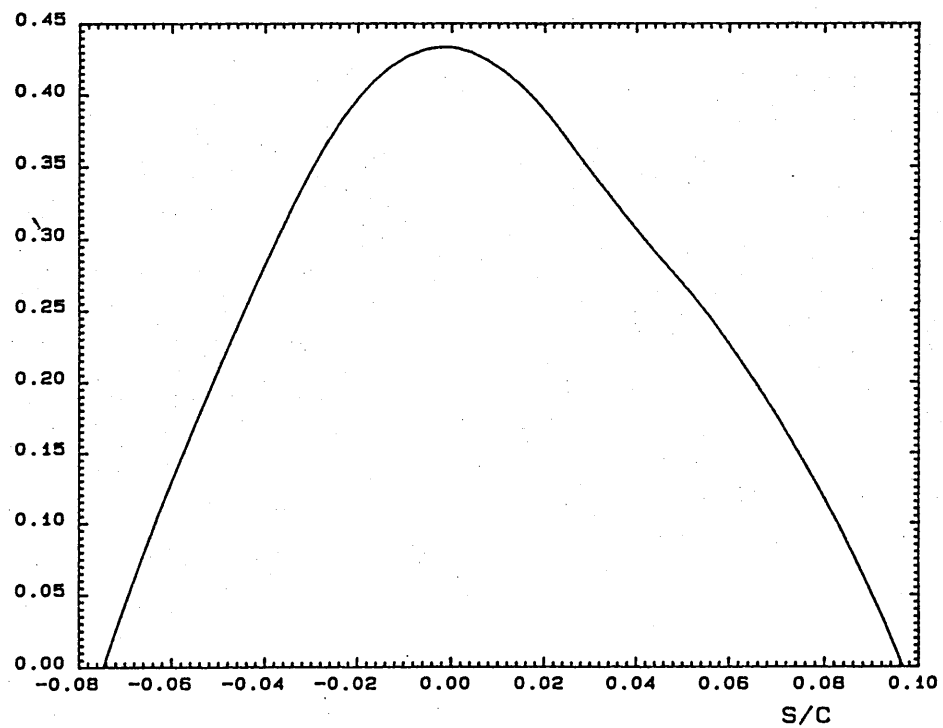
Fig.P146 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P106
Plot of Scimp and Scsp against s/c	= Fig.P126
Plot of Iced aerofoil	= Fig.P166
TRAJ2 equivalent plot	= Fig.P52



Catch Efficiency

Fig. P145



Catch Efficiency

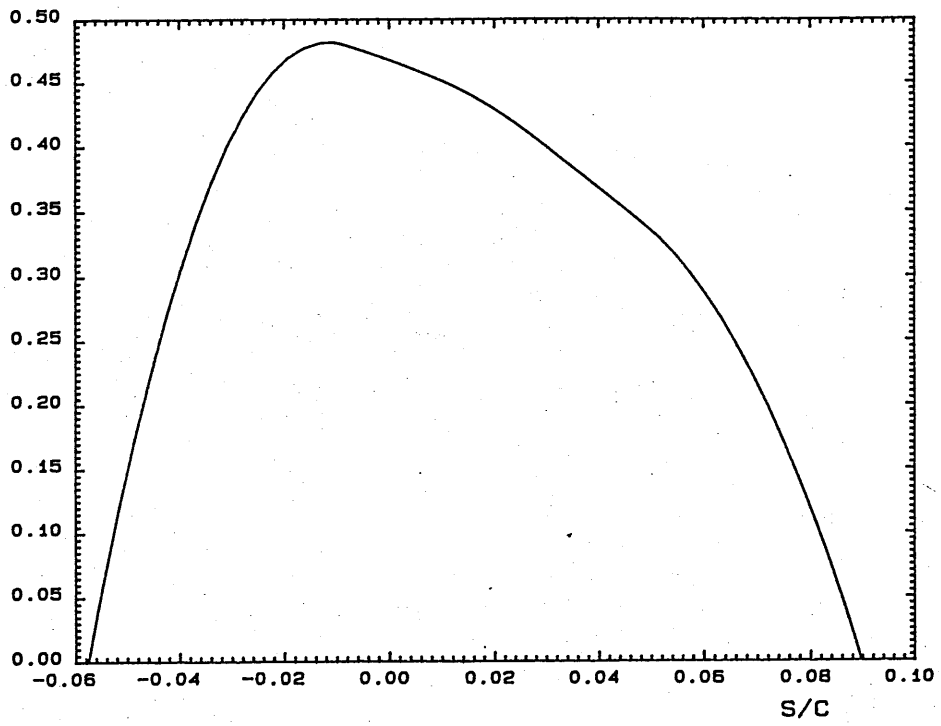
Fig. P146

Fig.P147 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/B;F	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P107
Plot of Scimp and Scsp against s/c	= Fig.P127
Plot of Iced aerofoil	= Fig.P167
TRAJ2 equivalent plot	= Fig.P53

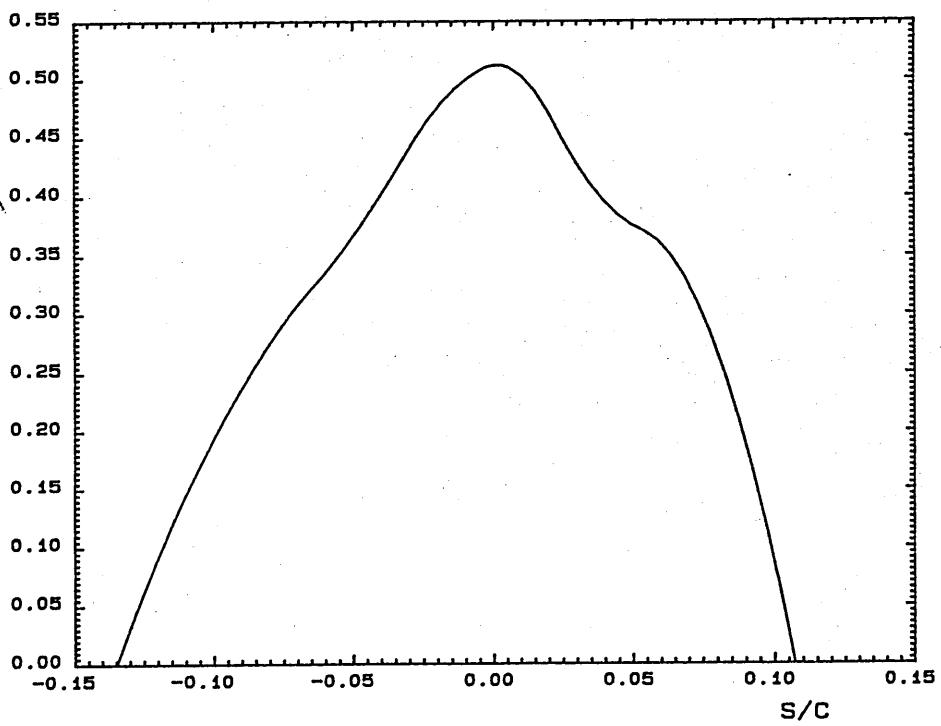
Fig.P148 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P108
Plot of Scimp and Scsp against s/c	= Fig.P128
Plot of Iced aerofoil	= Fig.P168
TRAJ2 equivalent plot	= Fig.P54



Catch Efficiency

Fig.P147



Catch Efficiency

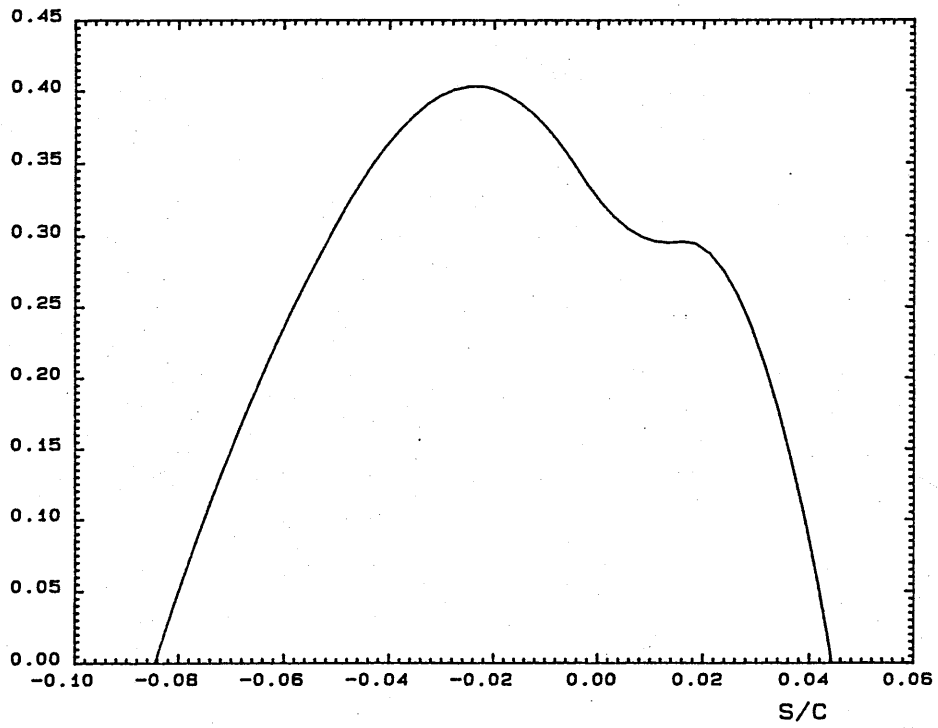
Fig.P148

Fig.P149 (Case 7)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P109
Plot of Scimp and Scsp against s/c	= Fig.P129
Plot of Iced aerofoil	= Fig.P169
TRAJ2 equivalent plot	= Fig.P55

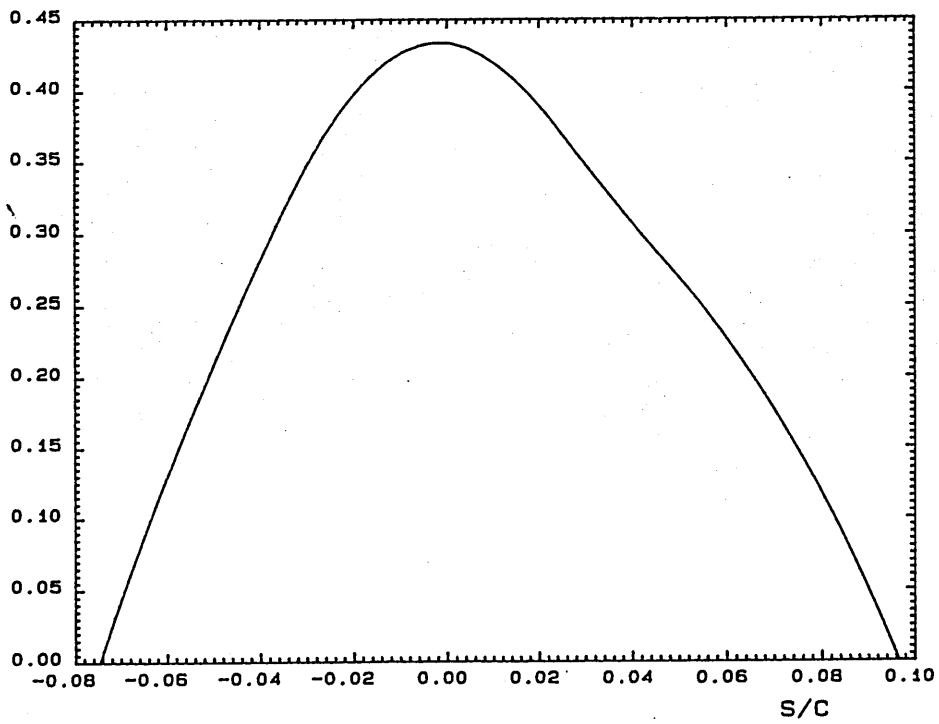
Fig.P150 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P110
Plot of Scimp and Scsp against s/c	= Fig.P130
Plot of Iced aerofoil	= Fig.P170
TRAJ2 equivalent plot	= Fig.P56



Catch Efficiency

Fig.P149



Catch Efficiency

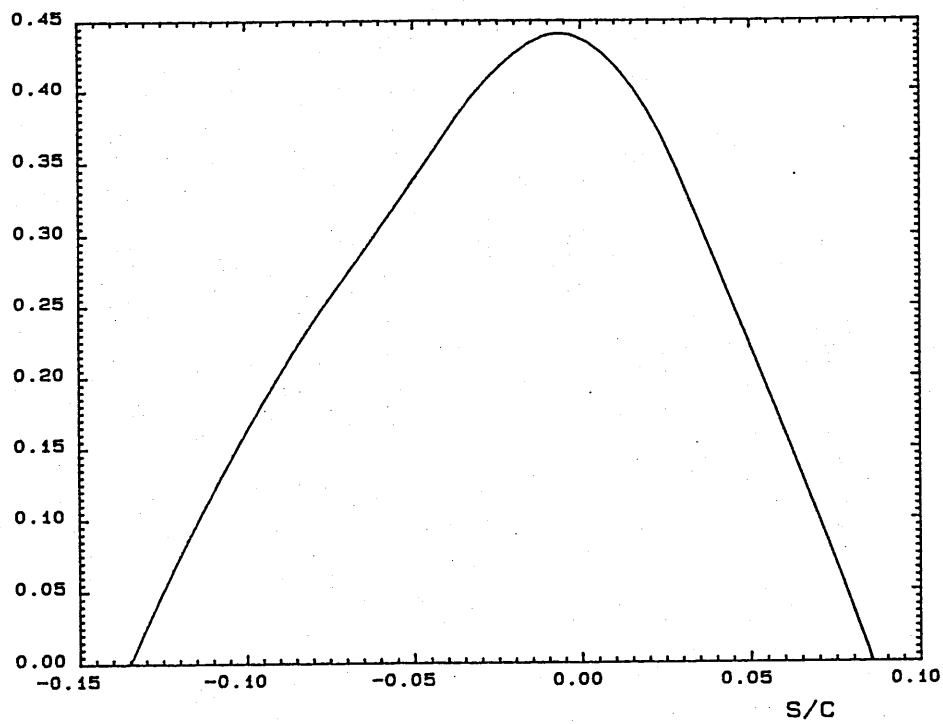
Fig.P150

Fig.P151 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 57.7% original lip section chord = 8.6% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P111
Plot of Scimp and Scsp against s/c	= Fig.P131
Plot of Iced aerofoil	= Fig.P171
TRAJ2 equivalent plot	= Fig.P57

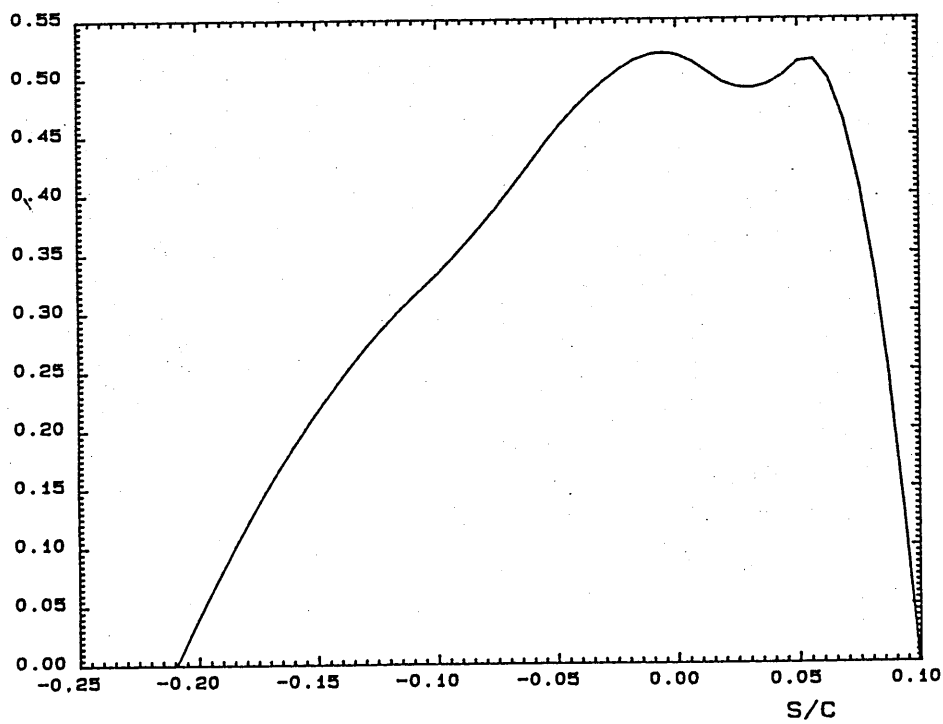
Fig.P152 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.1/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.302 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 37.2% original lip section chord = 10.0% s/c = 30 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 35.5% original lip section chord = 21.0% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P112
Plot of Scimp and Scsp against s/c	= Fig.P132
Plot of Iced aerofoil	= Fig.P172
TRAJ2 equivalent plot	= Fig.P58



Catch Efficiency

Fig.P151



Catch Efficiency

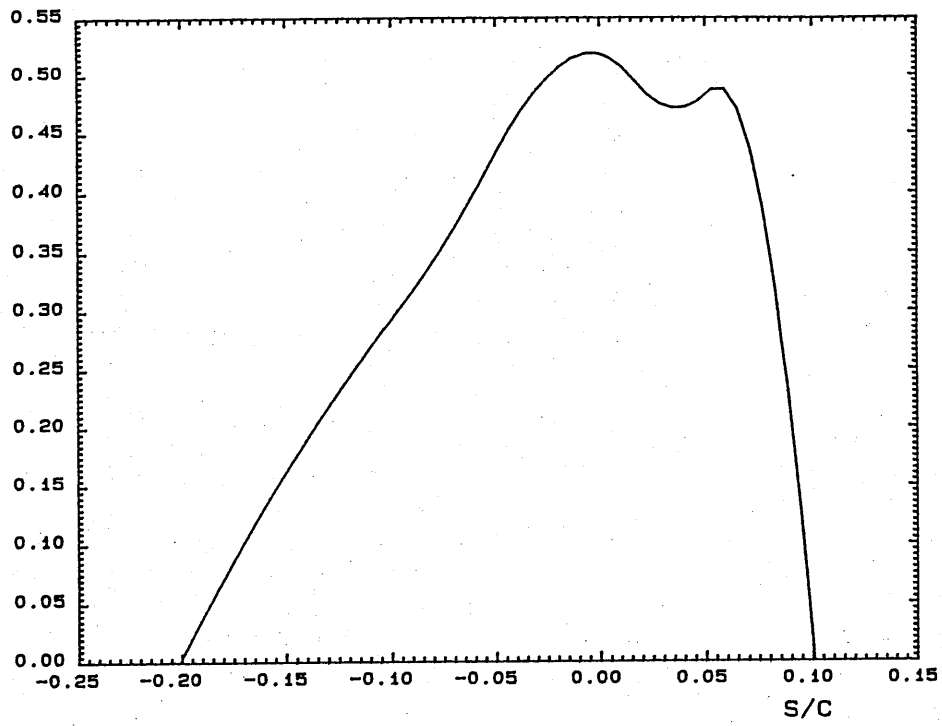
Fig.P152

Fig.P153 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.2/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P113
Plot of Scimp and Scsp against s/c	= Fig.P133
Plot of Iced aerofoil	= Fig.P173
TRAJ2 equivalent plot	= Fig.P59

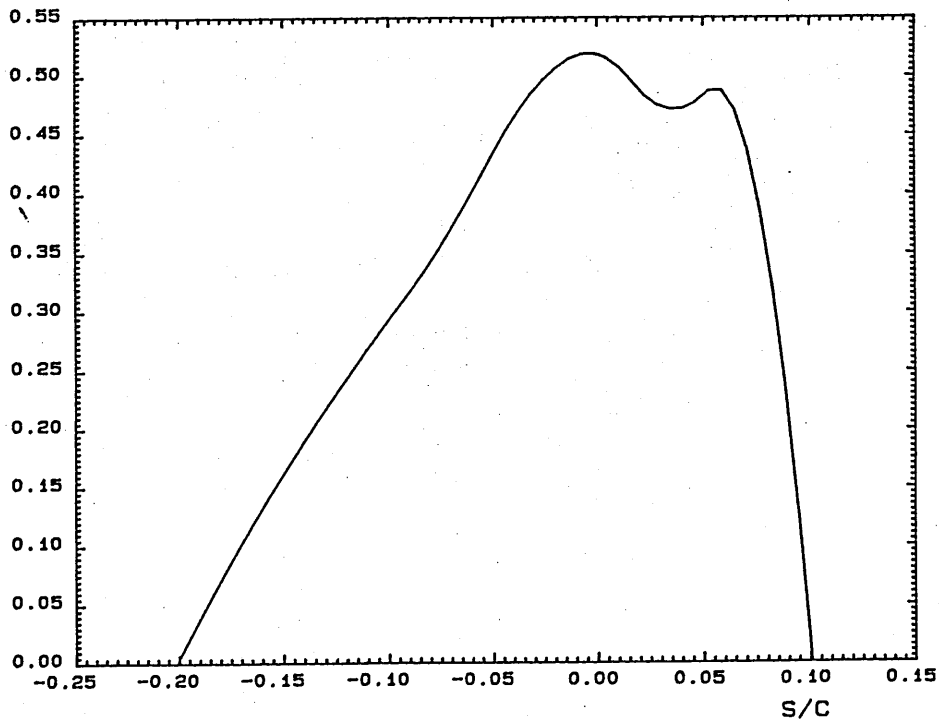
Fig.P154 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.3/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P104
Plot of Scimp and Scsp against s/c	= Fig.P134
Plot of Iced aerofoil	= Fig.P174
TRAJ2 equivalent plot	= Fig.P60



Catch Efficiency

Fig.P153



Catch Efficiency

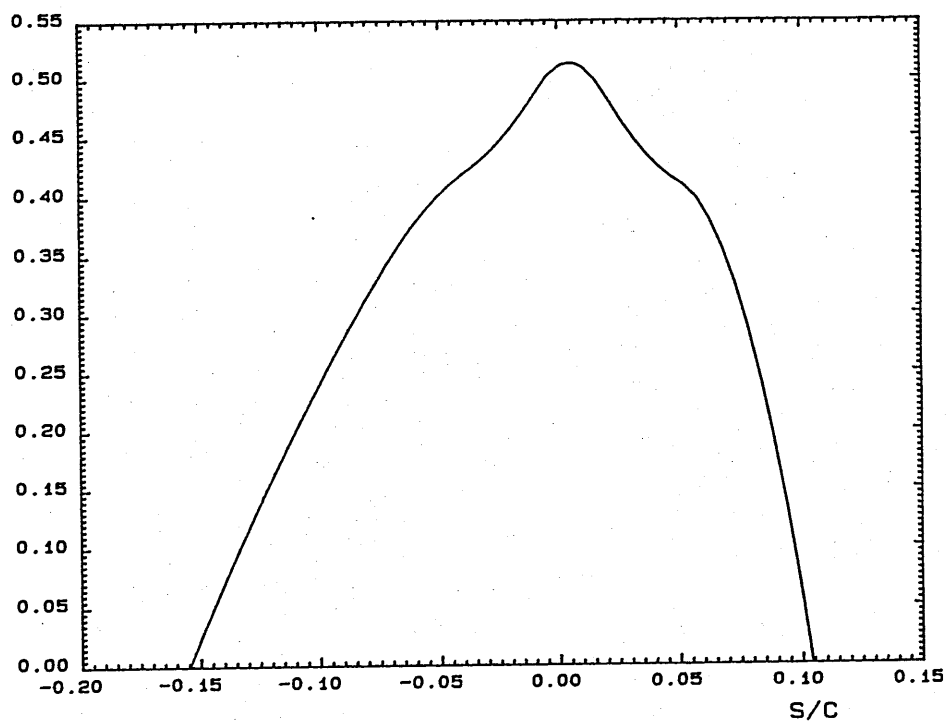
Fig.P154

Fig.P155 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.4/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.420 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 μm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.7% developed aerofoil chord = 65.8% original lip section chord = 10.4% s/c = 44 mm aft over lip surface
Inner (lower) surface catch limit	= 7.5% developed aerofoil chord = 37.1% original lip section chord = 15.5% s/c = 65 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P115
Plot of Scimp and Scsp against s/c	= Fig.P135
Plot of Iced aerofoil	= Fig.P175
TRAJ2 equivalent plot	= Fig.P61

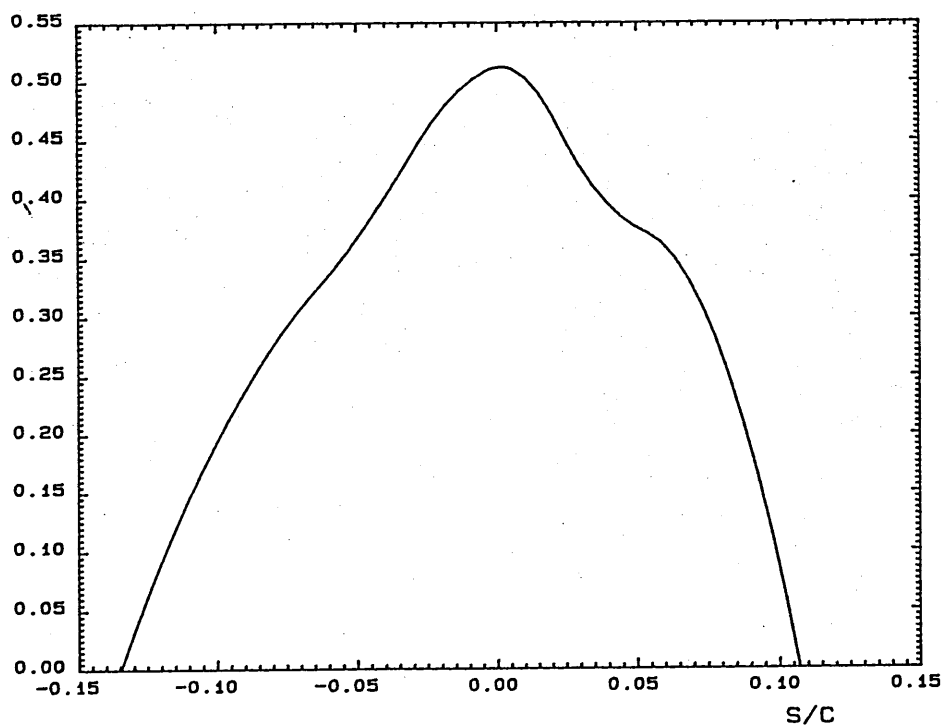
Fig.P156 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 μm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P116
Plot of Scimp and Scsp against s/c	= Fig.P136
Plot of Iced aerofoil	= Fig.P176
TRAJ2 equivalent plot	= Fig.P62



Catch Efficiency

Fig.P155



Catch Efficiency

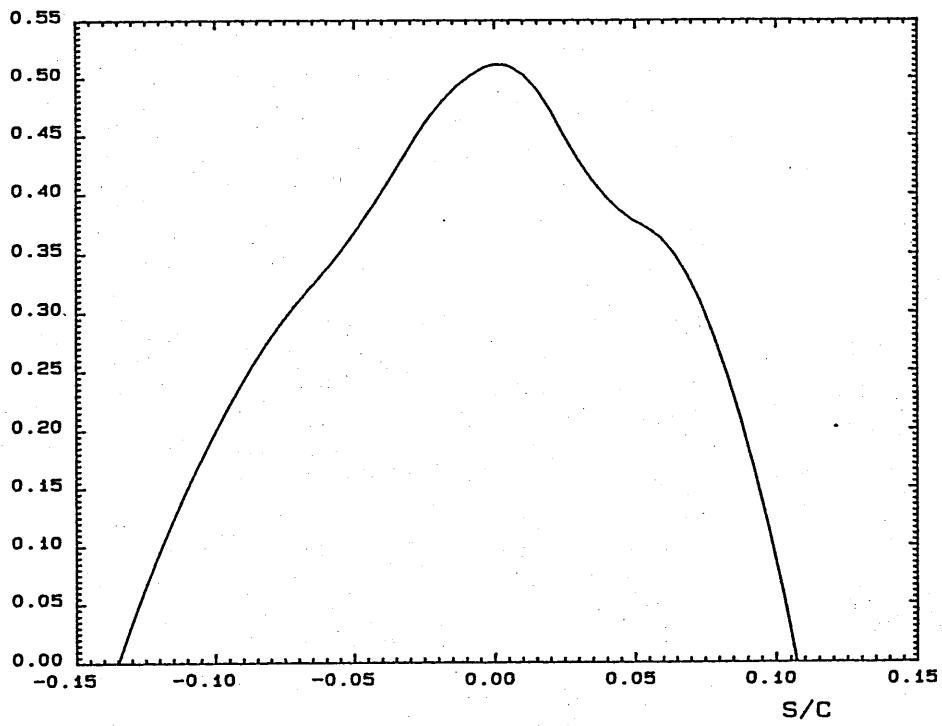
Fig.P156

Fig.P157 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P117
Plot of Scimp and Scsp against s/c	= Fig.P137
Plot of Iced aerofoil	= Fig.P177
TRAJ2 equivalent plot	= Fig.P63

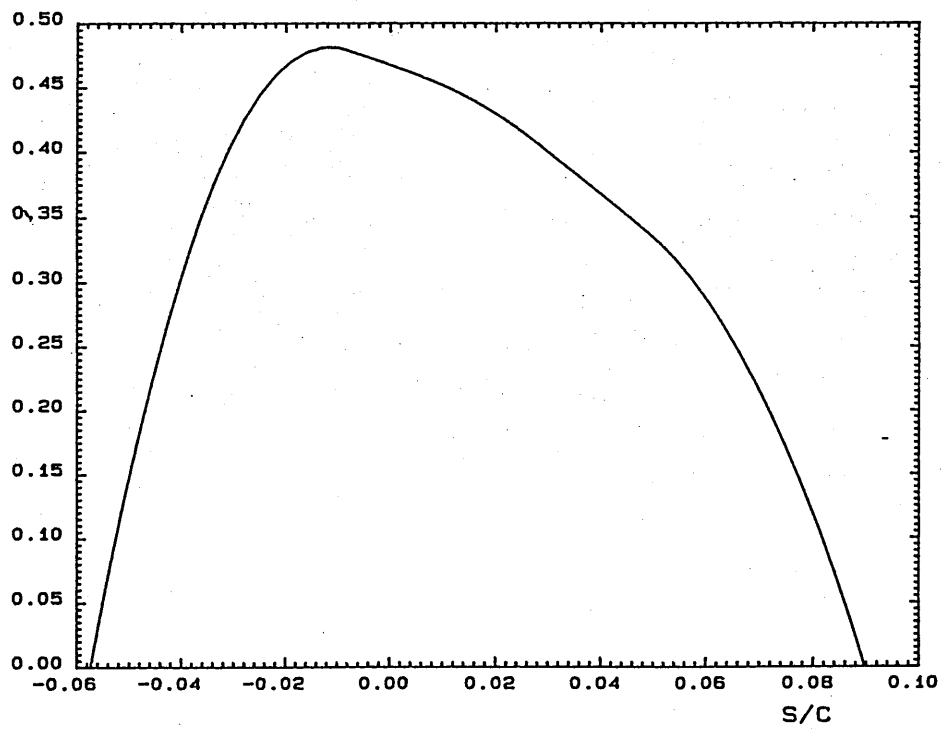
Fig.P158 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m ₋₁
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.7% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P118
Plot of Scimp and Scsp against s/c	= Fig.P138
Plot of Iced aerofoil	= Fig.P178
TRAJ2 equivalent plot	= Fig.P64



Catch Efficiency

Fig.P157



Catch Efficiency

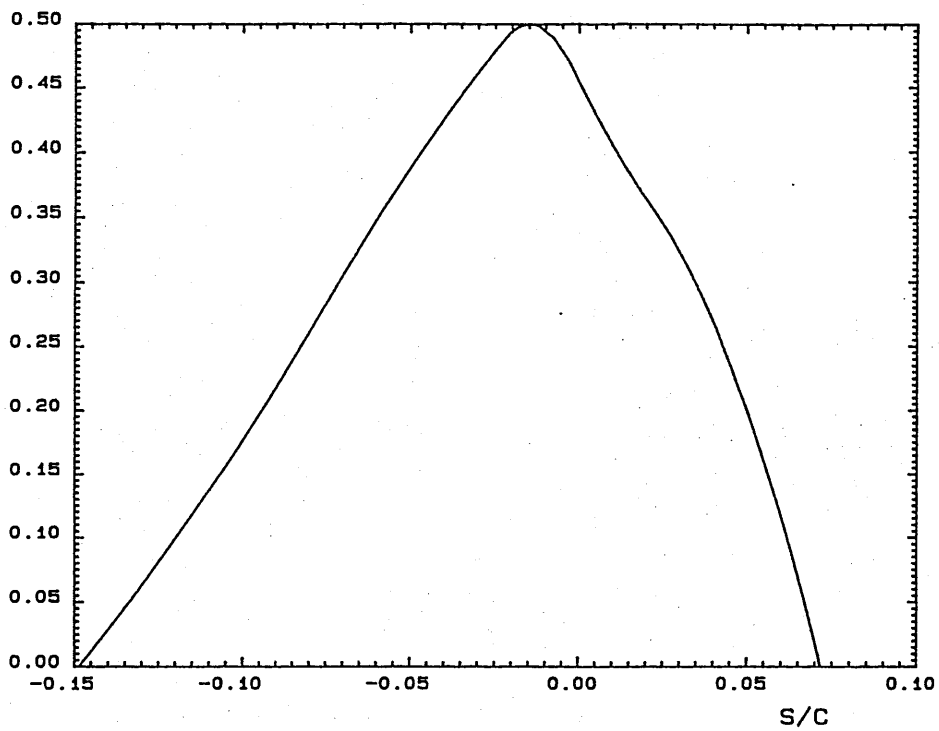
Fig.P158

Fig.P159 (Case 17)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.2% developed aerofoil chord = 72.2% original lip section chord = 7.2% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 50.7% original lip section chord = 14.9% s/c = 83 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P119
Plot of Scimp and Scsp against s/c	= Fig.P139
Plot of Iced aerofoil	= Fig.P179
TRAJ2 equivalent plot	= Fig.P65

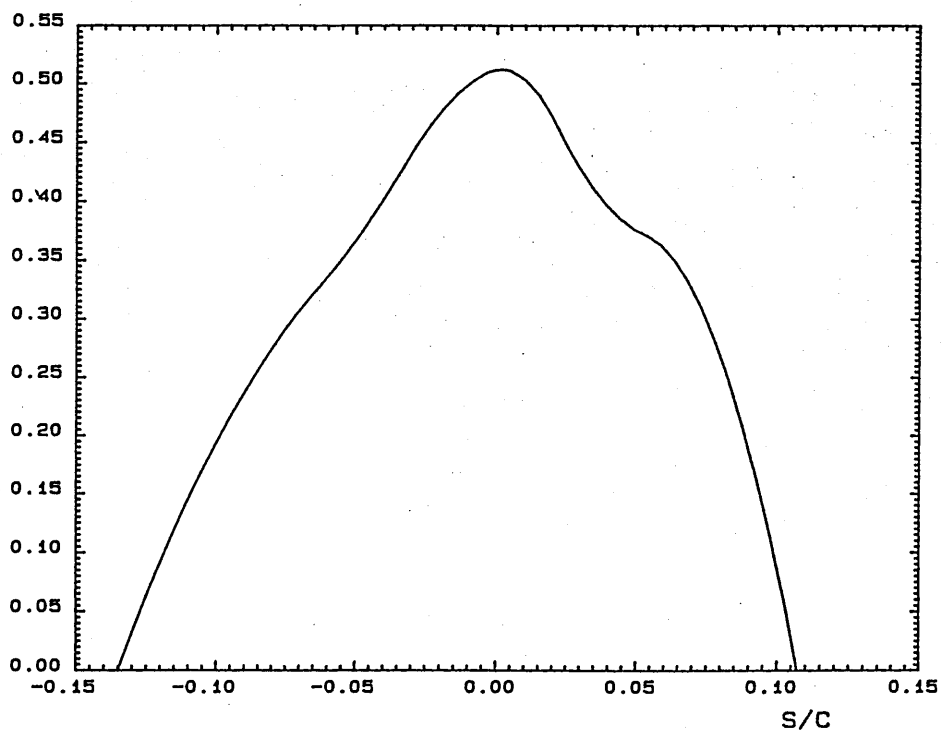
Fig.P160 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P120
Plot of Scimp and Scsp against s/c	= Fig.P140
Plot of Iced aerofoil	= Fig.P180
TRAJ2 equivalent plot	= Fig.P66



Catch Efficiency

Fig.P159



Catch Efficiency

Fig.P160

Fig.P161 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 μm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord =131.3% original lip section chord = 10.0% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P121
Plot of Scimp and Scsp against s/c	= Fig.P141
Plot of Iced aerofoil	= Fig.P181
TRAJ2 equivalent plot	= Fig.P67

Fig.P162 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 μm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord =131.3% original lip section chord = 10.1% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P122
Plot of Scimp and Scsp against s/c	= Fig.P142
Plot of Iced aerofoil	= Fig.P182
TRAJ2 equivalent plot	= Fig.P68

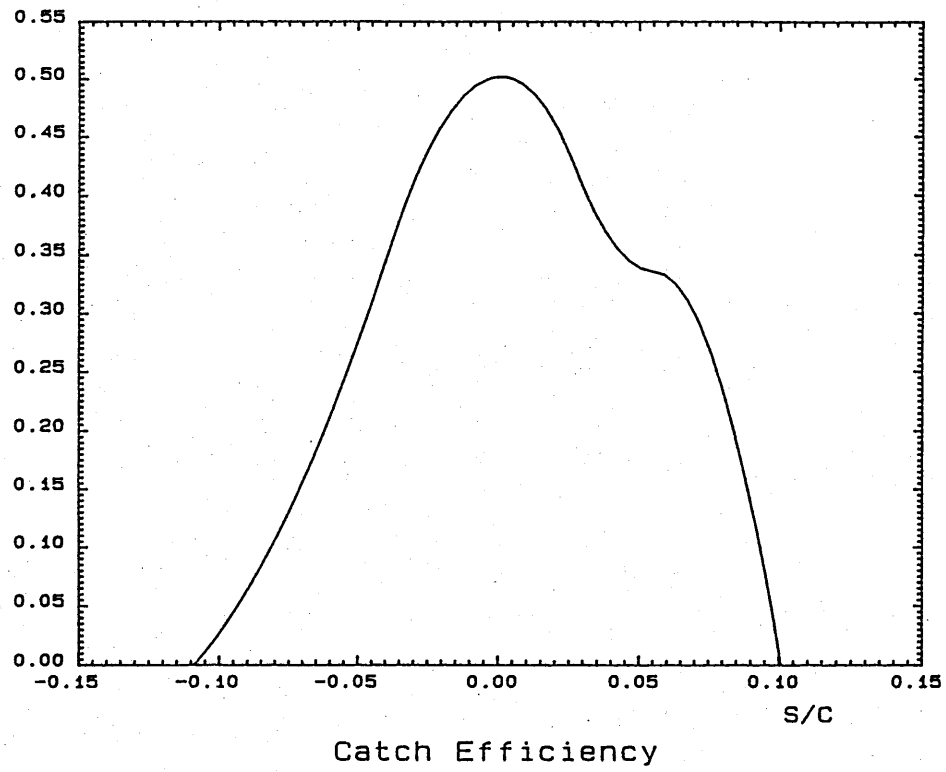


Fig.P161

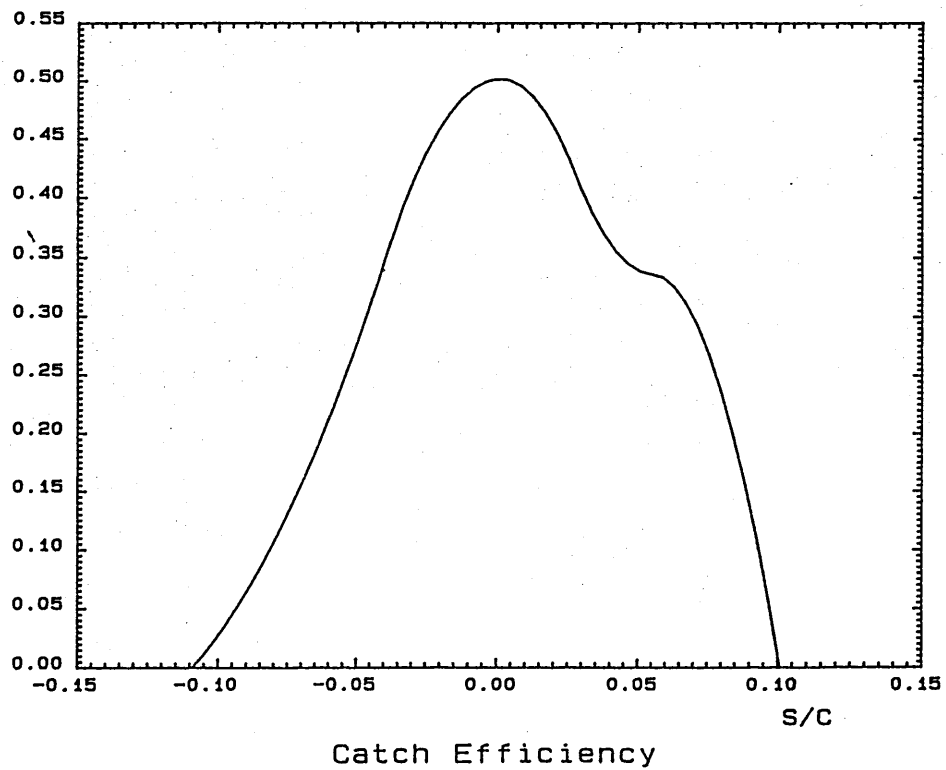


Fig.P162

Fig.P163 (Case 1)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P103
Plot of Scimp and Scsp against s/c	= Fig.P123
Plot of Beta against s/c	= Fig.P143
TRAJ2 equivalent plot	= Fig.P69

Fig.P164 (Case 2)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P104
Plot of Scimp and Scsp against s/c	= Fig.P124
Plot of Beta against s/c	= Fig.P144
TRAJ2 equivalent plot	= Fig.P70

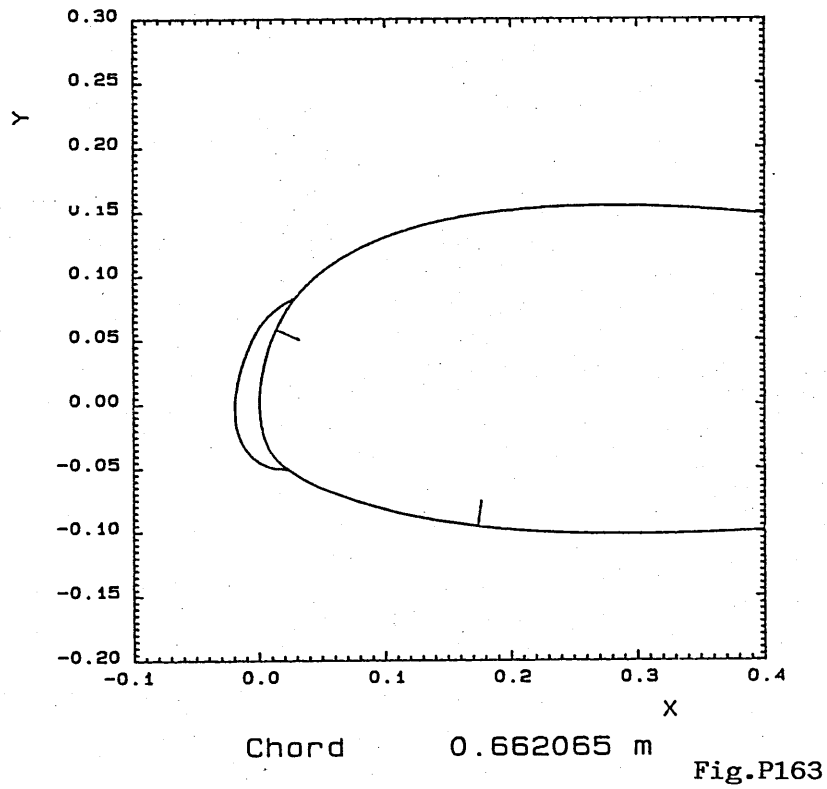
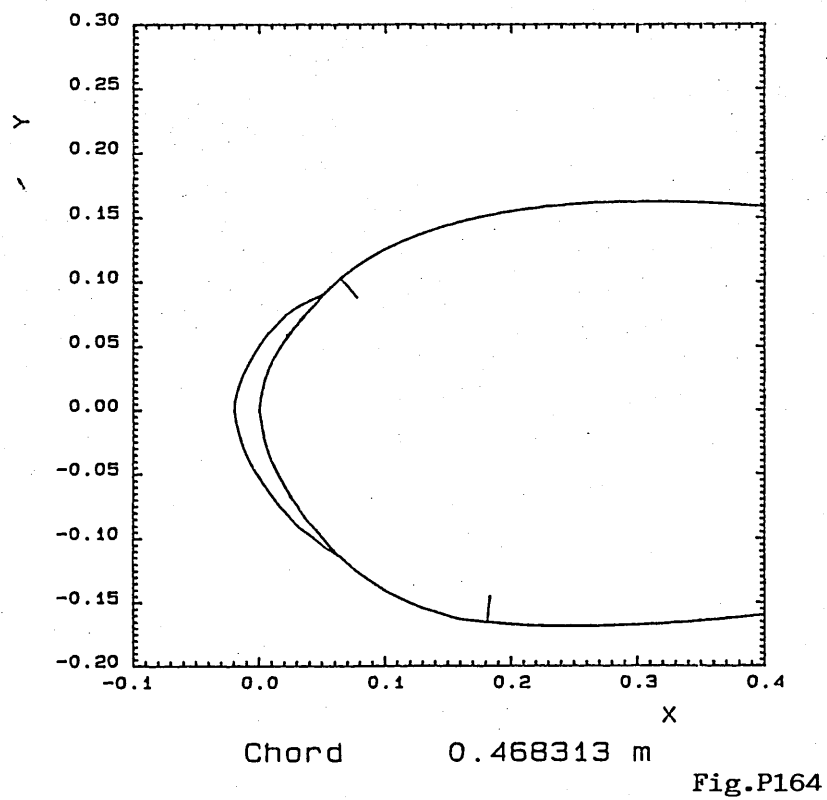
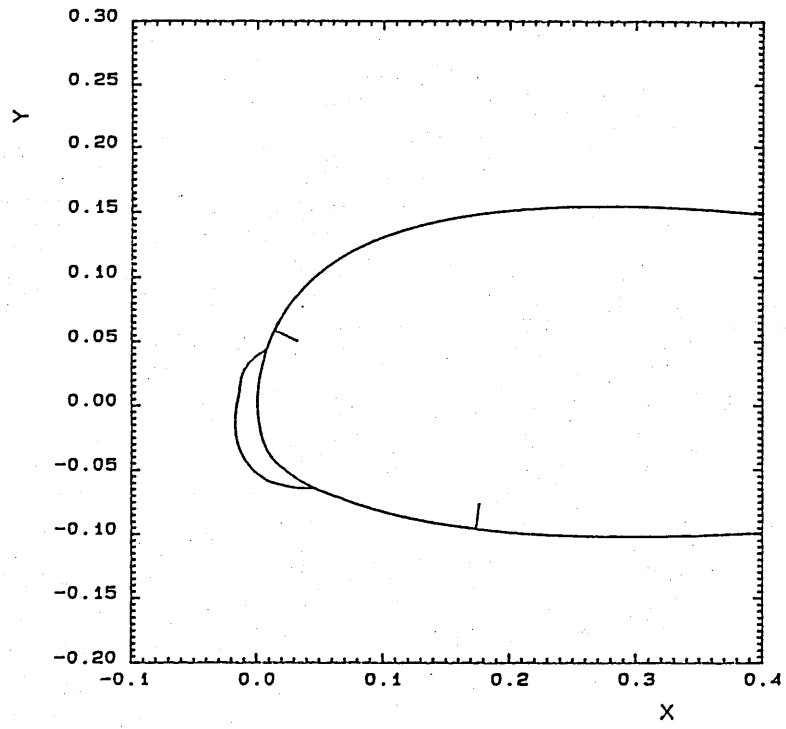


Fig.P165 (Case 3)

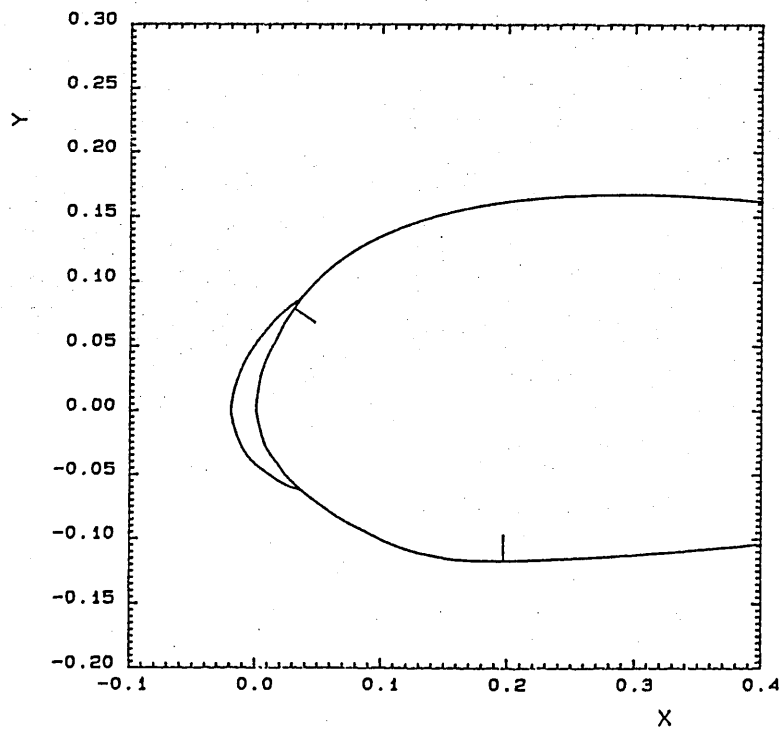
Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P105
Plot of Scimp and Scsp against s/c	= Fig.P125
Plot of Beta against s/c	= Fig.P145
TRAJ2 equivalent plot	= Fig.P71

Fig.P166 (Case 4)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P106
Plot of Scimp and Scsp against s/c	= Fig.P126
Plot of Beta against s/c	= Fig.P146
TRAJ2 equivalent plot	= Fig.P72



Chord 0.662065 m Fig.P165



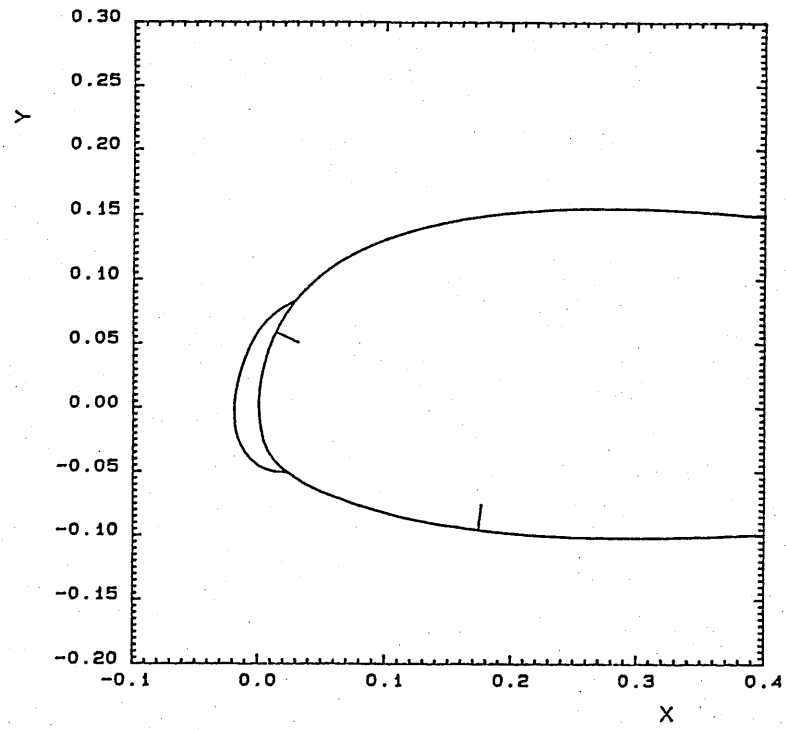
Chord 0.558118 m Fig.P166

Fig.P167 (Case 5)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/B;F	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.8% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P107
Plot of Scimp and Scsp against s/c	= Fig.P127
Plot of Beta against s/c	= Fig.P147
TRAJ2 equivalent plot	= Fig.P73

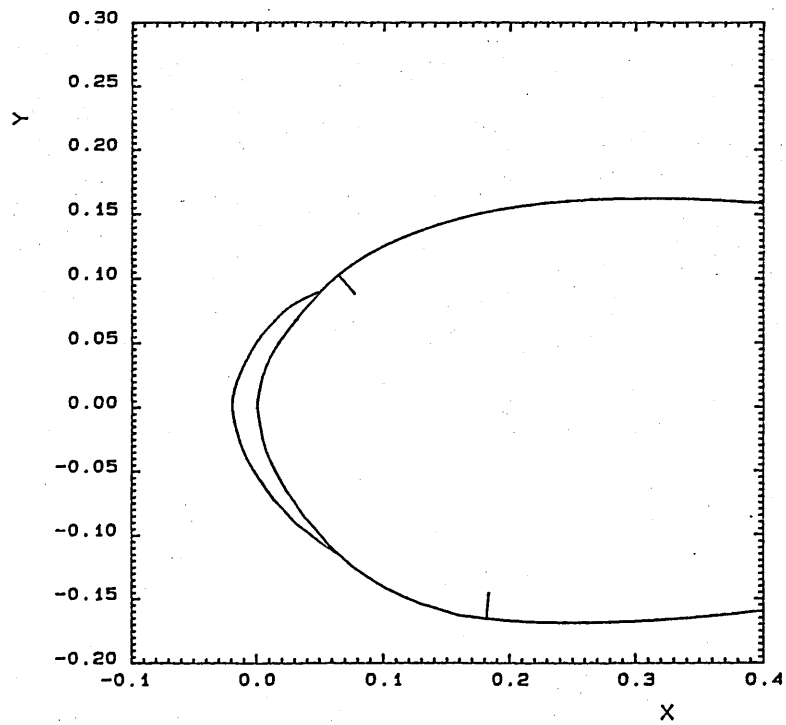
Fig.P168 (Case 6)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P108
Plot of Scimp and Scsp against s/c	= Fig.P128
Plot of Beta against s/c	= Fig.P148
TRAJ2 equivalent plot	= Fig.P74



Chord 0.662065 m

Fig.P167



Chord 0.468313 m

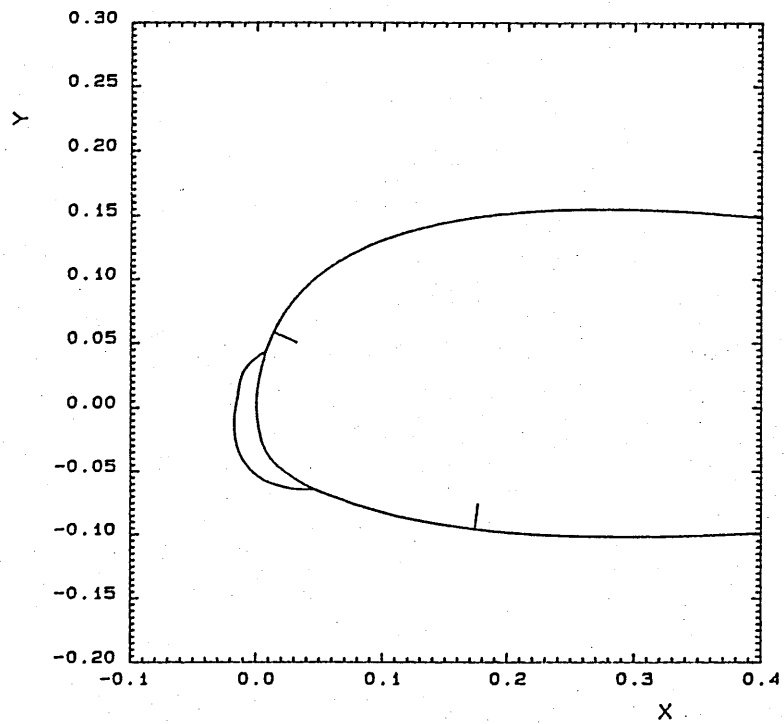
Fig.P168

Fig.P169 (Case 7)

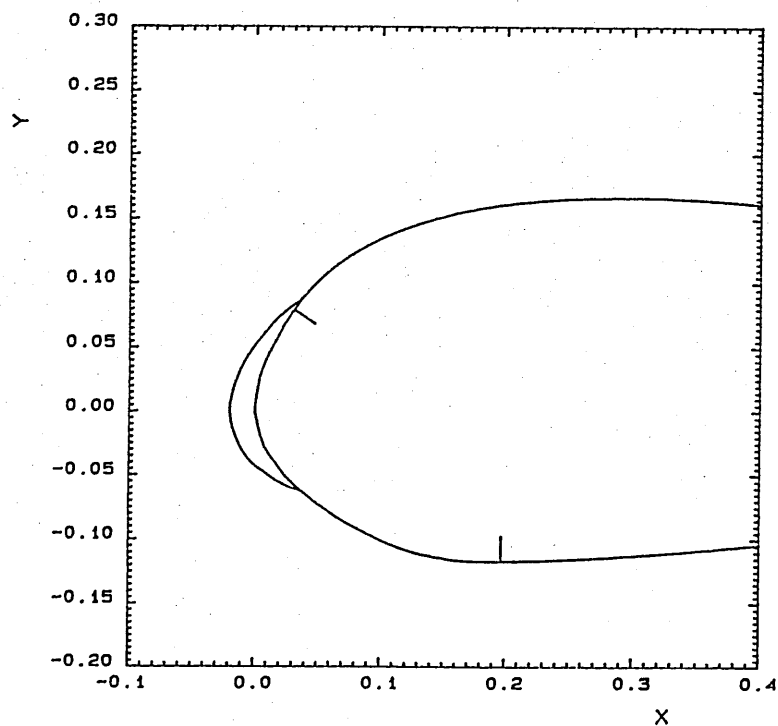
Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 0.7% developed aerofoil chord = 5.4% original lip section chord = 4.4% s/c = 29 mm aft over lip surface
Inner (lower) surface catch limit	= 4.6% developed aerofoil chord = 26.0% original lip section chord = 8.5% s/c = 56 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P109
Plot of Scimp and Scsp against s/c	= Fig.P129
Plot of Beta against s/c	= Fig.P149
TRAJ2 equivalent plot	= Fig.P75

Fig.P170 (Case 8)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 121.4% original lip section chord = 9.7% s/c = 54 mm aft over lip surface
Inner (lower) surface catch limit	= 3.7% developed aerofoil chord = 18.8% original lip section chord = 7.5% s/c = 42 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P110
Plot of Scimp and Scsp against s/c	= Fig.P130
Plot of Beta against s/c	= Fig.P150
TRAJ2 equivalent plot	= Fig.P76



Chord 0.662065 m Fig.P169



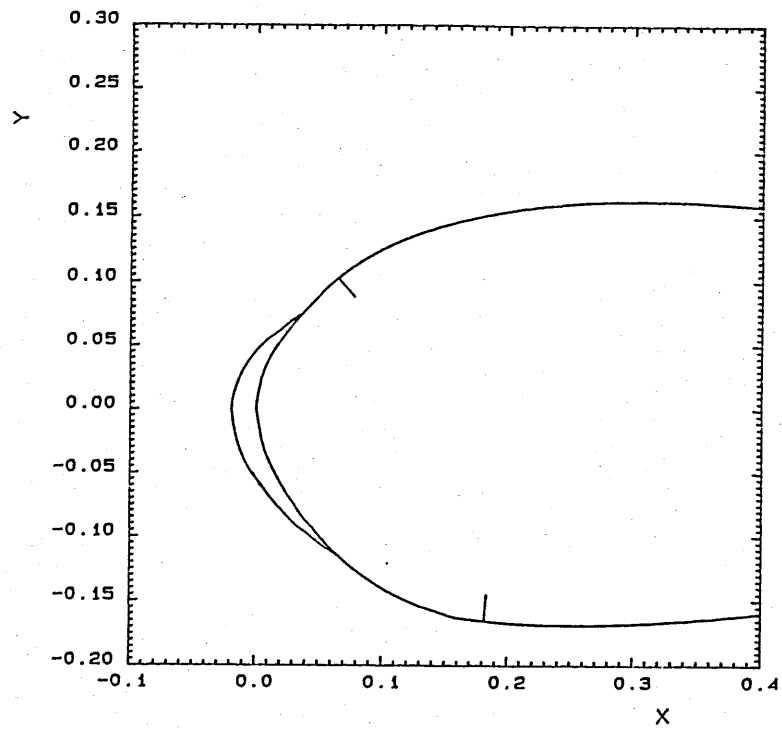
Chord 0.558118 m Fig.P170

Fig.P171 (Case 9)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= -0.0010 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 57.7% original lip section chord = 8.6% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P111
Plot of Scimp and Scsp against s/c	= Fig.P131
Plot of Beta against s/c	= Fig.P151
TRAJ2 equivalent plot	= Fig.P77

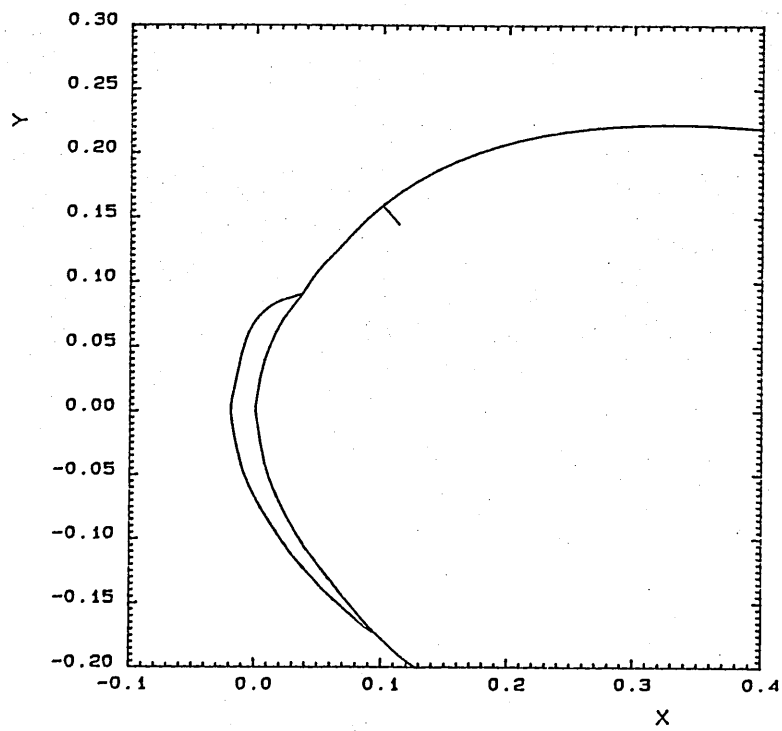
Fig.P172 (Case 10)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.1/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.302 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.7% developed aerofoil chord = 37.2% original lip section chord = 10.0% s/c = 30 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 35.5% original lip section chord = 21.0% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P112
Plot of Scimp and Scsp against s/c	= Fig.P132
Plot of Beta against s/c	= Fig.P152
TRAJ2 equivalent plot	= Fig.P78



Chord 0.468313 m

Fig.P171



Chord 0.301778 m

Fig.P172

Fig.P173 (Case 11)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.2/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P113
Plot of Scimp and Scsp against s/c	= Fig.P133
Plot of Beta against s/c	= Fig.P153
TRAJ2 equivalent plot	= Fig.P79

Fig.P174 (Case 12)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.3/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.337 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 44.9% original lip section chord = 10.1% s/c = 34 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 39.6% original lip section chord = 20.1% s/c = 68 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P104
Plot of Scimp and Scsp against s/c	= Fig.P134
Plot of Beta against s/c	= Fig.P154
TRAJ2 equivalent plot	= Fig.P80

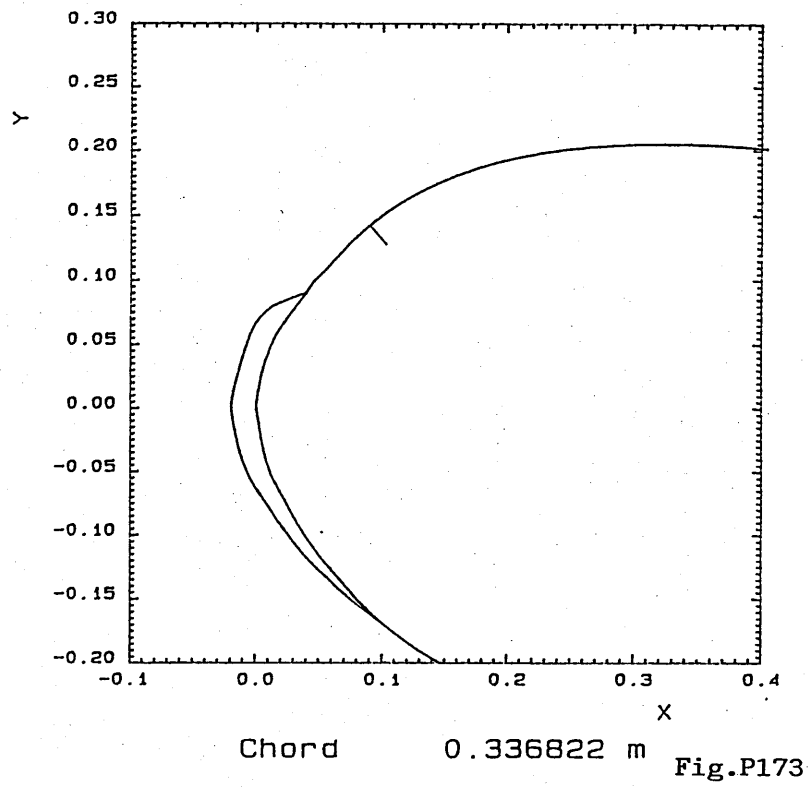
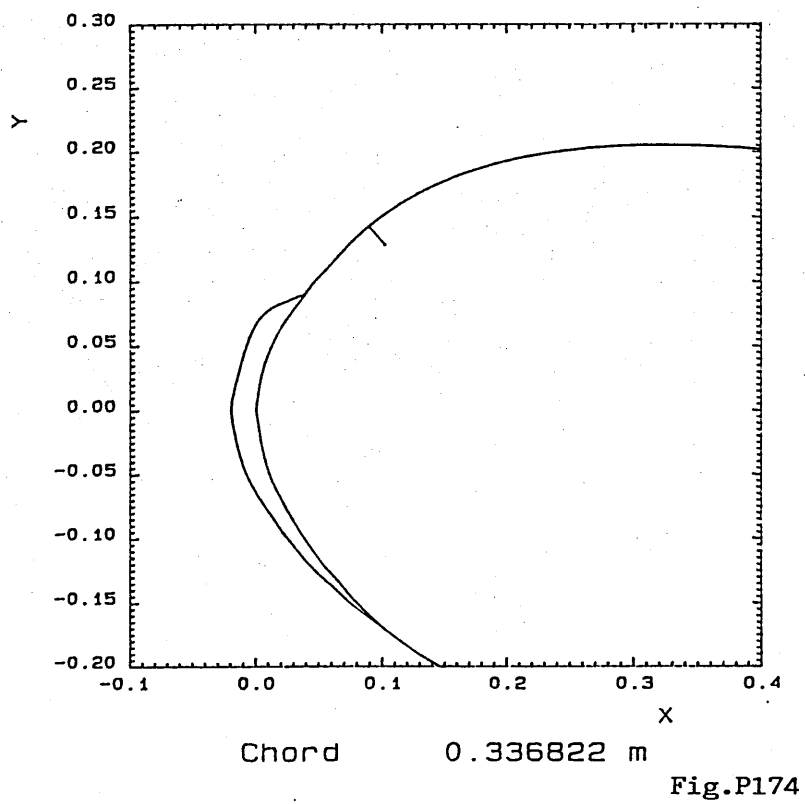
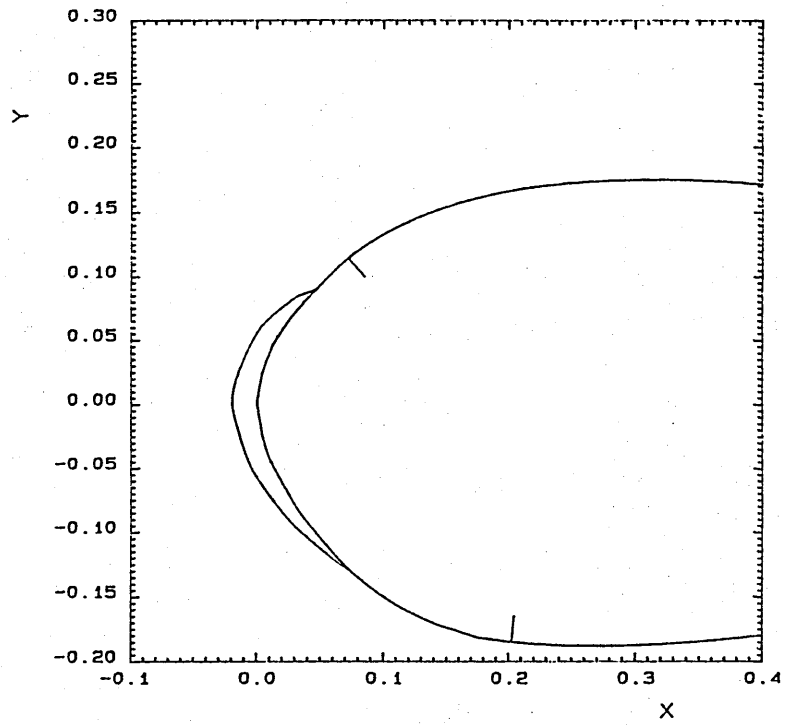


Fig.P175 (Case 13)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.4/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.420 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.7% developed aerofoil chord = 65.8% original lip section chord = 10.4% s/c = 44 mm aft over lip surface
Inner (lower) surface catch limit	= 7.5% developed aerofoil chord = 37.1% original lip section chord = 15.5% s/c = 65 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P115
Plot of Scimp and Scsp against s/c	= Fig.P135
Plot of Beta against s/c	= Fig.P155
TRAJ2 equivalent plot	= Fig.P81

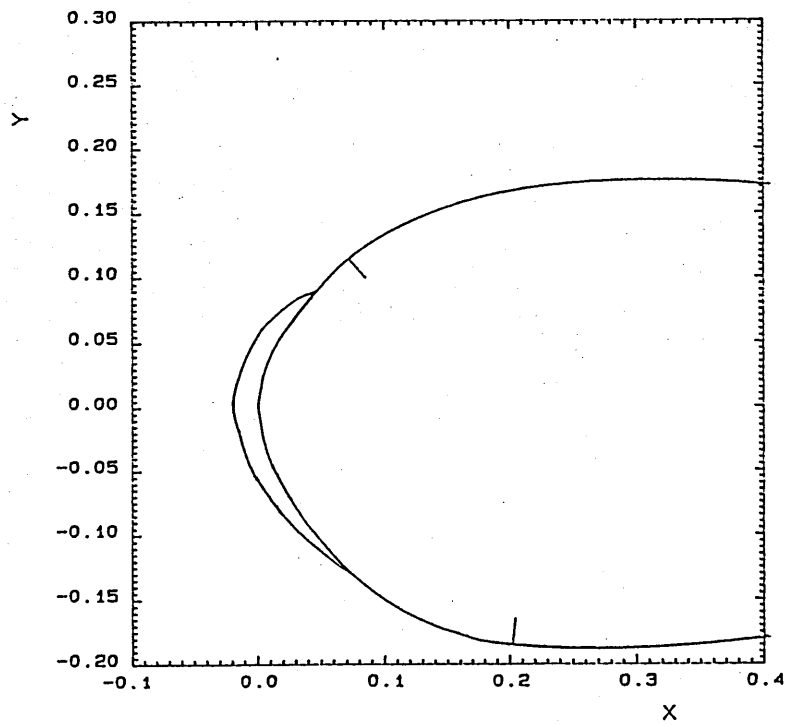
Fig.P176 (Case 14)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= time to accrete maximum 2% chord ice thickness.
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P116
Plot of Scimp and Scsp against s/c	= Fig.P136
Plot of Beta against s/c	= Fig.P156
TRAJ2 equivalent plot	= Fig.P82



Chord 0.419589 m

Fig.P175



Chord 0.419589 m

Fig.P176

Fig.P177 (Case 15)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.5 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P117
Plot of Scimp and Scsp against s/c	= Fig.P137
Plot of Beta against s/c	= Fig.P157
TRAJ2 equivalent plot	= Fig.P83

Fig.P178 (Case 16)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.662 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 2.9% developed aerofoil chord = 22.3% original lip section chord = 9.0% s/c = 60 mm aft over lip surface
Inner (lower) surface catch limit	= 2.2% developed aerofoil chord = 12.4% original lip section chord = 5.7% s/c = 38 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P118
Plot of Scimp and Scsp against s/c	= Fig.P138
Plot of Beta against s/c	= Fig.P158
TRAJ2 equivalent plot	= Fig.P84

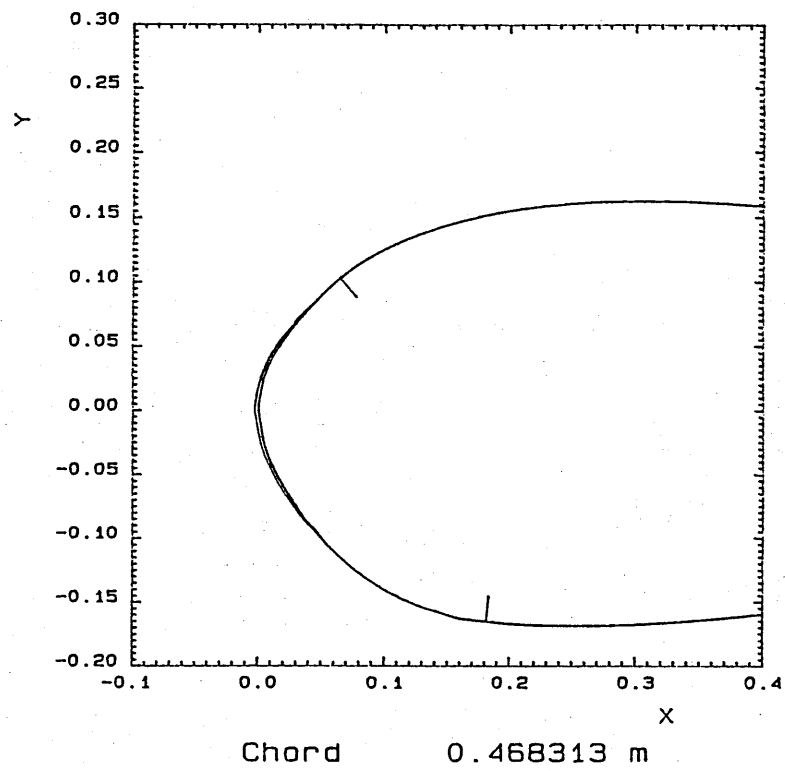


Fig.P177

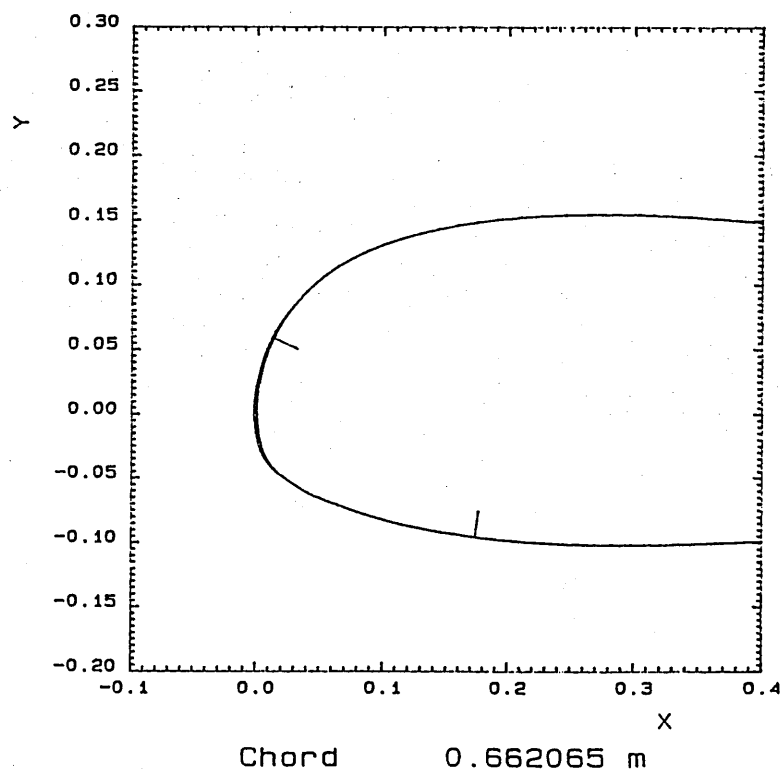


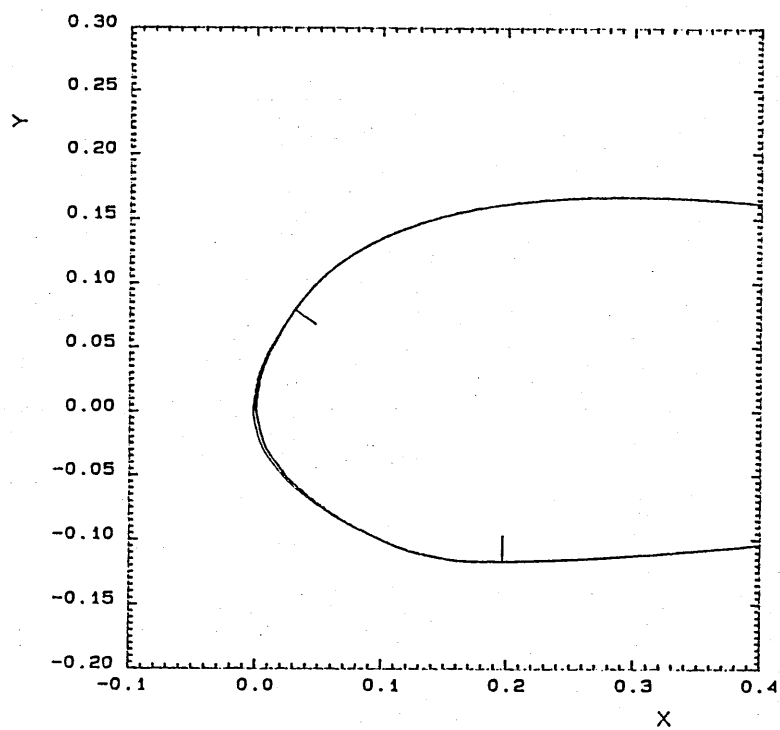
Fig.P178

Fig.P179 (Case 17)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0035 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 2.2% developed aerofoil chord = 72.2% original lip section chord = 7.2% s/c = 40 mm aft over lip surface
Inner (lower) surface catch limit	= 10.0% developed aerofoil chord = 50.7% original lip section chord = 14.9% s/c = 83 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P119
Plot of Scimp and Scsp against s/c	= Fig.P139
Plot of Beta against s/c	= Fig.P159
TRAJ2 equivalent plot	= Fig.P85

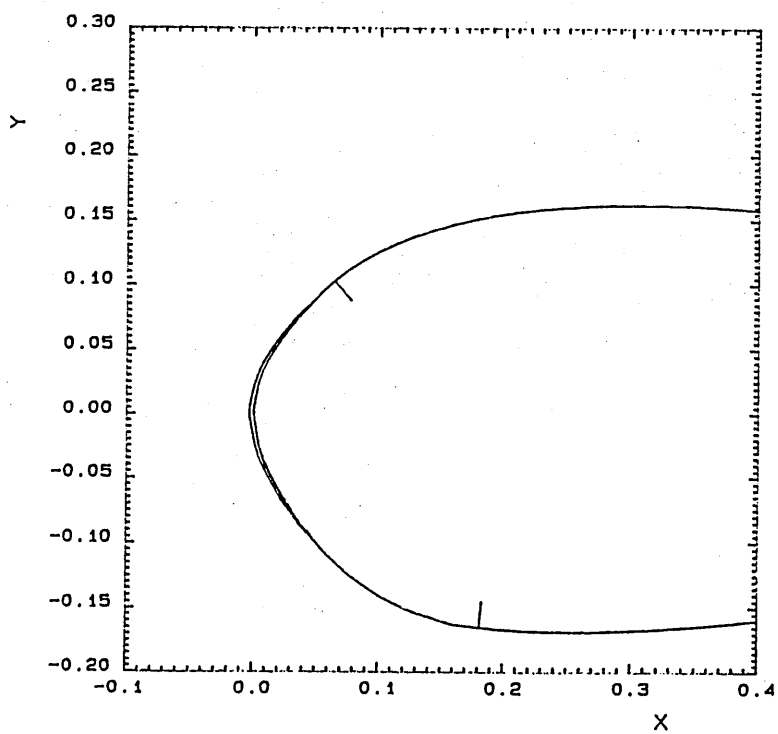
Fig.P180 (Case 18)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.468 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -19.8°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 5.2% developed aerofoil chord = 81.1% original lip section chord = 10.7% s/c = 50 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 35.8% original lip section chord = 13.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P120
Plot of Scimp and Scsp against s/c	= Fig.P140
Plot of Beta against s/c	= Fig.P160
TRAJ2 equivalent plot	= Fig.P86



Chord 0.558118 m

Fig.P179



Chord 0.468313 m

Fig.P180

Fig.P181 (Case 19)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord =131.3% original lip section chord = 10.0% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P121
Plot of Scimp and Scsp against s/c	= Fig.P141
Plot of Beta against s/c	= Fig.P161
TRAJ2 equivalent plot	= Fig.P87

Fig.P182 (Case 20)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/1.0
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.558 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord =131.3% original lip section chord = 10.1% s/c = 56 mm aft over lip surface
Inner (lower) surface catch limit	= 6.5% developed aerofoil chord = 33.0% original lip section chord = 10.9% s/c = 61 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P122
Plot of Scimp and Scsp against s/c	= Fig.P142
Plot of Beta against s/c	= Fig.P162
TRAJ2 equivalent plot	= Fig.P88

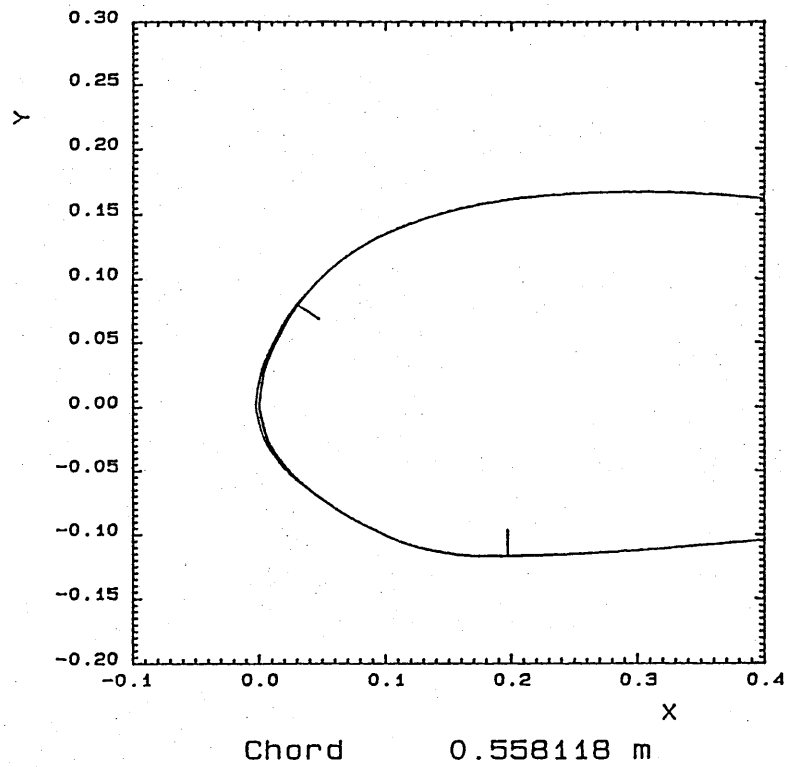


Fig.P181

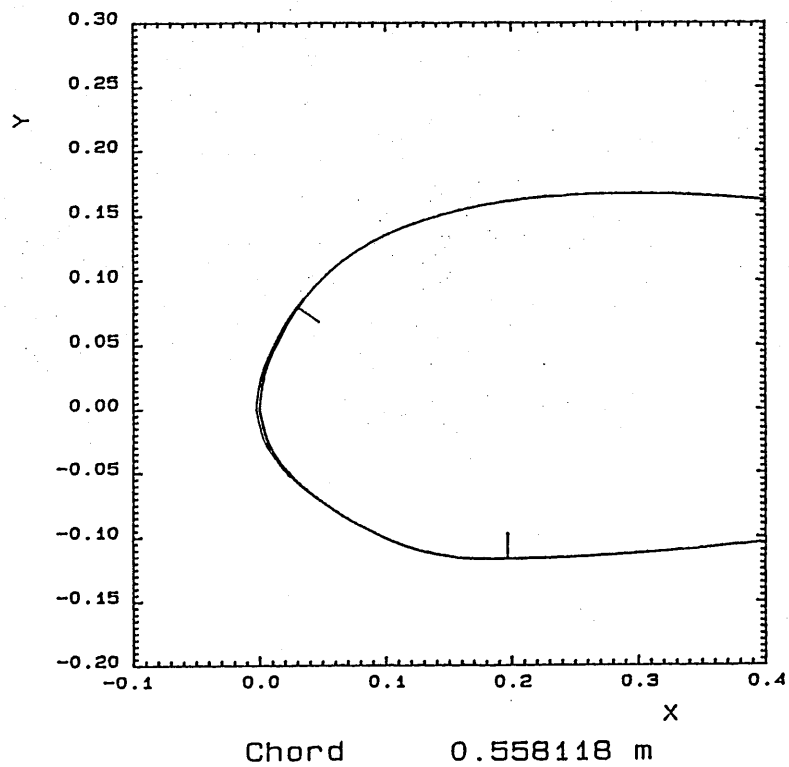


Fig.P182

Fig.P183 (Case 21)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.8
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.439
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.9% developed aerofoil chord = 71.7% original lip section chord = 10.5% s/c = 46 mm aft over lip surface
Inner (lower) surface catch limit	= 6.9% developed aerofoil chord = 35.6% original lip section chord = 14.4% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P188
Plot of Beta against s/c	= Fig.P193
Plot of Iced aerofoil	= Fig.P198

Fig.P184 (Case 22)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.6
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.409 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ₋₃
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 4.6% developed aerofoil chord = 21.9% original lip section chord = 10.4% s/c = 43 mm aft over lip surface
Inner (lower) surface catch limit	= 7.4% developed aerofoil chord = 25.9% original lip section chord = 15.5% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P189
Plot of Beta against s/c	= Fig.P194
Plot of Iced aerofoil	= Fig.P199

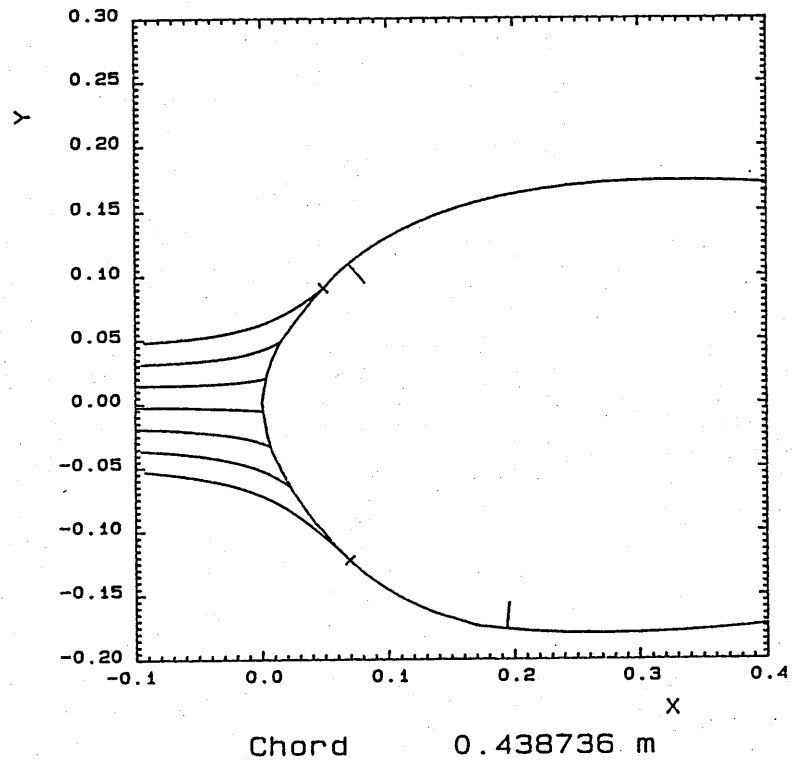


Fig.P183

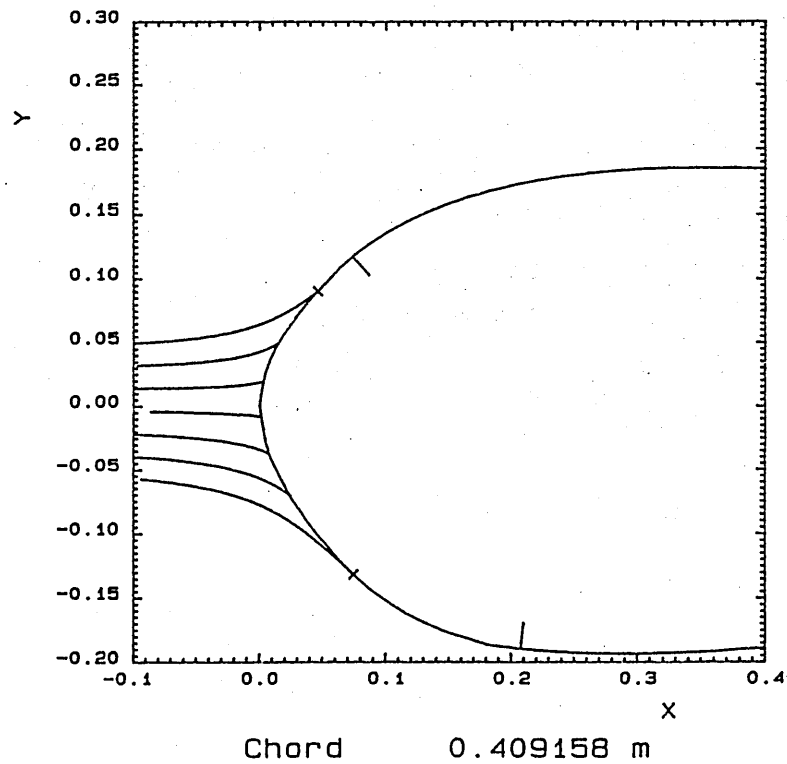


Fig.P184

Fig.P185 (Case 23)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.4
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.380 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.4% developed aerofoil chord = 98.4% original lip section chord = 10.3% s/c = 39 mm aft over lip surface
Inner (lower) surface catch limit	= 8.0% developed aerofoil chord = 27.6% original lip section chord = 16.7% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P190
Plot of Beta against s/c	= Fig.P195
Plot of Iced aerofoil	= Fig.P200

Fig.P186 (Case 24)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.2
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.350 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 16.3% original lip section chord = 10.1% s/c = 35 mm aft over lip surface
Inner (lower) surface catch limit	= 8.7% developed aerofoil chord = 26.0% original lip section chord = 18.1% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P191
Plot of Beta against s/c	= Fig.P196
Plot of Iced aerofoil	= Fig.P201

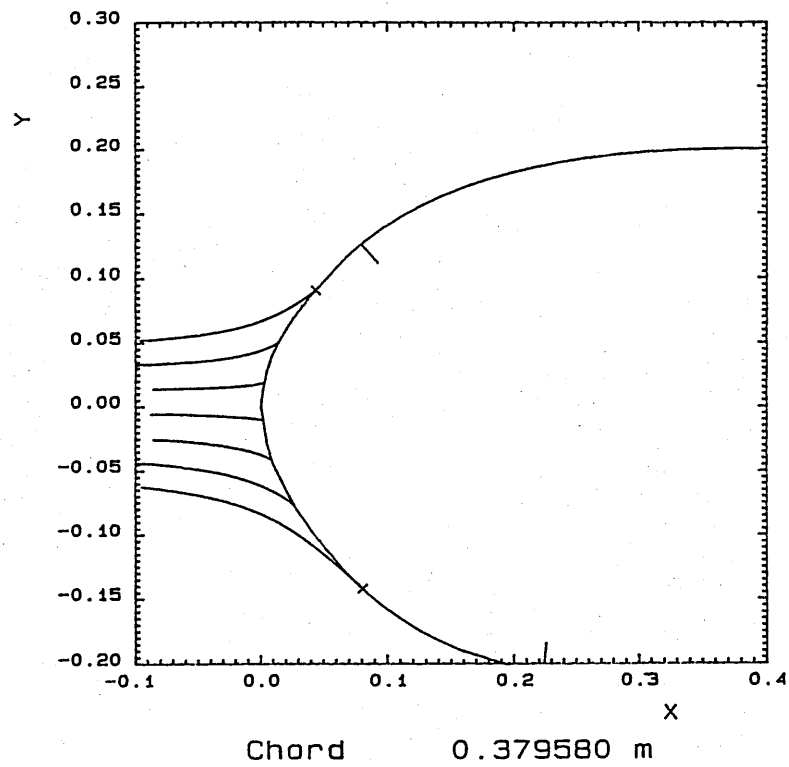


Fig.P185

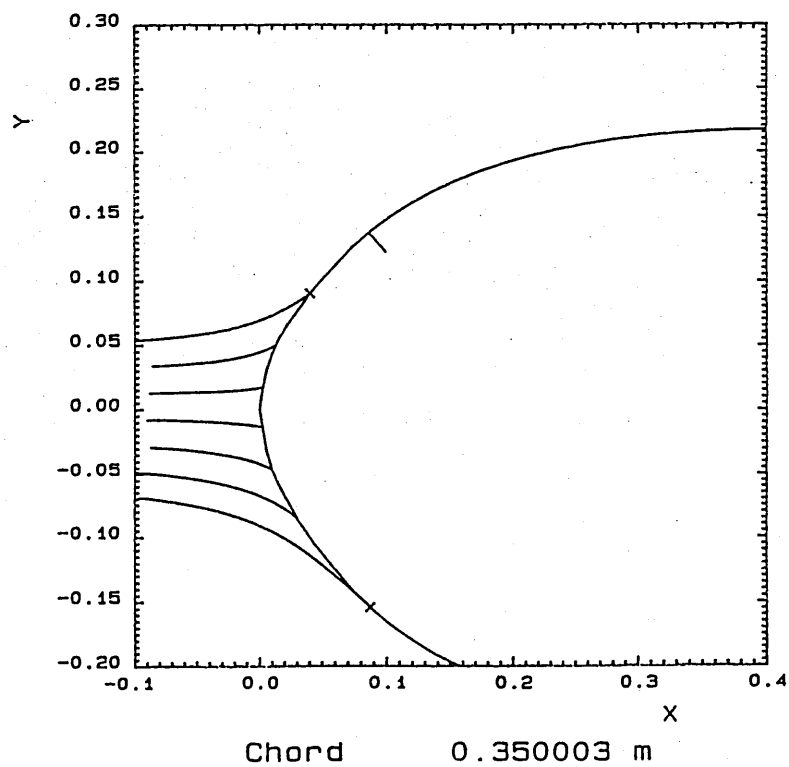


Fig.P186

Fig.P187 (Case 25)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.320 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.8% developed aerofoil chord = 40.5% original lip section chord = 10.0% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 35.8% original lip section chord = 19.8% s/c = 63 mm aft over lip surface
Plot of Scimp and Scsp against s/c	= Fig.P192
Plot of Beta against s/c	= Fig.P197
Plot of Iced aerofoil	= Fig.P202

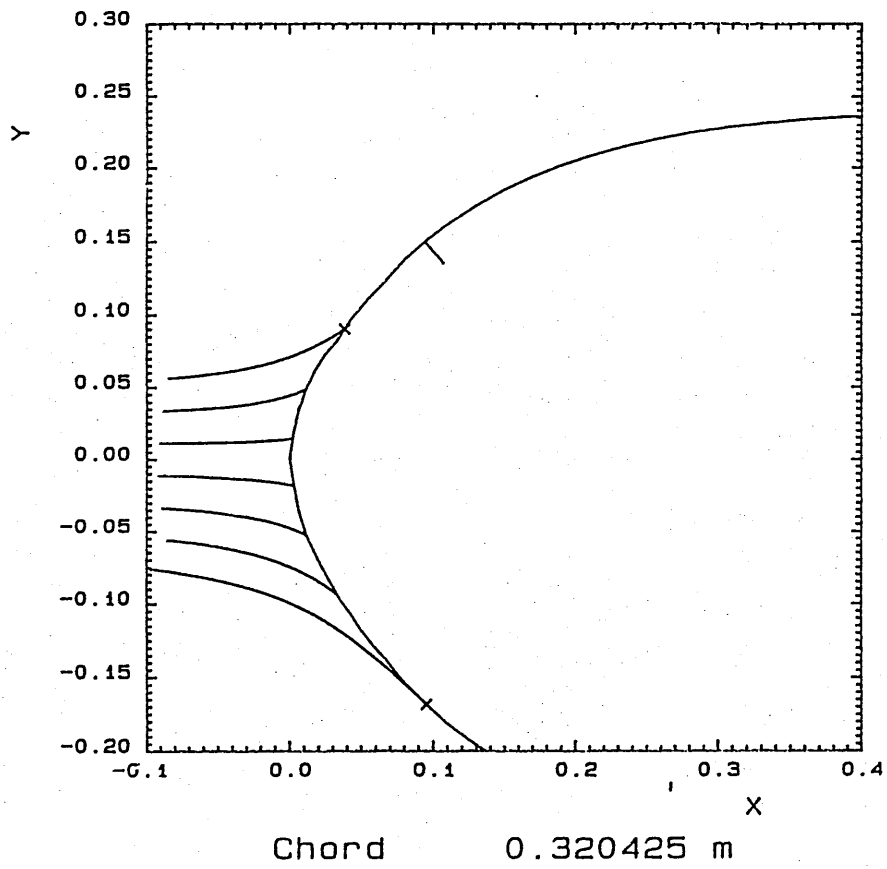


Fig.P187

Fig.P188 (Case 21)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.8
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.439
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.9% developed aerofoil chord = 71.7% original lip section chord = 10.5% s/c = 46 mm aft over lip surface
Inner (lower) surface catch limit	= 6.9% developed aerofoil chord = 35.6% original lip section chord = 14.4% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P183
Plot of Beta against s/c	= Fig.P193
Plot of Iced aerofoil	= Fig.P198

Fig.P189 (Case 22)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.6
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.409 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 4.6% developed aerofoil chord = 21.9% original lip section chord = 10.4% s/c = 43 mm aft over lip surface
Inner (lower) surface catch limit	= 7.4% developed aerofoil chord = 25.9% original lip section chord = 15.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P184
Plot of Beta against s/c	= Fig.P194
Plot of Iced aerofoil	= Fig.P199

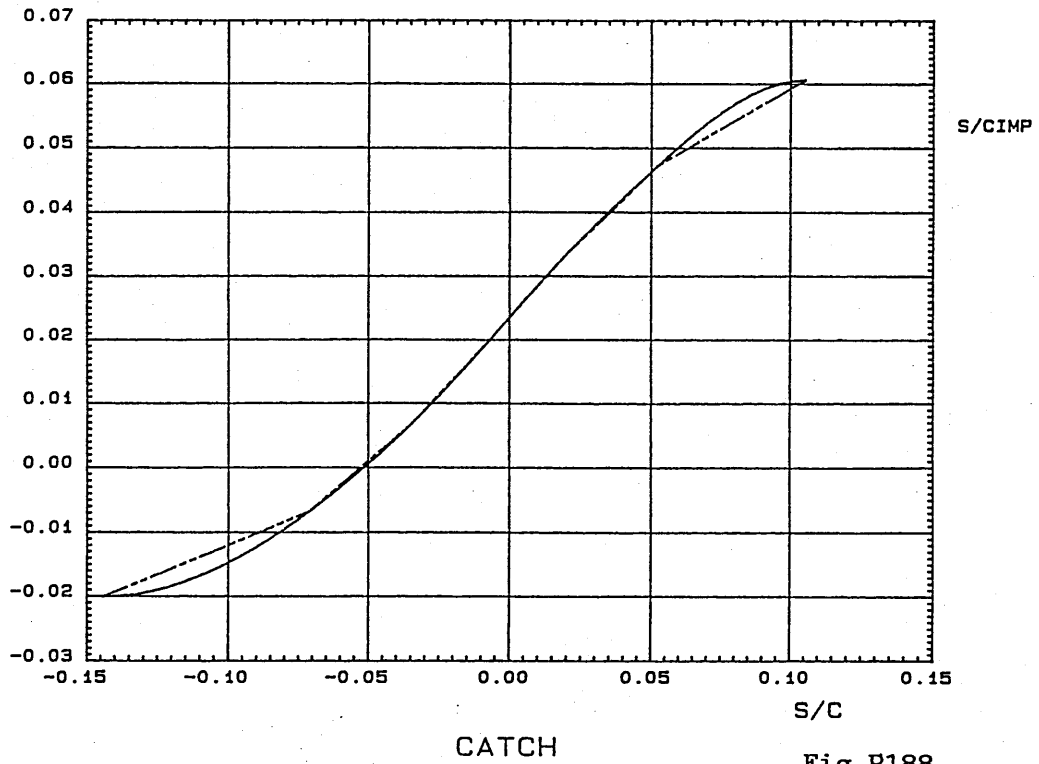
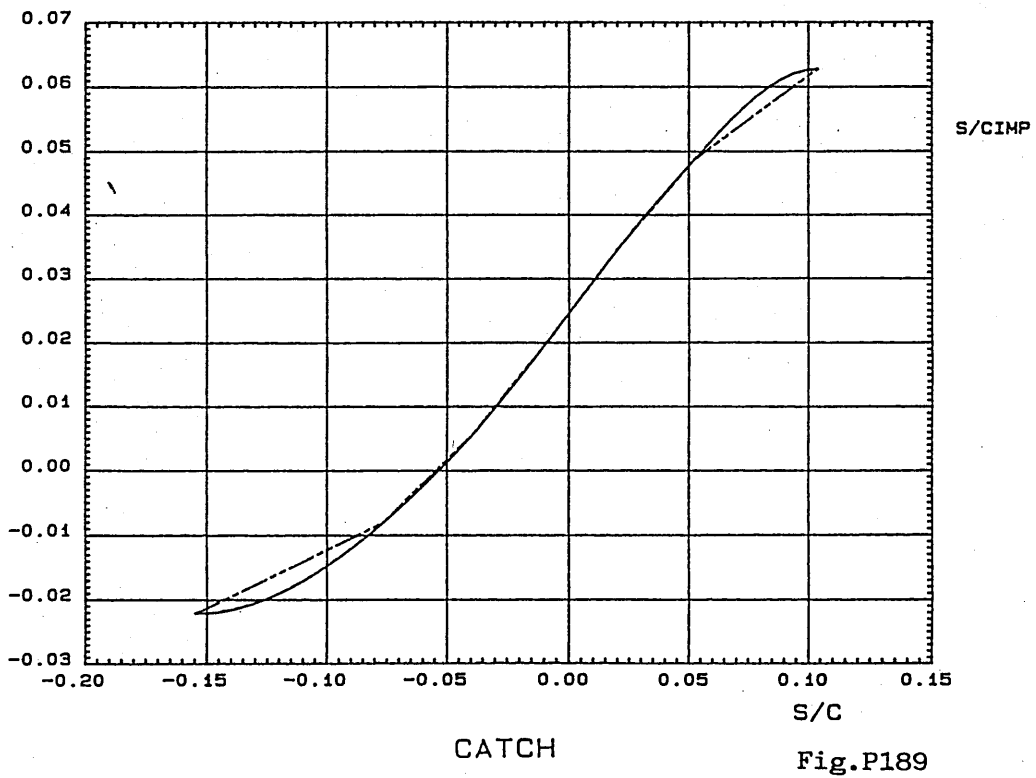
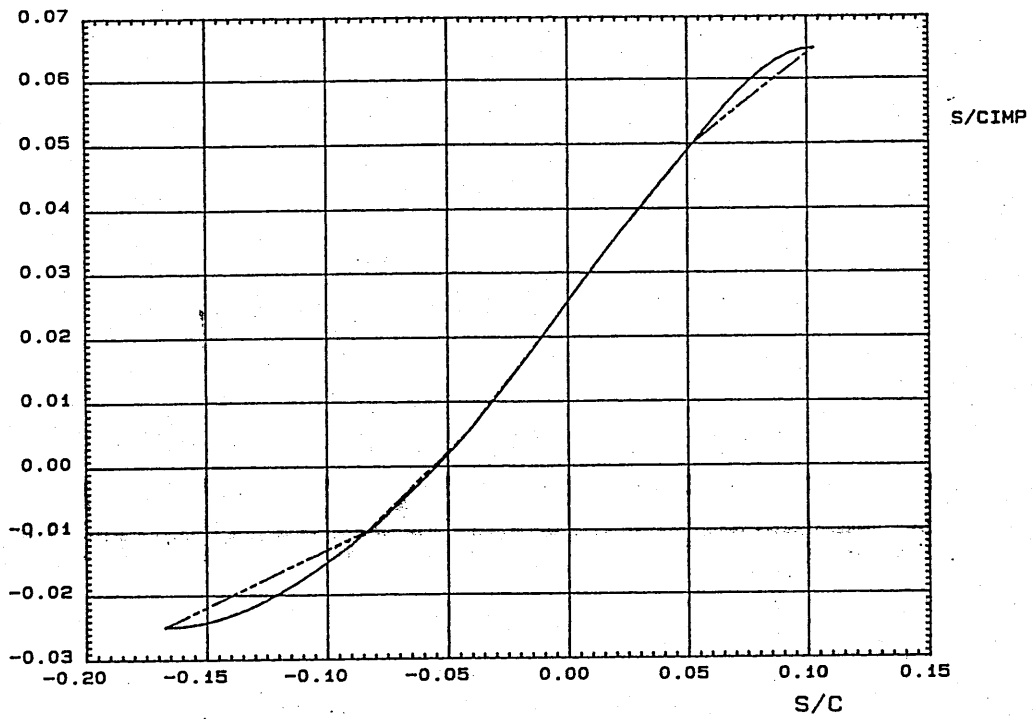


Fig.P190 (Case 23)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.4
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.380 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.4% developed aerofoil chord = 98.4% original lip section chord = 10.3% s/c = 39 mm aft over lip surface
Inner (lower) surface catch limit	= 8.0% developed aerofoil chord = 27.6% original lip section chord = 16.7% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P185
Plot of Beta against s/c	= Fig.P195
Plot of Iced aerofoil	= Fig.P200

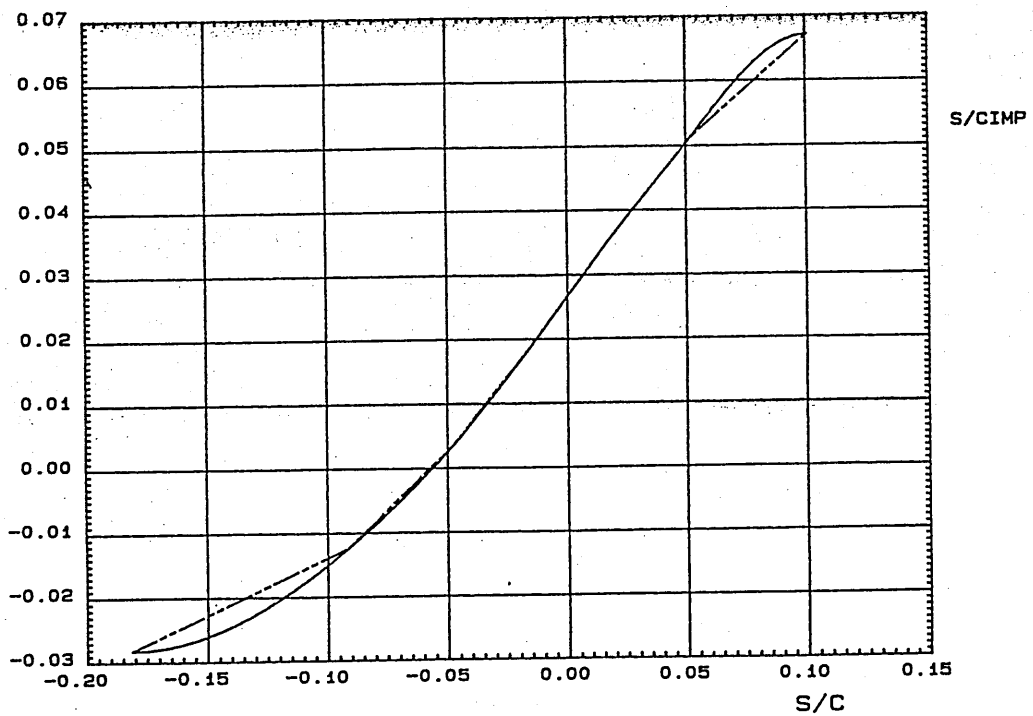
Fig.P191 (Case 24)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.2
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.350 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 16.3% original lip section chord = 10.1% s/c = 35 mm aft over lip surface
Inner (lower) surface catch limit	= 8.7% developed aerofoil chord = 26.0% original lip section chord = 18.1% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P186
Plot of Beta against s/c	= Fig.P196
Plot of Iced aerofoil	= Fig.P201



CATCH

Fig.P190



CATCH

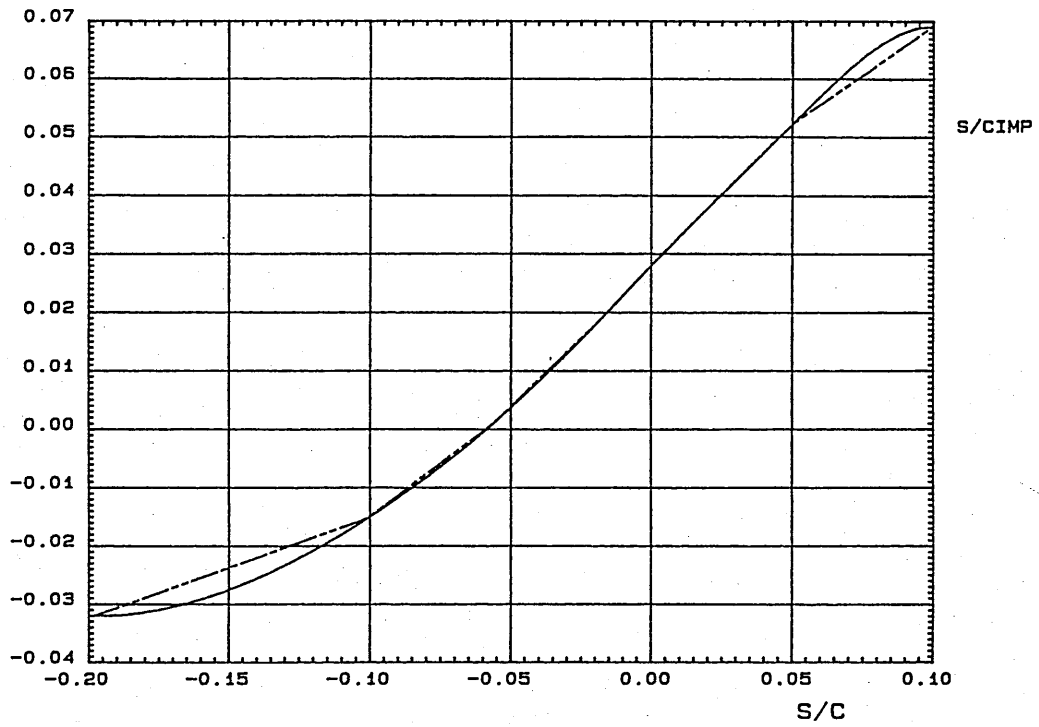
Fig.P191

Fig.P192 (Case 25)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.320 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.8% developed aerofoil chord = 40.5% original lip section chord = 10.0% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 35.8% original lip section chord = 19.8% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P187
Plot of Beta against s/c	= Fig.P197
Plot of Iced aerofoil	= Fig.P202

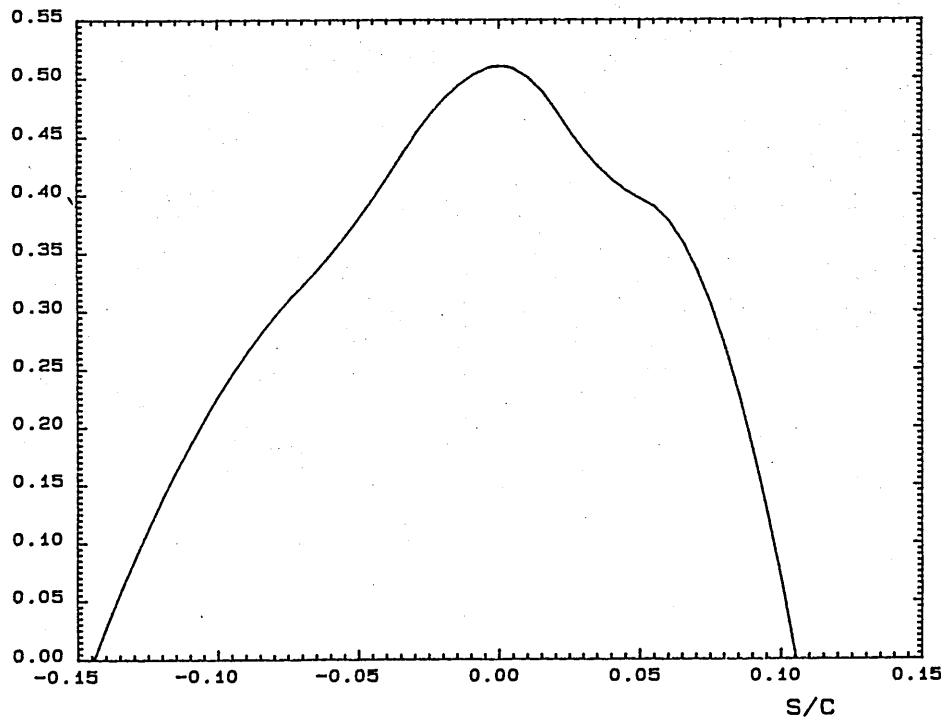
Fig.P193 (Case 21)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.8
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.439
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.9% developed aerofoil chord = 71.7% original lip section chord = 10.5% s/c = 46 mm aft over lip surface
Inner (lower) surface catch limit	= 6.9% developed aerofoil chord = 35.6% original lip section chord = 14.4% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P183
Plot of Scimp and Scsp against s/c	= Fig.P188
Plot of Iced aerofoil	= Fig.P198



CATCH

Fig.P192



Catch Efficiency

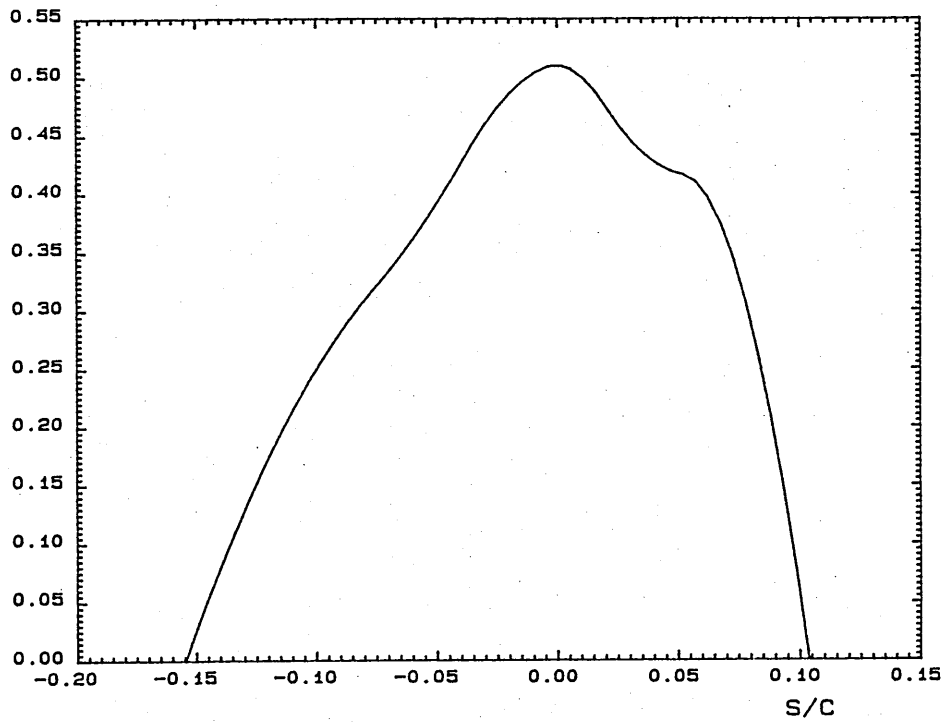
Fig.P193

Fig.P194 (Case 22)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.6
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.409 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 4.6% developed aerofoil chord = 21.9% original lip section chord = 10.4% s/c = 43 mm aft over lip surface
Inner (lower) surface catch limit	= 7.4% developed aerofoil chord = 25.9% original lip section chord = 15.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P184
Plot of Scimp and Scsp against s/c	= Fig.P189
Plot of Iced aerofoil	= Fig.P199

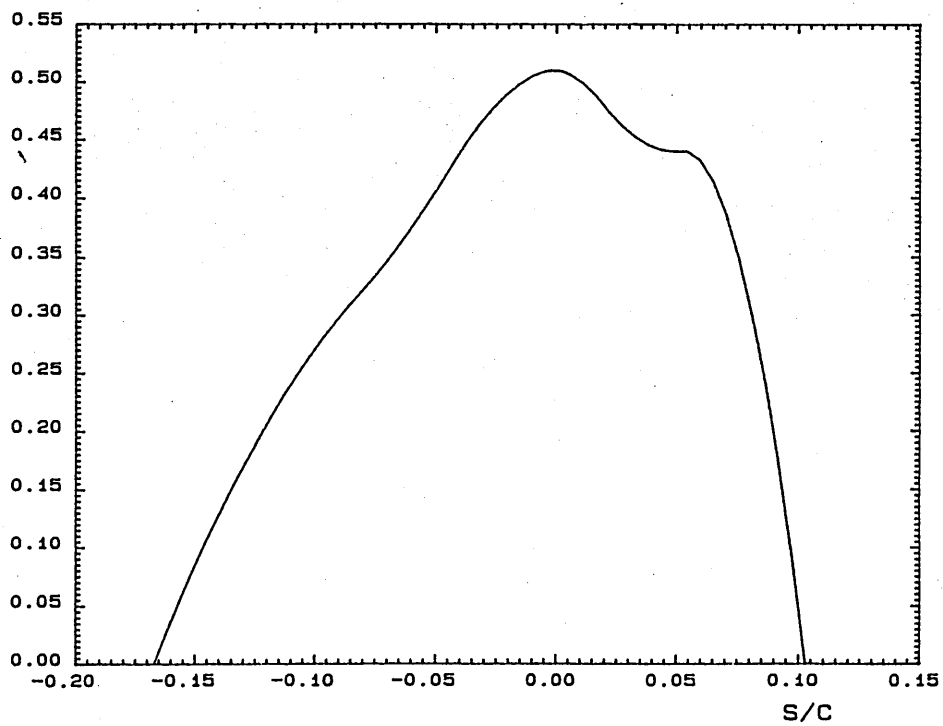
Fig.P195 (Case 23)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.4
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.380 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.4% developed aerofoil chord = 98.4% original lip section chord = 10.3% s/c = 39 mm aft over lip surface
Inner (lower) surface catch limit	= 8.0% developed aerofoil chord = 27.6% original lip section chord = 16.7% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P185
Plot of Scimp and Scsp against s/c	= Fig.P190
Plot of Iced aerofoil	= Fig.P200



Catch Efficiency

Fig.P194



Catch Efficiency

Fig.P195

Fig.P196 (Case 24)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.2
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.350 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 16.3% original lip section chord = 10.1% s/c = 35 mm aft over lip surface
Inner (lower) surface catch limit	= 8.7% developed aerofoil chord = 26.0% original lip section chord = 18.1% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P186
Plot of Beta against s/c	= Fig.P191
Plot of Iced aerofoil	= Fig.P201

Fig.P197 (Case 25)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.320 m ⁻¹
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.8% developed aerofoil chord = 40.5% original lip section chord = 10.0% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 35.8% original lip section chord = 19.8% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P187
Plot of Scimp and Scsp against s/c	= Fig.P192
Plot of Iced aerofoil	= Fig.P202

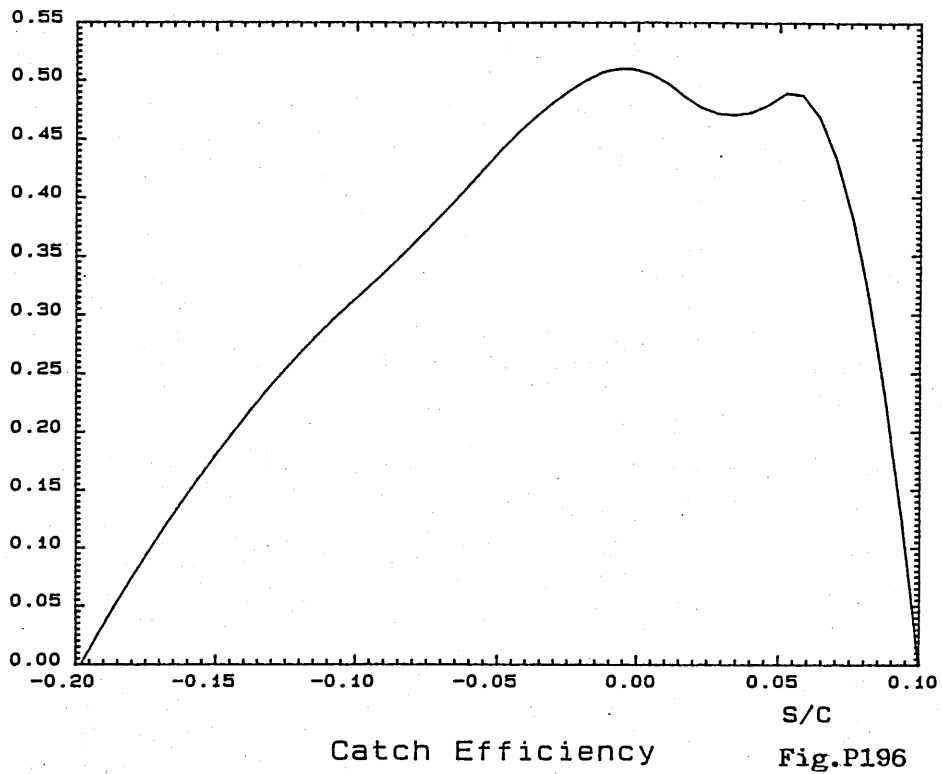
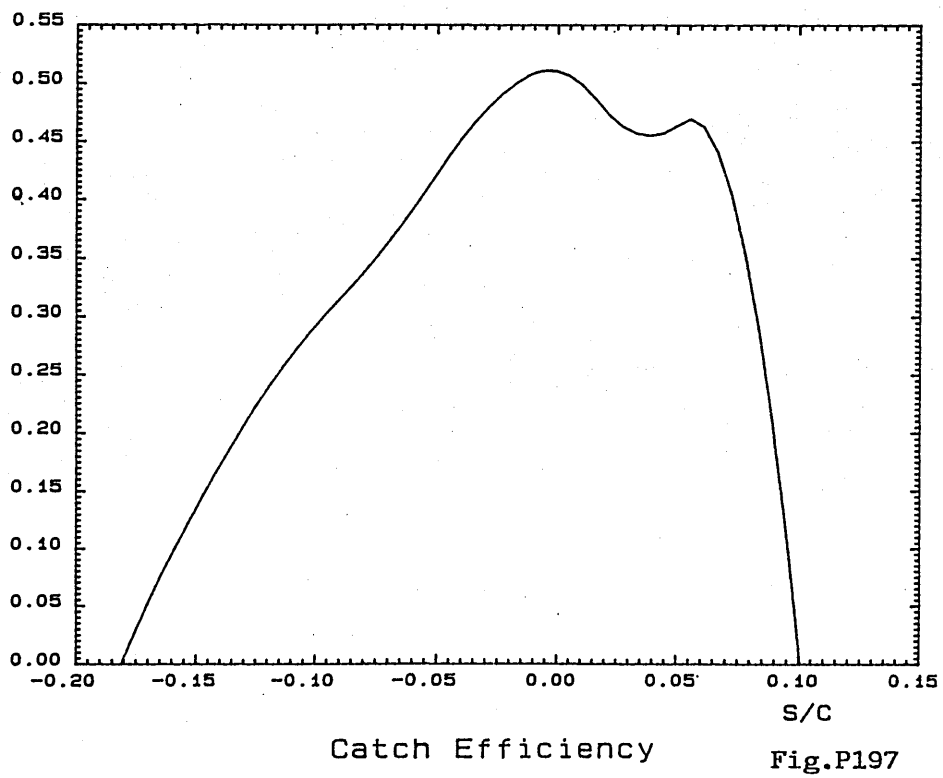


Fig.P198 (Case 21)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.8
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.439
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
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Plot of aerofoil plus trajectories	= Fig.P183
Plot of Scimp and Scsp against s/c	= Fig.P188
Plot of Beta against s/c	= Fig.P193

Fig.P199 (Case 22)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.6
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.409 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 ₋₃ kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= -0.0030 m (ie. on the lower surface)
Outer (upper) surface catch limit	= 4.6% developed aerofoil chord = 21.9% original lip section chord = 10.4% s/c = 43 mm aft over lip surface
Inner (lower) surface catch limit	= 7.4% developed aerofoil chord = 25.9% original lip section chord = 15.5% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P184
Plot of Scimp and Scsp against s/c	= Fig.P189
Plot of Beta against s/c	= Fig.P194

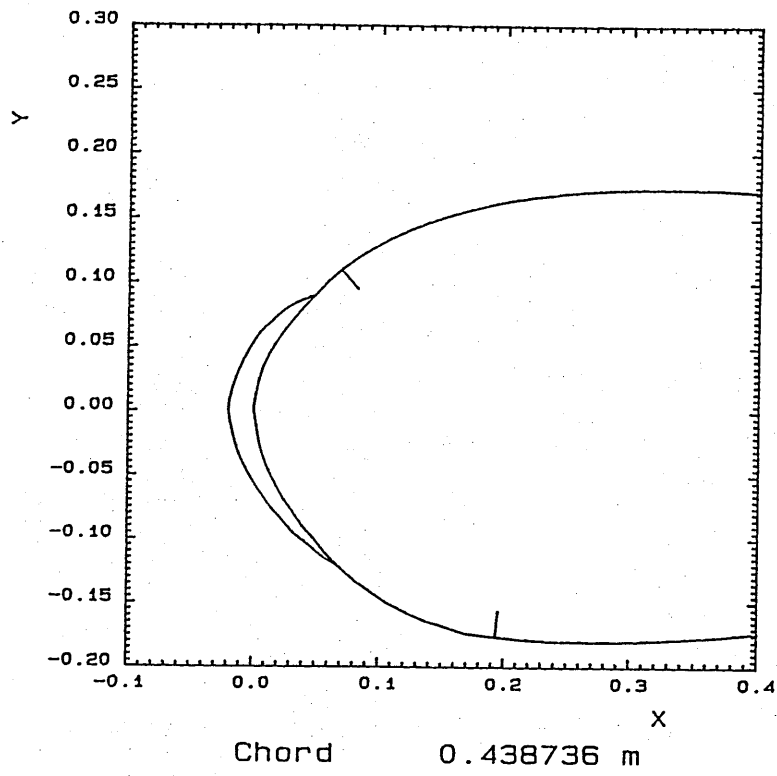


Fig.P198

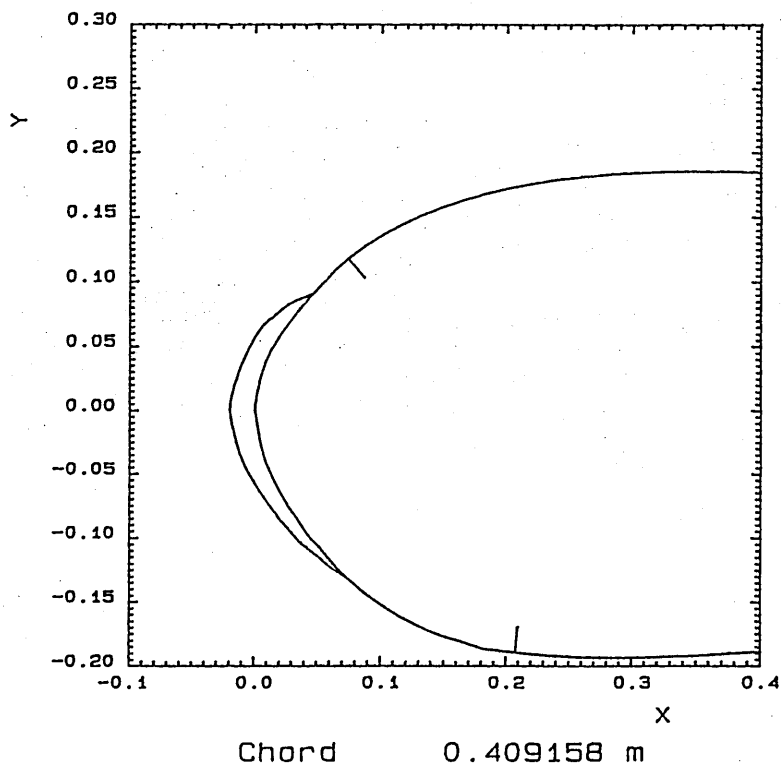


Fig.P199

Fig.P200 (Case 23)

Lip Section	135°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.4
Lip chord	= 0.017 m (upp.), 0.110 m (low.)
Developed aerofoil chord	= 0.380 m
Ambient flow velocity	= 61.73 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.3 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
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Plot of aerofoil plus trajectories	= Fig.P185
Plot of Scimp and Scsp against s/c	= Fig.P190
Plot of Beta against s/c	= Fig.P195

Fig.P201 (Case 24)

Lip Section	90°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.2
Lip chord	= 0.086 m (upp.), 0.117 m (low.)
Developed aerofoil chord	= 0.350 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 4.0% developed aerofoil chord = 16.3% original lip section chord = 10.1% s/c = 35 mm aft over lip surface
Inner (lower) surface catch limit	= 8.7% developed aerofoil chord = 26.0% original lip section chord = 18.1% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P186
Plot of Beta against s/c	= Fig.P191
Plot of Beta against s/c	= Fig.P196

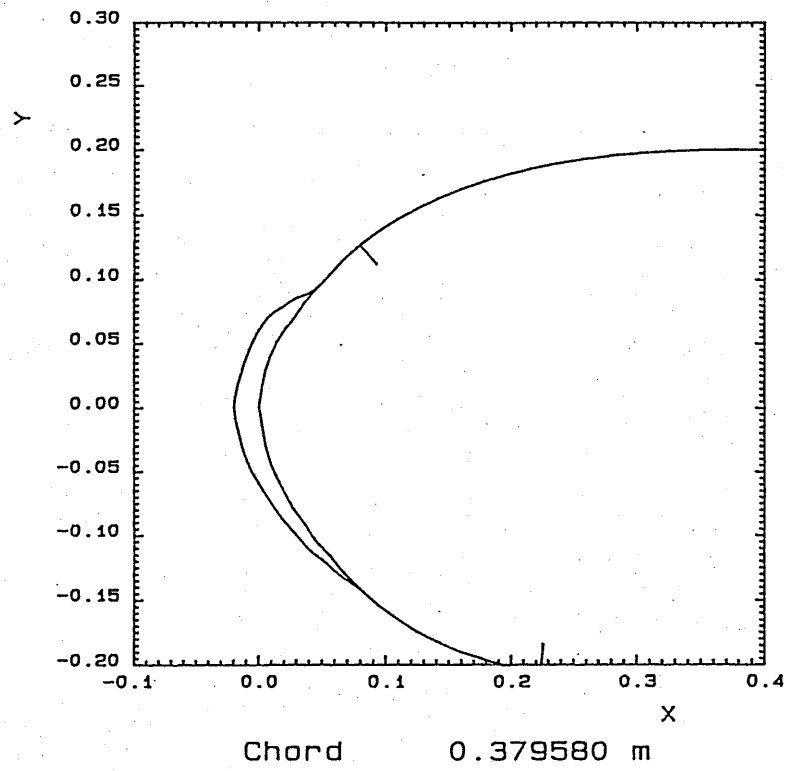


Fig.P200

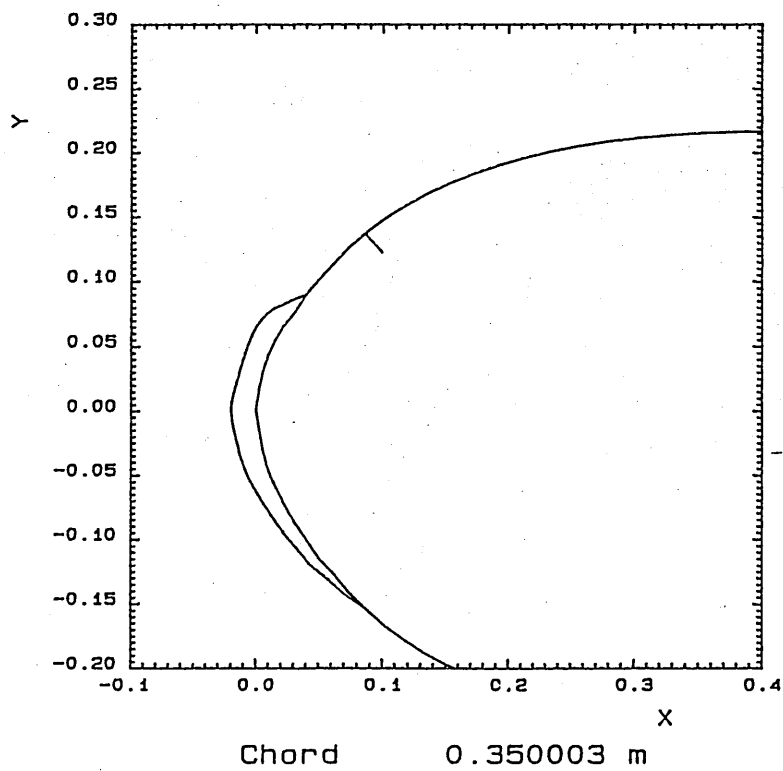


Fig.P201

Fig.P202 (Case 25)

Lip Section	180°
Preprocessor program	PTRAJ3
Main ice prediction program	TRAJ3
CLE/BLF	= 1.5/0.0
Lip chord	= 0.030 m (upp.), 0.085 m (low.)
Developed aerofoil chord	= 0.320 m
Ambient flow velocity	= 92.6 ms ⁻¹
Ambient temperature	= -20.0°C
Ambient air pressure	= 74.808 kPa
Flow liquid water content	= 0.6 gm ⁻³
Water droplet diameter	= 20 µm
Time in icing cloud	= 1.75 minutes
Forward stagnation point abscissa	= 0.0000 m (ie. on the leading edge)
Outer (upper) surface catch limit	= 3.8% developed aerofoil chord = 40.5% original lip section chord = 10.0% s/c = 32 mm aft over lip surface
Inner (lower) surface catch limit	= 9.5% developed aerofoil chord = 35.8% original lip section chord = 19.8% s/c = 63 mm aft over lip surface
Plot of aerofoil plus trajectories	= Fig.P187
Plot of Scimp and Scsp against s/c	= Fig.P192
Plot of Beta against s/c	= Fig.P197

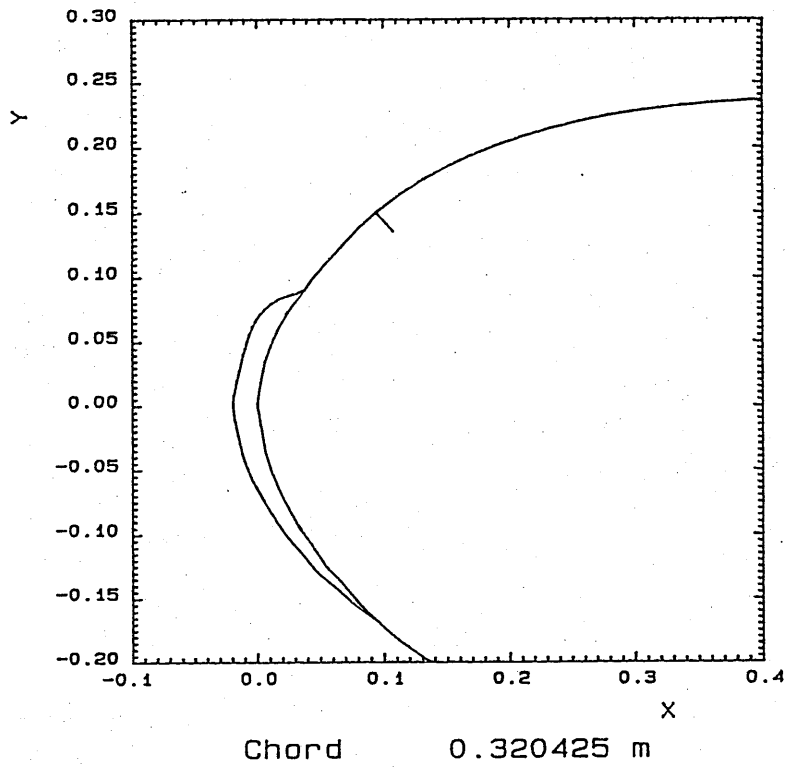


Fig.P202

CRANFIELD INSTITUTE OF TECHNOLOGY

COLLEGE OF AERONAUTICS

Ph.D Thesis

C.W. LEAH

THE APPLICATION OF COMPUTATIONAL TECHNIQUES
TO THE DESIGN OF THERMAL ICE PROTECTION SYSTEMS

Vol 2

Supervisor

Dr M.E. ESHELBY

March 1990

12 ACKNOWLEDGEMENTS

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13 REFERENCES

See "Note on Referencing" at the end of the "Figures Index".

1. Aviation Week and Space Technology November 6, 1978, pp.36; December 11, 1978, pp.25; February 5, 1979, pp.29; March 12, 1979, pp.159; April 30, 1979, pp.46; June 4, 1979, pp.35.
2. "Aircraft Icing" AGARD Advisory Report No. 127. Fluid Dynamics Panel Round Table Discussion on Aircraft Icing held at the Government Conference Centre, Ottawa, Canada. 30 September, 1977
3. Artington Cold Store, Lucas Aerospace, Icing Wind Tunnel, Peasmarsh, Guildford.
4. "Ice Protection Equipment". Lucas Aerospace, Engineering and Heating Systems, Luton International Airport, Luton Bedfordshire, LU2 9NQ
5. "Flight International", May 14, 1988, pp.23
6. "Helicopter Rotor Icing". Royal Aeronautical Society, London. Symposium Proceedings, R. W. Gent, RAE Farnborough, pp.77, January 14, 1986
7. "Physical Chemistry of Surfaces". Arthur W. Adamson, Department of Chemistry, University of Southern California, Los Angeles, California, Wiley-Interscience 1976.
8. J. H. Sewell. Department of Chemistry, Royal Aircraft Establishment, Farnborough, Hants.
9. (Bib.156), One-Dimensional Treatment of Thermal Transients in Electrically De-Iced Helicopter Rotor Blades". R. W. Gent, Royal Aircraft Establishment, Farnborough, Hants.
10. "Calculation of Water Droplet Trajectories About an Aerofoil in Steady, Two-Dimensional, Compressible Flow". "Ice Accretion on Aerofoils in Two-Dimensional Compressible Flow, - a Theoretical Model". R. W. Gent. Royal Aircraft Establishment, Farnborough, Hants.
11. "Effective Marketing Management". Martin Christopher, Sherril H. Kennedy, Malcolm McDonald, Gordon Wills, School of Management, Cranfield Institute of Technology, Cranfield, Bedford.
12. "Product Range". Lucas Aerospace, Engineering and Heating Systems, Luton International Airport, Luton, Bedfordshire, LU2 9NQ
13. "Ice Protection Equipment". Lucas Aerospace, Engineering and Heating Systems, Luton International Airport, Luton, Bedfordshire, LU2 9NQ

14. "HOVACC - An Aerofoil Ice Accretion Prediction Program for Steady, Two-Dimensional, Compressible Flow Conditions". R. W. Gent, RAE, Farnborough, Hants.
15. "Engineering Thermodynamics Work and Heat Transfer". Rogers and Mayhew, SI Units, 1978, Longman.
16. "Experimental Ice Shapes for Validation of a Theoretical Ice Accretion Prediction Program". R. W. Gent and A. R. Beauchamp, Royal Aircraft Establishment, Farnborough, Hants., Technical Report 86025, May 1986.
17. "Engineering Thermodynamics Work and Heat Transfer". Rogers and Mayhew, Longman. SI Units, 1978, page 515 Section 22.2
"Forced Convection in Laminar Flow Past a flat Plate". Fig.22.6.
18. "Protection of Aircraft Against Ice". J. K. Hardy, Report SME.3380.
19. "Boundary Layers". A. D. Young, BSP Professional Books, ISBN 0-632-02122-5, 1989
20. "Aerodynamics for Engineering Students". E. L. Houghton and N. B. Carruthers, Third Edition, Arnold, 1982

14 BIBLIOGRAPHY (Summary)

The bibliography to this thesis is included in (Appendix C) and was also reported, at an earlier stage in its compilation, as Cranfield College of Aeronautics Report 8817 to render it accessible for reference.

To initiate the research programme, before embarking upon any detailed research work, it is necessary to obtain some knowledge of related information already available. It was discovered that many reports exist worldwide on various associated aspects of this researcher programme. To be of sufficient use to justify its compilation, the bibliography should not be limited by becoming outdated soon after the programme reaches completion, or be so specialised as to only be of use in a small number of studies. It should preferably be of use to the whole of the part of Lucas Aerospace Limited concerned with aircraft icing indefinitely, particularly with respect to any subsequent icing/de-icing research work. It should be regularly updated and form a reference library for addition to the Company technical library to extend existing material on these subjects.

The nature of such a research programme where each subsequent sub-programme is influenced in its direction and content by the results, findings and implications of the present work, renders it difficult to define a detailed proposed programme of research in the initial stages. The bibliography must include all reasonably related and predictably related subjects associated with the main theme of the work. The bibliography presented is therefore a list of references to which areas of more definite interest are analysed in closer detail as and when required, e.g. ice adhesion literature survey. The references in the bibliography carry a secondary numbering system (bracketed numbers) which remain constant throughout the programme and in all reports within the programme (as explained in the introduction), for cross referencing and particularly, to maintain consistency with other reports after additions to the bibliography during updating amendments. This is all fully explained in detail in the introduction attached to the bibliography.

15 ACRONYMS and ABBREVIATIONS

A&AEE	Aeroplane and Armament Experimental Establishment, Boscombe Down, England
AAF	Army Air Force
AARL	Aeronautical and Astronautical Research Laboratory
AASL	Army Atmospheric Sciences Laboratory
abs	absolute
ACS	American Chemical Society
AEC	Atomic Energy Commission
AEL	Aeronautical Engineering Laboratory
AFB	Air Force Base
AFDL	Air Force Flight Dynamics Laboratory
AFGL	Air Force Geographical Laboratory
AGARD	Advisory Group for Aerospace Research and Development
AH	Advanced Helicopter
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
All	Allowable
AMS	American Meteorological Society
ARC	Aeronautical Research Centre
ARDC	Air Research and Development Command
ARL	Aviation Research Laboratory
ARR	Aeronautical Research Report
ASEE	American Society for Engineering Education
ASME	American Society of Mechanical Engineers
ASRE	American Society of Refrigeration Engineers
ATC	Air Traffic Control
ave	average
BAC	British Aircraft Corporation
BAe	British Aerospace
BERP	British Experimental Rotor Programme (Ref. Interavia 3/1986)
BFZ	Bubble free zone
BHTI	Bell Helicopter Textron Incorporated
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacture
CAPRI	Civil Aircraft Protection Against Ice
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Plastic
CIL	Computer Instrumentation Limited
CIM	Computer Integrated Management
circ	circumferential
CiT	Cranfield Institute of technology
Co	Company
CoA	College of Aeronautics
Corp	Corporation
CRAC	Careers Research Advisory Centre
CRREL	Cold Regions Research and Engineering Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSME	Canadian Society of Mechanical Engineers
C-46	Canadair 46

D.C.	District Capital
deg	degrees
Dept	department
Dev	Development
dia	diameter
DOS	Disc Operating System
DOT	Department of Transport
DR	Dowty Rotol Limited
DRMAT	Dowty Rotol Materials Laboratory
DTP	Desk Top Publishing
EH	European Helicopter
EL	Electroluminescent Lighting
Eng	Engineering
Est	Establishment
FAA	Federal Aviation Authority
FAR	Federal Air Requirements
FEA	Finite Element Analysis
Fig	Figure
GE	General Electric
GRP	Glass Reinforced Plastic
Hp	Horse Power
HTC	Heat Transfer Coefficient
IAS	Indicated Airspeed
IAS	Institute of Aerospace Sciences
IBM	International Business Machines
ICAS	International Council of the Aeronautical Sciences
IGV	Inlet guide vane
Inc	Incorporated
Ind	Industries
Inst	Institute
I/O	Input/Output
IRB	International Research Bureau
ISA	International Standard Atmosphere
Jr	Junior
Lab	Laboratory
LAN	Local Area Network
l.e.	leading edge
LR	Laboratory Report
Ltd	Limited
LWC	Liquid Water Content
M.I.T.	Massachusetts Institute of Technology
Mk	Mark
MoD	Ministry of Defence
MVD	Median Volume Diameter
NACA	National Advisory Committee for Aeronautics
NAE	National Aeronautical Establishment
NAEC	National Aeronautical Establishment of Canada
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NFP	Not for Publication
NGTE	National Gas Turbine Establishment
No	Number
NPL	National Physical Laboratory
NRC	National Research Council (Canada)

NRL	Naval Research Laboratory
OAT	Outside Air Temperature
o/h	overheads
PC	Personal Computer
PCB	Printed Circuit Board
Pgm	Program
pp	page
Pt	Part
RAA	Ross Aviation Associates
rad	radius
RAE	Royal Aircraft Establishment (Farnborough)
RAeS	Royal Aeronautical Society
RAM	Random Access Memory
RB	Research Bulletin
R&D	Research and Development
Ref	Reference
Res	Research
R.F.	Reserve Factor
RM	Reports and Memorandum
RMR	Research Memorandum Report
RR	Rolls Royce
SAE	Society of Automotive Engineers
Sch	School
Sci	Science
SCO	Santa Cruz Operation
SERC	Science and Engineering Research Council
SIPRE	Snow Ice and Permafrost Research Establishment
SME	Society of Manufacturing Engineers
SoM	School of Management
SST	Supersonic Transport
Std	Standard
TAS	True Airspeed
Tech	Technical
Temp	Temperature
TM	Technical Memorandum
TP	Test Proposal
TR	Technical Report
TN	Technical Note
UDF	Unducted Fan
UK	United Kingdom
Ult	Ultimate
UNO	United Nations Organisation
US	United States (of America)
USA	United States of America
USSR	Union of Soviet Socialist Republics
UV	Ultra violet
UVGA	Ultra Video Graphics Array
vel	velocity
VGA	Video Graphics Array
VMS	Virtual Memory System
WADC	Wright Air Development Center
WHL	Westland Helicopters Limited
WMO	World Meteorological Organisation
WR	Wartime Report

WR-A	Wartime Report - Aeronautical
WWII	World War Two
YMP	Young Managers Programme

2-D	Two-Dimensional
3-D	Three-Dimensional
+ve	Positive
-ve	Negative

APPENDIX A

16 APPENDIX A

16.1 Courses Attended

"Flight Test Appreciation"

College of Aeronautics, Cranfield Institute of Technology,
Cranfield.

"Project Management"

Dowty Rotol Limited, February 1986.

"Young Managers Programme"

School of Management, Cranfield Institute of Technology,
Cranfield, September 1986.

"PhD Research Student Development"

CRAC, SERC, Durham University, March 1987.

"The Marketing of Technological Products" (short course)

School of Management, Cranfield Institute of Technology,
Cranfield, September 1987.

"Introduction to Computational Fluid Dynamics"

College of Aeronautics, Cranfield Institute of
Technology, Cranfield, June 1988.

"Managing People Effectively"

School of Management, Cranfield Institute of Technology,
Cranfield, September 1988.

16.2 SUPPORTING MATERIAL

The supporting material entered for submission (with the exception of the Bibliography) was produced as a series of interim progress reports to the sponsor during the research programme. It is summarised within the thesis and the major relevant data appears in (Appendix A). The Bibliography is included in (Appendix C) and also published separately as Cranfield College of Aeronautics Report 8817 to make it accessible for reference. For commercial reasons, the actual computer program codings cannot be included in the thesis and the programs created as a part of the research programme are submitted as supporting material (Sup.7).

The reports considered as supporting material to the thesis are referenced (Sup.m - n) within this text, where "m" refers to the reference number and "n" the section within that report. All are written by the author of this thesis and carry NFP (not for publication) reference numbers of the College of Aeronautics, Cranfield Institute of Technology.

1. "Ice Shear Adhesion Test Rig Design Report", NFP 86/28
2. "Ice Shear Adhesion Test Rig Stress Report", NFP 86/22
3. "Preliminary Ice Freezing Tests", NFP 86/23
4. "Adhesion Tests", NFP 86/21
5. "Ice Adhesion - Results from the Literature, Tests at Dowty Rotol Limited, and Flight Test Photographs" NFP 87/04
6. "Preliminary One-Dimensional Steady State Thermodynamic Estimations for Metal and Composite Propeller Blades", NFP 86/27
7. "PTRAJ2". Computer program compiled as a part of this research programme to form a preprocessor unit to 'TRAJ2'.
8. "PTRAJ3". Computer program compiled as a part of this research programme to form a preprocessor unit to 'TRAJ3'.
9. "TRAJ2". Computer program modified from RAE aerofoil icing prediction program TRAJICE2 as apart of this research programme.
10. "TRAJ3". Computer program modified from RAE aerofoil icing prediction program TRAJICE2 as a part of this research programme.

16.3 Data Lists

16.3.1 List 1 :Mandatory Test Rig Design Requirements

(Sup.1 - 4)

1. Economic to design, manufacture and operate.
2. Durable.
3. Reasonably portable (to and from a suitable cold environment).
4. Transportable (Company to Cranfield and vice versa).
5. Small enough to be incorporated in a cold room (or possibly a domestic chest freezer) and a transport vehicle.
6. Not so heavy as to hinder handling unnecessarily.
7. Safety of operation, regarding the operator(s), nearby personnel and surrounding equipment.
8. Simplicity of operation to reduce operating costs, experimental error, "set-up" time, and to increase reliability, the accuracy of repeatability, the number of different samples able to test, and the time available to carry out repeatability check tests.
9. The value of the applied load must be accurately known.
10. The load should be applied so as to achieve a separating force at the ice/substrate interface which is as close to pure shear as possible.
11. The load should be applied to the whole of the interface area simultaneously and homogeneously.
12. The load should be applied without shock, impact or vibration.
13. There should be no vibration transmitted to the ice/substrate interface before or during testing, (although vibration at the interface would occur on the propeller blade and, to a small level, on the intake lip, in flight, this would vary with propeller and intake design, engine power setting and atmospheric conditions. It being infeasible to test all likely situations, then vibration should be omitted from testing to reduce the number of unknown variables.
14. The area of the ice/substrate interface should be accurately known, either by predetermination, (e.g. mould size), or by reasonable ease of measurement i.e. it should take some simple geometric form.
15. The temperature of the bond area should be homogeneous, of a known value, or inhomogeneous of an accurately known

distribution, the former being more practicable. It should also be measurable and variable in a reasonably controlled manner.

16. The test equipment and instrumentation must not interfere with the ice bond.
17. The substrate samples must be simple and economic to produce with accurate repeatability, relevant to the actual application under study, and capable of being tested several times.
18. The test conditions should be accurately repeatable, and recordable, e.g. temperature (or if required, temperature distribution and variation), loading characteristics (ie. load v time), ice type and method of formation.

16.3.2 List 2 :Desirable Test Rig Design Requirements

1. The ability to produce ice specimens with physical properties representative of those experienced in flight conditions, e.g. density, crystallographic size and structure, air content and distribution, and specimen dimension aspect ratios (ie. length v thickness, etc.).
2. The ability to observe and record the interface appearance before, during and after testing, ie. it should not be hidden by the equipment.
3. The ability to vary the temperature of the interface in such a manner as to simulate thermal de-icing units.
4. The ability to test actual, or parts of actual, de-icing equipment.
5. The ability to test rime, glaze and mixed rime/glaze ice specimens.
6. The production of ice specimens with a predetermined impurity type, content and distribution. A variable which may be addressed, is that of ice purity with respect to dust particles and dissolved ions (Bib.- 1.7). Its effect on adhesion is probably negligible in comparison to its effect on freezing temperature, but may become significant in cases at temperatures around 0°C.
7. The ability to load the interface in tension, (as well as shear).
8. The ability to apply controlled, monitored vibration to the substrate during testing throughout a wide frequency range and using frequency distributions simulating those experienced on the intake during flight.
9. The ability to load the interface in shear in two orthogonal directions.

10. The ability to apply various methods of microwave de-icing to the bond during testing. Other systems to be considered could include pneumatic, electro-impulsive, electro-expulsive, freezing point depressant fluid, and acoustic de-icing (Bib. - 4).
11. The rig should be operated by one person and require a minimum of skill, although for insurance and safety standards purposes, it may be mandatory to maintain a second person present.

16.3.3 List 3 :Previous Ice Adhesion Test Rigs

(Sup.1 - 5)

Taken from the bibliography, this survey does not include all relevant test rigs previously designed, but presents a representative cross-section of all available.

Interest was taken in designs to test ice adhesion strength when loaded in tension and compression as well as in shear, as this may yield a rig design which could be modified to test in shear. The previous designs located are individually described as follows:-

1. (Sup.1), (Fig.R1), also see (Sup.3) for additional information and associated figures.

This test rig was designed by a propeller de-icer manufacturer mainly with the intention of studying cycling times of thermal rubber boot de-icing equipment. The ice bond to the rubber substrate is mechanically loaded in shear using a hand operated hydraulic jack. Two one-inch cube ice specimens are frozen onto opposite faces of a double-sided, substrate coated, plate which is pulled by the jack. The ice cubes are located by plates frozen within them, and fastened together by a cross member hooked to a support frame. It is intended that the whole system be placed in a "cold room", and the bond interface temperature assumed to be equal to that ambient within the "cold room".

2. (Bib.290), (Fig.R2)

This apparatus also employs a hand operated hydraulic jack to provide the mechanical shear force to break the ice/substrate bond. The main design objective as stated in (Bib.290) was to minimise friction by providing opposite parallel forces. The apparatus, except for the jack and pressure gauge is located in a chest type domestic freezer and the maximum hydraulic pressure achieved in breaking the ice/substrate bond is recorded on a maximum pressure gauge.

3. (Bib.319), (Fig.R3)

The same apparatus as used in (Bib.290), showing a little more detail in the working area.

4. (Bib.146), (Fig.R4)

In this reference Jellinek uses two rigs to test ice adhesion in shear. Both employ a hand driven worm gear input work to provide the shear force at the ice/specimen interface. A Baldwin load cell measures the applied shear force. The operation of the first rig (pp.1296) is not clearly apparent from the figure and thus no attempt has been made to re-draw this figure in this case. Reference to the original article should be made if necessary. However it suffices to say that the apparatus appears to be rather complex in some areas and perhaps a little lacking in others. The second test rig (pp.1302) re-drawn here as (Fig.R4), is much simpler. An inclined plane allows accurate alignment of the bond interface and loading plane, and the load cell is fitted between the work input and the specimen instead of situating the specimen between the work input and the load cell as previously.

5. (Bib.597), (Fig.R5)

The most recently reported test rig in the survey, employing a mechanically produced shear load by means of a hydraulic ram and measured using a load cell. Ice is formed on an inner cylinder through a window in an outer cylinder. Temperature is varied during testing using a cartridge type heater inside the inner cylinder and monitored by a thermocouple in the wall of the inner cylinder. The experimenter recognises the absence of previous experimental data on ice shear adhesion using ice specimens of a physical nature similar to that of ice adhered to airborne structures, and thus forms ice specimens by supercooled water droplet impingement on the substrate within an icing research tunnel.

6. (Bib.10), (Fig.R6)

A very simple but effective test rig employing the torque applied to a shaft to produce a shear force at the circumference where the shaft is bonded to an outer cylinder by ice between the two.

7. (Bib.10), (Fig.R7)

In an effort to avoid applying a direct mechanical load to the ice specimen, possibly causing deterioration of the sample, internal cracking, changes in the crystallographic structure, crumbling of the surface of the specimen etc., these two experimenters made use of a centrifuge oriented design philosophy. A sample of substrate is fastened to a disc and a small button of ice applied to the substrate. The ice specimen is previously formed and then frozen to the substrate. The disc is rotated and accelerated until the ice/substrate bond is broken by the action of centrifugal force on the ice. The apparatus contains its own refrigeration system, shield and protective outer box.

8. (Bib.335), (Fig.R8)

This report contains details of two pieces of test apparatus; one for applying a shear load to an ice/substrate bond, and the other for use in tensile loading of the bond.

(a). The strength of two ice/substrate bonds in tension is tested using two flat plates attached perpendicular to two hooks which are pulled in opposite directions.

(b). A simple apparatus, two flat rectangular plates held together over an overlapping area by ice formed between them. Shear loading of the two ice/substrate bonds is achieved by pulling the plates in opposite directions.

9. (Bib.412), (Fig.R9)

Apparatus for testing loaded in tension, almost identical to that of (Bib.335) with only a change of shape of the flat plates from circular to square.

10. (Bib.333), (Fig.R10)

Two sets of apparatus, one for testing ice adhesion in shear, the other in tension.

(a). The substrate is applied to a circular test piece which is held in place in the lower, fixed part of the apparatus, whilst the ice frozen to the substrate and the upper, sliding part of the apparatus is moved to place the bond in shear.

(b). Very similar to the apparatus of (Bib.335), employing two substrate surfaces frozen to opposite faces of the ice specimen and pulled in opposite directions to load the two interfaces in tension. 11. (Bib.173), (Fig.R11)

Adhesion is tested in tension using a rig similar in some ways to that of (Sup.1 - 5), but using a threaded rod driven by a worm gear as in (Bib.146) to apply the tensile load. Work input is from an electric motor. A load cell measures the tensile load.

12. (Bib.172), (Fig.R12)

The tensile strength of the adhesion of an ice specimen to a substrate is determined from the rate of propagation of a crack at the centre of the bond. A PTFE disc, using a temporary cylindrical mould, is placed over a circular hole in the base of the rig, the upper surface of which forms the substrate to be tested. Water is frozen in the form of a solid cylinder over the disc and the upper surface of the test rig base. Pressurised gas is allowed into the hole in the base thus applying a force to the lower surface of the PTFE disc perpendicular to the plane of the bond interface. The crack in the bond of the ice to the upper surface of the rig base formed by the presence of the PTFE disc

propagates over the area of adhesion. From a knowledge of the gas pressure history and crack propagation rate, the ice tensile adhesion strength is determined.

13. (Bib.239), (Fig.R13)

In this case the ice/substrate bond is loaded in torque. The ice specimen and substrate are situated in a refrigerator and torque applied via a rod through a hole in the refrigerator wall, the rod being driven by a worm gear. Care is taken to observe creep of the ice prior to debonding, employing a mirror attached to the rod close to the ice specimen. The temperature of the bond is assumed to be equal to that ambient within the refrigerator and is controllable to within 1°C.

16.3.4 List 4 :Previous Test Rig Suitability/Adaptability

(Sup.1 - 6)

1. Requirements 2 - 7 (List 1), (Sup.1 - 6.1)

In weighing up the suitability or adaptability of the previous designs featured in (Figs.R1 to R13) against the mandatory requirements listed earlier (List 1), it can be seen that requirements 2 - 7 are satisfied by all of the designs.

2. Requirement 9 (List 1), (Sup.1 - 6.2)

Several of the designs employ a load cell thereby satisfying requirement 9 but violating requirement 1 somewhat as load cells are inherently costly to acquire. For those rigs not making use of a load cell, the method of load measurement is not always stated but, apart from (Fig.R1) employing the hydraulic jack input pressure as a means of measuring applied load, (Fig.R12) where the gas pressure determines the load, and (Fig.R13) where the twist angle of the torque rod is used for load derivation, some form of load measurement using one of the former mentioned methods or otherwise is required.

3. Requirements 10 and 11 (Sup.1 - 6.3)

Regarding requirement 10 and considering only those rigs designed for shear testing: in (Fig.R1) the bond interface is loaded in shear by pulling the substrate vertically downwards. Movement of the ice is restricted by means of two perforated flat plates frozen into the ice so that their planes are parallel to the bond interfaces. Thus, in the cross section, (left) view of (Fig.R1), the restraining plates may be considered to apply a point load in the ice at a perpendicular distance (of approximately 10 mm) from the bond interface, thus applying a considerable moment to that bond plane. This test rig has not at this present time been operated for experimentation but as the force required to "peel" ice from a substrate (or visa versa) has

been shown in several other reports from the bibliography to be much smaller than that required to remove the ice in pure shear (Bib.597), it is likely that peeling will occur during testing with this rig. This would be accommodated by bending of the restraining plates, allowing rotation of the ice specimens relative to the substrate plate.

(Fig.R2) represents some improvement over (Fig.R1) in the application of the load to the ice specimen. Four faces of a rectangular plate of ice are adhered to the slider component which applies load to the ice. Hence the ice in contact with one face is in tension, that in contact with the two adjacent faces is in shear and that in contact with the opposite face is in compression. The internal load paths within the specimen may therefore be rather complex, but in general the forces on all four faces aid each other in an attempt to provide a homogeneous load application to the specimen. In the other plane, ((Fig.R3) side elevation), it is obvious that the load is distributed to the ice interfaces with the slider, in pure tension, shear and compression at the level of the ice-test substrate interface but with an added moment as the distance above this plane is increased. This moment, like the one in (Fig.R1), attempts to peel the ice from the test substrate. However, in (Fig.R1), only the bond area of the ice to the two vertical restraining plates in the ice, and thus also the stiffness of those plates, attempt to prevent peeling of the specimen as a whole from the substrate. In (Fig.R2), the four adjacent faces of the square hole through the thick slider located on four stiff bolts are provided to prevent rotation of the complete specimen.

The load path from the slider to the ice specimen is exactly the same in (Fig.R3) as for (Fig.R2). Observing (Fig.R4) it can be seen that load transfer to the ice is similar to that of (Figs.R2 and R3), except that peeling is further reduced using a larger aspect ratio of specimen bond area to specimen thickness. Whilst bringing about an apparent improvement in shear loading, the use of a thin plate ice specimen may lead to tumbling or rotating of small sections of the ice relative to one another causing cracking across the specimen. This is a result of increased adhesion to the substrate beyond the cohesion providing structural integrity within the ice. The reduced thickness also results in reduced load diffusion within the sample. In (Fig.R5) the load is applied via a metal annular surface on to an annular ice surface perpendicular to the test interface. If (Fig.R5) was considered to be a side elevation of a rectangular construction of square cross section, then most of the offset load path problems inherent in the designs of (Figs.R2, R3 and R4) are still applicable. Considering the actual circular cross section, the rigidity of the ice cylinder and therefore resistance to distortion in any vertical plane is high due to the uniform circumferential stress in any horizontal plane through the cylinder. Thus, peeling of the ice from the test substrate surface is almost eliminated.

For the same reasons as in (Fig.R5), the ice cylinder in (Fig.R6) is dimensionally very stable (unless considering creep using a very slow loading rate). This method of using a torque load input at the central axis to produce shear at the interface, in addition to the use of a cylindrical ice sample results in a loading method close to pure shear.

(Fig.R7) appears to have eliminated most of the problems associated with direct mechanical loading applied to the ice specimen. However, observing the upper diagram of (Fig.R7), unless a relatively large bond interface area (large radial coverage) and thin substrate thickness (assuming a flexible substrate) are employed, then the bond interface may deviate considerably from parallel to the plane of the rotating disc. As many of the substrates to be tested in this research programme are relatively inflexible, this method of experimentation may present a viable solution to be adopted in the programme. However, in order to produce a good pure shear load, as implied earlier, a much larger specimen is required and thus much larger apparatus.

(Fig.R8(a)) presents a diagram of tension testing apparatus which, if adapted to test in shear, (as also for (Fig.R9)), would become like (Fig.R8(b)). It is obvious from observation of (Fig.R8(b)) that, unless employing a large bond area with a thin ice layer, peeling of the interfaces will predominate over shear of the specimen as a whole. Employing a large area thin ice layer presents all the inherent problems mentioned earlier.

(Fig.R10(a)) presents a reasonable solution to the problem of producing pure shear, in that rotation of the substrate from the ice specimen is well restrained by a thick, rigid test piece holder with a close tolerance location of the test piece, (ie. screw thread) and also in locating the ice specimen holder in guide rails in the substrate holder. However, the shape of the ice specimen in the plane perpendicular to the desired shear plane (interface plane) is still rectangular and thus does not inherit the rigidity of an ice cylinder in that moments are set up within the thickness of the ice specimen and substrate causing, an inhomogeneous load distribution and possible structural failure of the specimen. The apparatus of (Fig.R10(b)) is not easily adaptable for testing in shear which may be one of the original experimenters reasons for requiring the apparatus of (Fig.R10(a)).

Tension testing apparatus is featured in (Fig.R11), the bulk of which, (ie. load cell and screw gear) may be adapted for use in shear testing using additional apparatus, to become similar to (Fig.R1).

Considering of the tensile test apparatus of (Fig.R12), should the temporary moulding cylinder be incorporated as part of the rigid brass block, adhered to the ice, then further modification could yield a simple but effective shear testing

rig. Removal of the PTFE disc and replacement with a cylindrical substrate would result in all of the advantages previously attributed to the use of cylindrical ice specimens and test substrates (Fig.R14). The application of load through pressurised gas presents a simple, homogeneous, controllable and measurable method of loading the substrate whilst the ice remains static adhered to the rig on its base and circumferential wall.

The shear test apparatus of (Fig.R13) possesses many of the advantages of that of (Fig.R6), ie. cylindrical specimens and the use of torque to produce shear at the circumference, plus a simple economic method of load measurement. However, the ice specimen is not well restrained from distortion in bursting of the cylinder.

4. Requirements 12 and 13 (List 1), (Sup.1 - 6.4)

A hand pumped hydraulic jack will always, to some extent result in a stepped loading rate. This is also the case (though not usually to the same extent) for hand operated screw thread and worm gear loading equipment. Anomalies exist where the full travel of the hand rotation or traverse is reached, unless on a rotary system, two hands are employed and transfer from one to the other is almost undetectable. Those test rigs employing hand driven loading equipment may be modified to incorporate electric motor drive units or electric pumps producing a smooth loading rate and eliminating vibration and impact induced through a stepped or oscillating loading rate. Care must be taken to ensure that vibration from motors, gears etc., in the drive unit are not transmitted in significant amplitude to the ice/substrate bond interface.

There are only two rigs featured which are not loaded using some form of mechanical loading gear, being (Figs.R7 and R12). The centrifuge type equipment of (Fig.R7) must be checked for vibrations transmitted to the ice bond interface from the motor and drive train of the spinning disc. In reality it will be almost impossible to totally eliminate vibration from such an arrangement but reduction to a minimum is advantageous. The most vibration free design is that of (Fig.R12) in which the vibration present should be capable of being reduced to that of outside environmental considerations and not connected with the test rig or testing equipment except perhaps, refrigeration equipment associated with producing the required ambient temperature.

5. Requirement 14 (List 1), (Sup.1 - 6.5)

The test rig of (Fig.R1) appears to produce ice/substrate interface areas of an accurately known value, until it is realised that the free surface of the ice cubes does not freeze in a smooth, flat plane. A significantly large dome is raised in the centre due to local freezing in this area during the final stages of freezing of the cube (Sup.2), (Figs.17 and 19). Also, the frozen meniscus in contact with the test substrate may curve

up or down quite sharply depending on whether the substrate surface is hydrophilic or hydrophobic (Fig.17). These errors are to some extent present with many of the designs. They are partially curable by such methods as adding a final layer of water on the uneven frozen free surface to freeze later producing a flatter surface and thickening the "lip" formed at the line of contact to the test substrate surface (Fig.23), (Sup.2). One of the greatest problems associated with setting up the experimental equipment of (Fig.R1), is in attaining two ice samples bonded to opposite faces of the same test piece with identical bond areas in size, shape and orientation. The adhesive strength of the bond, which may be as high as 250 psi (1.72 MPa), (Ref.8), (Bib.288), (Sup.5), applied to bond areas of such small magnitude results in a requirement for the areas to be equal to a high degree of accuracy. This is necessary to achieve meaningful test results and to avoid bending moments due to uneven loading, causing peeling of the ice from the substrate. Thus it is not good practice to test two interface bonds simultaneously, of small area and offset by a relatively large distance. For (Figs.R2-R5), the bond area is rigidly controlled by forming the ice within a cut-out area of accurately known value. The fact that this mould remains in place during testing is of advantage in reducing distortion of the sample and eliminating damage to the specimen during mould release. It has been assumed that a homogeneous and continuous bond has been achieved over the whole area in question in each case, ie. that no anomalies such as large bubbles etc., exist at the interface. In (Fig.R6) the bond area is controlled by the substrate height and water depth and thus to some extent, is variable in a controlled manner, although meniscus problems still exist as in previously mentioned cases.

For the case of (Fig.R7), the ice specimen is formed before being attached to the substrate. Care must be taken during this attachment if the bond area is to be accurately controlled. Only the area representing a horizontal cross section through the ice specimen, and a continuation of that area projected to the substrate, should be bonded to the substrate, and not that formed by water spread in capillary action or otherwise from the bond area over a larger area of the substrate, before freezing. This also applies to (Fig.R8(b)) where the area is controlled by the amount of overlap of the two plates but could be significantly increased by water spreading due to capillary action. For (Figs.R8(a), R9, R10(a), R10(b), R11 and R13), the bond area is perpendicular to the edge of the mould or substrate on or in which it is formed, thus eliminating capillary action spreading and making it possible in many cases to remove any excess. For (Fig.R12), modified as previously stated (Fig.R14), bond area control is as for (Fig.R6).

6. Requirement 15 (List 1), (Sup.1 - 6.6)

Many of the test rigs featured in (Figs.R1-R13) do not incorporate any form of temperature measurement, but rely on measurement of the ambient temperature within the testing

environment, assuming this to be equal to the temperature of the bond interface. Interface temperature measurement would be useful if possible without detriment to the test. The obvious method of temperature measurement in such cases is by the use of thermocouples due to their size, robust construction, versatility, reliability and accuracy. This is the case in (Figs.R5, R10(a) and R10(b)), but all of the other cases featured could employ a similar arrangement.

7. Requirement 16 (List 1), (Sup.1 - 6.7)

A thermocouple at or near the interface, considering Requirement 16, should not interfere with the bond to any significant extent, by crack initiation, area change, or otherwise. Running the same test with and without thermocouples to assess the error is not a satisfactory solution. Although the achievement of accurately equal test conditions may be possible, achieving two ice specimens of identical internal crystallographic construction is not possible, (and not recognisable should it ever be inadvertently achieved), (Sup.2). Past experience reported by nearly all of the mentioned experimenters shows the results obtained for adhesional strength to be rather scattered. The variation between them is greater than that expected due to removal or introduction of a thermocouple at or near the interface. Apart from (Fig.R12), where the PTFE disc interferes with the bond interface (a case which would not exist in shear testing), none of the figures show equipment or instrumentation other than a thermocouple as previously discussed to interfere with the bond interface during testing.

8. Requirement 17 (List 1), (Sup.1 - 6.8)

(Fig.R1) excels in this case in using flat rectangular substrates which are easily re-useable. However, using two substrates on opposite faces of the same plate requires them to have equal properties in material and surface finish, and the faces to be ice bonded must be accurately parallel.

With the exception of (Figs.R5, R6, R14) and the cylindrical interface case of (Fig.R13), all of the other test rigs employ flat rectangular or circular substrates. (Figs.R8(a), R8(b), R9 and R11) require two equal substrates as in (Fig.R1) with the associated difficulties. (Figs.R5, R6 and R14) require the substrate to be applied around a cylinder in the form of a film or sheet, or when using rigid materials, a cylinder of the material is manufactured. Plating, painting, spraying, dipping and other coating techniques are equally applicable.

9. Requirement 18 (List 1), (Sup.1 - 6.9)

In many reports, an accurate recording of the instrumentation employed during testing is not given. Thus apart from reproduction of equal ice specimens (already covered in

detail), the test conditions associated with all of the figures (except (Fig.R1) which is detailed later), are reasonably easily repeatable to a degree of accuracy which is not easily improved upon without a large increase in the cost of test rig design, manufacture and operation.

10. Requirements 1 and 8 (Sup.1 - 6.10)

Requirement 1 has been left until last because it is important to see the advantages of many of the rigs in light of the other requirements before considering such aspects as cost, design time, set-up time, etc.. Requirements 1 and 8 are dealt with together as they are somewhat related. Requirement 1 is concerned with the cost of the experimentation which is closely related to its simplicity in design, manufacture and operation as noted in Requirement 8.

Observing (Fig.R1) and noting that when setting up the equipment for testing to begin:-

(i) The hydraulic jack must be held vertical in two planes to a high degree of accuracy.

(ii) The two restraining plates attached via a beam to a hook must be positioned vertically in two planes to a high degree of accuracy. The addition of the plumb line to note this verticality means that the hook assembly is not mass balanced and thus free vertical hanging will not occur.

(iii) The substrate surfaces in test must be fitted parallel to each other and the test piece screwed onto the jack plunger so that the restraining plates to be set in the ice are parallel to the substrates.

(iv) The moulds for ice forming must be equal in size, shape, orientation in three rotations and location in three planes with respect to the substrate surfaces and restraining plates; clamped to the substrate surfaces and held in position, aligned accurately vertical whilst freezing of the ice specimens takes place.

(v) The water for freezing must be applied at the same temperature to both moulds to achieve equal freezing rates and ice specimens of equal size, shape and internal construction as previously detailed.

(vi) The bond strength achieved between ice and substrate and between ice and restraining plate must be equal for each specimen.

(vii) If the moulds are to remain in position during testing, then care should be taken to avoid adhering the mould edges to the substrate and to avoid using a clamping force which will exert a bond release pressure after removal of the clamps.

Thus some form of freezing point depressant fluid must be used on the mould edges. However, as it is the nature of most low viscosity fluids to creep under capillary action, this may result in creeping of the fluid on the substrate surface, reducing the bond area to an unknown value and producing a sharp inward facing "lip" at the substrate edges. This causes a large stress concentration during testing which is likely to initiate peeling of the ice from the substrate.

(viii) If the moulds are to be removed before testing, it must be realised that the area of ice in contact with the moulds is four times that in contact with the substrate. This prevents any application of force to remove the moulds as this would be impossible without degradation of the bond to the test substrate surface. Application of heat to the mould to melt the layer of ice in contact with the mould surfaces is not a viable proposition as the mould extends in contact with the ice up to the substrate surface. The use of square corners and edges in the design of the mould would effect more melting at these areas due to heat concentration, before bond release from the central areas of each side of the mould could occur. Considering careful use of some form of freezing point depressant mould release agent. This approach was considered and tested with no success in (Sup.2). The adhesion strength of the ice to the mould surfaces must be reduced to less than one quarter of that to the test substrate surface. The pressure seal formed by the thin liquid layer (fluid mould release agent or melt water) between the ice and the mould into virtually inaccessible corners of the mould requires considerable force to break and replace with air before removal of the ice from the mould can be achieved.

It should be realised that points (i) to (viii) must be achieved simultaneously, at the testing temperature in order to correctly assemble the equipment. During ice forming, assuming the equipment has been assembled correctly and assuming no induced moments in the ice samples, difficulties may arise in the representation of a realistic ice sample, due to the small dimensions of the specimen, especially considering the restraining plates which effectively reduce the maximum ice thickness available to less than 0.5 inches.

The assembly of the apparatus in (Figs.R2, R3 and R4) is similar and relatively simple, the only real difficulties being in controlling the flow of water from seals during freezing. (Fig.R5) depicts apparatus which uses ice specimens formed in an icing research tunnel. Whilst being of a more realistic nature than that of the other cases, it should be realised that this method of specimen production is much more costly than some of the less realistic methods. Assembly of the strength testing apparatus in this case is reasonably simple and vice free.

In the case of (Fig.R6), the main difficulty experienced during setting up is in avoiding bonding the lower edges of the substrate and substrate-former-cylinder to the outer cylinder,

and in accurately aligning the axes of the inner and outer cylinders in two planes and two rotations.

In the case of (Fig.R7), once the equipment, excluding the ice and substrate, is assembled, vibration free and parallel in the correct planes, then application of the substrate and ice is reasonably simple, but as previously noted, care must be taken in control of the ice bond area.

In (Figs.R8(a), R8(b) and R9) the main considerations during apparatus arrangement are those concerning alignment of the two pulling forces in relation to the plane of, and rotation of the bond interface. In (Fig.R10(a)), care must be taken to avoid bonding the edges of the upper sliding component around the ice specimen to the test substrate surface. In (Fig.R10(b)), the retaining screws must be tightened carefully whilst maintaining no contact between the mould ring around the ice and the edges of the main block, to avoid breaking of the bond prior to testing, and to achieve a good even bedding of the test sample in the block.

The apparatus in close proximity to the ice of (Fig.R11) is assembled in the same manner, and with the same vices as that of (Fig.R9). (Fig.R12), or rather, (Fig.R14) requires, as in the case of (Fig.R6), that care be taken to avoid bonding the lower edge of the substrate and former to the outer cylinder, and also that the axes of the two cylinders are aligned. In this case it may be noted if a leakage of water from the substrate surface to its lower edge has occurred as it may be visible through the hole required for the pressurised gas.

In (Fig.R13), care is required in the production of the ice specimens, and the accuracy of the adhesion force measurement system may be somewhat questionable.

16.3.5 List 5 :Test Rig Design Origin and Development

(Sup.1 - 7)

From the analysis of previous designs, several additional criteria for an ice shear adhesion test rig design to suit this programme have become apparent for the reasons mentioned in the texts referred to.

1. The use of cylindrical ice specimens and substrates loaded at one end with shear taking place on the whole of the curved surface to reduce distortion and increase the strength of the specimens. Although this may incur some error in predicting ice shear adhesional strength on a flat surface, it should be remembered that the situation for which the research applies is that of ice adhered to a propeller blade or air intake lip in which case the cylindrical surface is more representative than a

flat one, provided that the cylinder in question is of sufficient diameter.

2. The offset between the point at which the load may be considered to be applied and the point at which it may be considered to be reacted must be reduced to a minimum, and preferably zero.
3. Any bending moments intentionally produced must be equally opposed.
4. Point loads should be avoided wherever possible.
5. The load should be applied via some form of fluid pressure to maintain smooth diffusion into the ice and ease of variation of the applied load.
6. Both the substrate and the ice specimen should possess sufficient volume to avoid degradation of results through small material anomalies. However, the bond area is restricted by the magnitude of applied load available for debonding and the space available for the apparatus at the required testing temperature.
7. The ice specimen and substrate must be of a smooth shape, both separately and when in contact with each other to avoid stress concentrations.
8. The test rig should form its own mould which remains in place during testing and does not detriment the test results in any manner.
9. Only one bond surface should be tested at a time. It should be noted here that criteria 3, 7 and 9 from this text, as well as criterion 1 necessitate the use of a cylindrical specimen.
10. The apparatus should, wherever possible, be self-aligning and not require the use of several personnel simultaneously during assembly, which introduces errors and reduces repeatability.
11. It would be advantageous to be able to test ice specimens representative of the situation under research ie. ice accreted on propeller blades and air intake lips during flight. Thus the substrate samples could be capable of being used by some other form of equipment for producing this ice specimen, e.g. an icing research tunnel.

Note: A further rig was designed for use in conjunction with this test rig in order to produce ice specimens on the substrate samples of a more realistic nature to the research project than that of bulk frozen water. This rig involved an electric motor powered drive mechanism to rotate the cylindrical substrate in the flow produced by a small electric fan and nozzle. Into this airflow was sprayed water at a temperature just above 0°C. using a standard atomising insecticide spray gun. The whole apparatus was operated inside a standard domestic chest freezer at a

temperature of approximately -20 to -30°C. Several realistic rime ice samples were produced, but it was only possible to accrete an ice thickness of approximately 1 mm before the specific and latent heat energy in the impinging water combined with the rising chamber ambient temperature (lid open during testing), resulted in melting of the base layer of rime ice. Several cases were tested in the adhesion rig where the substrate with a 1 mm growth of rime ice was placed in the rig and the intervening gap filled gradually with cooled water to bulk freeze the specimen in place with a rime ice sample at the interface. However, in order to avoid melting the rime ice, this method was slow (several days) as the cold chamber had to be frequently allowed to re-cool to the working temperature. Also, the water infiltrated the rime ice to some extent, turning it into a mixed rime/glaze with emphasis on the latter. With these difficulties in mind, it was decided to return to testing simple bulk frozen ice specimens.

With these criteria in mind, several possible avenues of test rig design philosophy were explored and compared. The design approach finally chosen was a development of (Fig.R14) which was derived from (Fig.R12). (Fig.R15(a)) shows the bullet held in place for setting in the barrel using ice. The long bolt is then removed and replaced with a short one, as in (Fig.R15(b)), before attachment to the breech. This breech adaptor is not acceptable from a stressing consideration of the bending moment in the flange, hence (Fig.R15(c)). Material cost and machining considerations however, and flexibility of design for possible future development meant that the modifications adopted in the design shown in (Fig.R15(d)) represent some improvement over (Fig.R15(c)). The breech block is simplified, leaving the breech free for variation in design for different applications. Two lugs were added to the breech adaptor to aid removal after freezing.

After further simplification and a reduction in the number of components, enabling advantages in design flexibility, manufacture, cost, operation and stressing, the design featured in (Fig.R15(d)) became that of (Fig.R16). It was noted that sealing against a high pressure fluid is not satisfactorily achieved at a large radius where the two mating faces meet with a relatively large movement of one face parallel to the other (particularly when using an "o"-ring). Thus the bolted flange type seal was used to fasten the breech to the breech block. The radius at which the gas is sealed at this joint has been reduced to a minimum to reduce the bending moment at the locating bolts and a pressure release channel with associated nozzle is incorporated in the breech block to cater for failure of the "o"-ring. (Fig.R17) is a reduction of the full scale engineering drawing produced as a part of the research programme, from which the test rig was manufactured.

16.4 Tables

16.4.1 Table 1(a) :Substrate Test Specimens

1. Polished aluminium alloy.
2. Machined aluminium alloy.
3. Machined aluminium alloy.
4. Clear polyurethane paint on machined aluminium alloy.
5. Machined stainless steel.
6. Nickel plated mild steel.

Electroless nickel plating: Supplied by	A. T. Poeton	Part
number G81512-773147 Checked	10.01.86	Dowty
Materials Laboratory: Hardness		
606Hr Checked	John McKenna	
	R0118886	14.01.86

7. Neoprene coat on machined aluminium alloy.
8. Dowty neoprene de-icing boot on machined aluminium alloy.
9. Polyacetal

40mm extruded natural polyacetal rod
 Nylonic engineering Co. Ltd.
 Woodcock Hill
 Rickmansworth
 Herts
 WD3 1PN 10 Polyacetal (as above)

16.4.2 Table 1(b) :Adhesion Test Data Using the

Research Programme Test Rig -

Polished Aluminium Alloy - (Fig.40(a))

Temperature (°C)	Shear Adhesion (MPa)
-10.0	0.341
-14.1	0.325
-18.2	0.287
-24.6	0.244
-32.0	0.155
-38.1	0.289
average	0.274

Machined Aluminium Alloy - (Fig.40(b))

Temperature (°C)	Shear Adhesion (MPa)
-11.6	0.392
-16.3	0.374
-21.2	0.380
-28.9	0.412
-30.7	0.399
-35.5	0.463
average	0.403

Clear Polyurethane Paint - (Fig.40(c))

Temperature (°C)	Shear Adhesion (MPa)
-12.4	0.272
-14.7	0.221
-19.1	0.368
-26.1	0.402
-32.4	0.267
-35.1	0.353
average	0.314

Machined Stainless Steel - (Fig.40(d))

Temperature (°C)	Shear Adhesion (MPa)
-13.1	0.222
-18.6	0.278
-22.2	0.374
-29.6	0.431
-33.5	0.413
-37.9	0.470
average	0.365

Polyacetal - (Fig.40(e))

Temperature (°C)	Shear Adhesion (MPa)
- 4.8	0.010
- 8.0	0.019
-11.9	0.031
-17.9	0.028
-17.0	0.054
average	0.028

Neoprene - (Fig.40(f))

Temperature (°C)	Shear Adhesion (MPa)
- 9.8	0.340
-10.2	0.343
-12.6	0.436
-13.5	0.311
-18.0	0.764
-21.6	0.960
average	0.526

16.4.3 Table 2 :Adhesion Data from the Literature -

pp.nn or pp.ss.nn (for adhesional cases)

pp = test parameter ss = substrate nn = block number
 SA shear adhesion Al aluminium
 01 to 99
 TA tensile adhesion Br brass
 TS tensile strength Ne neoprene
 CS compressive Pa polyacetal
 strength Pe polyethylene
 SS shear strength Po polystyrene
 ST torsional shear Ru rubber
 strength SS stainless steel
 ME modulus of St steel
 elasticity Te teflon
 Dm density (mass) Ti titanium
 Vi viton
 Ot other
 Ac lubricant on
 aluminium
 Bc lubricant on
 brass
 Fc lubricant on
 steel
 Sc lubricant on
 stainless steel
 Tc lubricant on
 teflon

The data blocks are referenced by two numbers. The first refers to the reference section within this log, and the second (bracketed) refers to the bibliography. This number also appears in the reference section of this log for cross reference to the bibliography.

Shear Adhesion

Stainless Steel

SA.SS.01 (Bib.288) Stainless steel (grade 304/A), snow ice

Temp. (°C)	Adhesion (MPa)	Break
-2.0	0.22	Adhesional
-5.0	0.53	Adhesional
-7.7	1.04	Adhesional
-10.0	1.09	Adhesional
-11.6	1.46	Adhesional
-13.8	1.63	Adhesional
-20.0	1.61	Cohesional
-36.0	1.58	Cohesional

SA.SS.02 (Bib.290) temperature = -6°C, distilled water

Specimen column height (mm)	Adhesion (MPa)
12.7	0.427
	0.483
	0.483
Most common break = Cohesional	0.400
	0.496
	0.441
	0.386
Average	0.448 +/- 0.034
1.016	0.855
	0.600
Most common = Adhesional/cohesional	1.014
	0.724
	0.579
Average	0.752 +/- 0.145

SA.SS.03 (Bib.91) (91 Sub. Ref. 1)
L.E. Raraty and D. Tabor (03.06.58)
All adhesional breaks

Surface treatment	Gradient of adhesion with temperature from results presented in (Bib.91), (zero adhesion at 0°C)
Electrolytically degreased	-0.152
Refluxed in Benzene	-0.078
Monolayer of Stearic Acid absorbed on surface	-0.025

SA.SS.04 (Bib.91) Impact ice, all adhesional breaks

Temperature (°C)	Adhesion (MPa)	Temperature (°C)	Adhesion (MPa)
-15.0	0.103	-9.4	0.020
	0.091		0.007
	0.079		
	0.038	-6.7	0.016
			0.010
-12.2	0.107		0.003
	0.091		
	0.083		
	0.076		
	0.069		
	0.041		

SA.SS.05 (Bib.146)

Temperature = -4.5°C, all adhesional breaks, snow ice

Test plate surface finish	Adhesion (Mpa)
	(average of 12)

Rough	0.598
Polished (mat)	0.265
Polished (mirror)	0.067
Polished (mirror)	0.085
Polished (mirror)	0.131

SA.SS.06 (Bib.333) Temperature = -7.8°C, adhesion = 0.345 - 0.594 MPa

SA.SS.07 (Sup.4) Test Temp. (°C) Fracture Adhesion (MPa)

3	-38	cohesional	0.081
5	-13	adhesional/cohesional	0.138

Steel

SA.St.01 (Bib.319) temperature = -6°C, adhesional/cohesional breaks

Surface finishing material	Adhesion (MPa)
0.05 microns Alumina	0.931
"4/0" emery paper	1.255

SA.St.02 (Bib.333) temperature = -7.8°C, adhesion = 0.110 - 0.583 MPa

Titanium

SA.Ti.01 (Bib.91)

A = adhesional break peeling occurred at one edge until the adhesional bond area was reached when a sudden break occurred. C = cohesional break Impact ice

Temperature (°C)	Adhesion (MPa)		Temperature (°C)	Adhesion (MPa)	
-17.8	0.496	C	-15.0	0.097	A
	0.465	C		0.077	A
	0.465	C		0.070	A
	0.365	C		0.058	A
	0.348	C			
	0.341	C	-9.4	0.035	A
	0.264	A		0.028	A
	0.255	A		0.014	A
	0.190	A			
	0.177	A	-6.7	0.016	A
	0.177	A		0.012	A
	0.165	A		0.006	A

0.148 A
0.141 A
0.133 A
0.109 A
0.097 A
0.084 A

Aluminium

SA.A1.01 (Bib.290) temperature = -6°C, distilled water

Adhesion (MPa)

0.690
0.662 Most common break
0.772 = Adhesional/cohesional
0.841
1.000
Average 0.793 +/- 0.103

SA.A1.02 (Bib.91) Impact ice, all adhesional breaks

Temperature (°C)	Adhesion (MPa)	Temperature (°C)	Adhesion (MPa)
-15.0	0.377	-13.3	0.218
	0.333		0.197
	0.184		0.113
	0.105		0.075
	0.093		
	0.083	-12.2	0.167
	0.065		0.159
	0.065		0.152
	0.050		0.101
	0.041		0.067
	0.034		
		-9.4	0.073
			0.064
			0.054
		-6.7	0.031
			0.023
			0.016

SA.A1.03 (Bib.333)

Temperature = -7.8°C, 11 tests, adhesion = 0.532 - 1.071 MPa

SA.A1.04 (Bib.333)

Resaxed aluminium, temperature = -7.8°C, all
adhesional breaks, adhesion = 0.391 - 1.034 MPa

SA.A1.05 (Sup.4) Test

Temp. (°C)	Fracture	Adhesion (MPa)
1	-32	cohesional 0.152
2	-38	adhesional 0.276
4	-13.5	adhesional/cohesional 0.138
10	-10	cohesional 0.338

Brass

SA.Br.01 (Bib.290) temperature = -6°C, distilled water

Adhesion (MPa)

	0.910	
	0.972	
	0.979	Most common break
	0.696	= Adhesional/cohesional
	0.772	
Average	0.869 +/- 0.103	

SA.Br.02 (Bib.333)

temperature = -7.8°C, 23 tests, adhesion = 0.423 - 1.034 MPa

Teflon

SA.Te.01 (Bib.91) Impact ice, all adhesional breaks

Temperature (°C)	Adhesion (MPa)	Temperature (°C)	Adhesion (MPa)
-17.8	0.124	-9.4	0.097
	0.105		0.079
	0.069		0.072
			0.055
-15.0	0.103	-6.7	0.048
	0.092		
	0.083		0.072
	0.066		0.061
	0.054		0.048
	0.047		0.038
-12.2			0.019
	0.142		
	0.124		
	0.103		
	0.091		
	0.084		
	0.064		

SA.Te.02 (Bib.290) temperature = -6°C, distilled water

Adhesion (MPa)

0.462

0.510

0.407

Average 0.462 +/- 0.034

Most common break = Adhesional/cohesional

SA.Te.03 (Bib.333)

Black teflon, temperature = -7.8°C, 18 tests

average adhesion = 0.391 - 0.732 MPa

SA.Te.04 (Bib.333)

White teflon, temperature = -7.8°C, 17 tests,

average adhesion = 0.105 - 0.377 MPa

Polystyrene

SA.Po.01 (Bib.288)

Snow ice, most common break = Adhesional

Temp. (°C)	Adhesion (MPa)
-5.0	0.012
-8.5	0.023
-15.0	0.042

SA.Po.02 (Bib.10)

temperature = -25°C,

snow ice Substrate thickness = 0.051 mm

Adhesion = 0.793 MPa

SA.Pa.01 (Sup.4)

Test	Temp. (°C)	Fracture	Adhesion (MPa)
6	-18	adhesional	0.055
7	-18	adhesional	0.034

Nylonic Engineering Company, Rickmansworth, Herts..

Rubber

SA.Ru.01 (Bib.10)

Pure gum rubber, temperature = -25°C, bulk frozen water

Sample thickness (mm)	Adhesion (MPa)
0.84	1.034
1.40	0.688
1.68	0.624
1.68	0.515
4.21	0.345
5.62	0.312
7.86	0.287
9.83	0.273
20.00	0.263
40.00	0.226
60.00	0.195
80.00	0.193
100.00	0.254

SA.Ru.02 (Bib.10) bulk frozen water

Temperature (°C)	Adhesion (MPa)
-10	0.552
-20	1.172
-30	1.379

SA.Ru.03 (Bib.10)

Pure gum rubber (1.0 inch thick), bulk frozen water

Temperature (°C)	Adhesion (MPa)
-4.6	0.335
-10.0	0.347
-15.0	0.252
-20.0	0.266
-25.0	0.225
-28.9	0.146
-35.4	0.124
-39.1	0.030

SA.Ru.04 (Bib.10)

Pure gum rubber (0.002 inch thick), bulk frozen water

Temperature (°C)	Adhesion (MPa)
-10.0	0.402
-25.0	1.056

SA.Ru.05 (Bib.10)

Rubber stock 1.724 mm thick temperature = -25°C,
bulk frozen water

Backing material	Adhesion (MPa)
Polished steel	1.276
Polished copper	0.855
24 ST Aluminium	1.517
Glass (96% silica)	1.089
Microscope slide	0.841
Polyethylene	1.103
Rubber	1.172

Neoprene

SA.Ne.01 (Bib.10) temperature = -20°C, bulk frozen water

Surface roughness description	Percentage of adhesion of untreated surface
Pricked with a pin	125
Covered with santonel	164
Cut with razor blade	182
Roughened with emery	210

SA.Ne.02 (Bib.10)

temperature = -25°C, substrate thickness = 0.051 mm
Adhesion = 1.034 MPa

SA.Ne.03 (Sup.4)

Test	Temp. (°C)	Fracture	Adhesion (MPa)
11	-10	adhesional/cohesional	0.345
12	-10	adhesion	0.345

Viton (elastomer)

SA.Vi.01 (91) Impact ice

A = adhesional break, peeling occurred at one edge until the adhesional bond area was reached when a sudden break occurred.

C = cohesive break

Temperature (°C)	Adhesion (MPa)		Temperature (°C)	Adhesion (MPa)	
-17.8	0.558	C	-12.2	0.201	A
	0.519	C		0.192	A
	0.493	C		0.183	A
	0.484	C		0.163	A
	0.383	C		0.154	A
	0.328	C		0.124	A
	0.247	C		0.119	A
	0.193	C		0.077	A
				0.077	A
-15.0	0.586	A		0.064	A
	0.414	A		0.064	A
	0.345	A		0.054	A
	0.339	A		0.044	A
	0.314	A			
	0.299	A	-9.4	0.084	A
	0.290	A		0.069	A
	0.272	A		0.062	A
	0.265	A		0.055	A
	0.235	A		0.048	A
	0.209	A		0.041	A
	0.175	A		0.033	A
	0.165	A		0.022	A
	0.152	A		0.008	A
	0.145	A			
			-6.7	0.055	A
				0.046	A
				0.028	A
				0.021	A
				0.014	A
				0.007	A
				0.003	A

Polyethylene

SA.Pe.01 (Bib.333)

temperature = -7.8°C, 9 tests,

adhesion = 0.127 - 0.587 MPa

Lubricant on Stainless Steel

SA.Sc.01 (Bib.290)

Bis (2 - ethylhexyl) sebacate (Plexol 201)
temperature = -6°C, distilled water

Adhesion (MPa)

0.772

0.538

0.531

0.469

0.455

Average 0.552 +/- 0.090

Most common break = Cohesional

SA.Sc.02 (Bib.290)

Barium phenylstearate in bis (2 - ethylhexyl)
sebacate (Plexol 201) temperature = -6°C, distilled water

Adhesion (MPa)

0.421

0.290

0.221

0.207

0.165

0.165

Average 0.248 +/- 0.076

Most common break = adhesional/cohesional

SA.Sc.03 (Bib.290)

Sodium dinonylnaphthalene sulfonate (NaDNNS) in bis (2 - ethylhexyl)
sebacate (Plexol 201) temperature = -6°C, distilled water

Adhesion (MPa)

0.069

0.055

0.041

0.041

0.014

0.000

Average 0.034 +/- 0.014 Most common break = adhesional

SA.Sc.04 (Bib.290)

Polyphenyl ether, temperature = -6°C, distilled water Adhesion = 0.662
MPa, cohesional break

SA.Sc.05 (Bib.290)

HB - 40(terphyl), temperature = -6°C, distilled water
Adhesion = 0.634 MPa, cohesive break

SA.Sc.06 (Bib.290)

Bis (phi - C5) glutarate, temperature = -6°C, distilled water

Adhesion (MPa)

0.607

0.455

0.331

0.283

Average 0.421 +/- 0.110 Most common break = cohesive

SA.Sc.07 (Bib.290)

Isopropylbiphenyl, temperature = -6°C,
distilled water Adhesion = 0.752 MPa

Lubricant on Steel

SA.Fc.01 (Bib.319)

(05.06.69) Octadecylamine, water contact angle = 104°
temperature = -6°C, adhesive break

Surface polishing grit

Adhesion (MPa) (microns of Alumina)

0.05

0.490

1.0

0.641

SA.Fc.02 (Bib.319)

Stearic Acid, water contact angle = 104°
temperature = -6°C, adhesive break, Adhesion = 0.600 MPa

SA.Fc.03 (Bib.319)

11 - H - Perfluoroundecanoic Acid, Water contact angle = 97°,
temperature = -6°C, adhesive break, Adhesion = 0.627 MPa

SA.Fc.04 (Bib.319)

Polymethylsiloxane, Water contact angle = 103°
temperature = -6°C, adhesive break

Surface polishing grit Adhesion (MPa)

0.05 microns of Alumina 0.627

1.0 microns of alumina 0.593

"4/0" emery paper 0.896

Lubricant on Aluminium

SA.Ac.01 (Bib.290)

Bis (2 - ethylhexyl) sebacate (Plexol 201)
temperature = -6°C, distilled water Adhesion = 0.517 MPa,
cohesional break

SA.Ac.02 (Bib.290)

Barium phenylstearate in bis (2 - ethylhexyl)
sebacate (Plexol 201), temperature = -6°C, distilled water

Adhesion (MPa)

0.517

0.496

Average 0.510 Most common break = adhesional/cohesional

SA.Ac.03 (Bib.290)

Sodium dinonylnaphthalene sulfonate (NaDNNS) in bis (2 - ethylhexyl)
sebacate (Plexol 201)
temperature = -6°C, distilled water

Adhesion (MPa)

0.110

0.110

0.076 Most common break = adhesional

0.055

Average 0.090 +/- 0.021

SA.Ac.04 (Bib.290)

Isopropylbiphenyl, temperature = -6°C,
distilled water Adhesion = 0.793 MPa

SA.Ac.05 (Bib.336) Wax

Water Adhesion (MPa)

Distilled 0.406

Schenectady tap water 0.124

Mt. Washington tap water 0.076

Lubricant on Brass

SA.Bc.01 (Bib.290)

Bis (2 - ethylhexyl) sebacate (Plexol 201)
temperature = -6°C, distilled water

Adhesion (MPa)

0.772
0.703
0.634
0.600 Most common break = adhesional/cohesional
0.496
Average 0.641 +/- 0.076

SA.Bc.02 (Bib.290)

Barium phenylstearate in bis (2 - ethylhexyl) sebacate (Plexol 201),
temperature = -6°C, distilled water

Adhesion (MPa)

0.324
0.255
0.248 Most common break = cohesional
0.221
Average 0.262 +/- 0.034

SA.Bc.03 (Bib.290)

Sodium dinonylnaphthalene sulfonate (NaDNNS) in bis (2 - ethylhexyl)
sebacate (Plexol 201) temperature = -6°C, distilled water

Adhesion (MPa)

0.055
0.055
0.041
0.028 Most common break = adhesional
0.014
Average 0.041 +/- 0.014

SA.Bc.04 (Bib.319)

Dimethylpolysiloxane, Cross-linked temperature = -6°C, adhesional
break

Water contact angle (°)

Adhesion (Mpa)

111 (Filled)	0.062
113 (Filled)	0.076
111	0.103
111	0.117

SA.Bc.05 (Bib.319)

Polyorganosiloxane, temperature = -6°C, adhesional break

Water contact angle (°)	Adhesion (Mpa)
-------------------------	----------------

111	0.152
106	0.310
108	0.841

SA.Bc.06 (Bib.319)

Polyurethane, water contact angle = 80° temperature = -6°C,
adhesional/cohesional break Adhesion = 0.483 MPa

SA.Bc.07 (Bib.319)

Perfluorooctylmethacrylate, water contact angle = 118°,
temperature = -6°C, adhesional break, Adhesion = 0.510 MPa

SA.Bc.08 (Bib.319)

Epoxy - Polyorganosiloxane, water contact angle = 96°
temperature = -6°C, cohesional break, Adhesion = 0.641 MPa

SA.Bc.09 (Bib.319)

Vinyl - Polyorganosiloxane, temperature = -6°C
Adhesion = 0.869 MPa, adhesional break

SA.Bc.10 (Bib.319)

Isopropylbiphenyl, temperature = -6°C,
distilled water Adhesion = 0.87 MPa

SA.Bc.11 (Bib.333)

temperature = -7.8°C, all adhesional breaks,
adhesion = 0.226 - 0.319 MPa

Lubricant on Teflon

SA.Tc.01 (Bib.290)

Bis (2 - ethylhexyl) sebacate (Plexol 201)
temperature = -6°C, distilled water

Adhesion (MPa)

	0.041	
	0.000	Most common break = adhesional
Average	0.021	

SA.Tc.02 (Bib.290)

Polyphenyl ether temperature = -6°C,
distilled water Adhesion = 0.165 MPa,
most common break = adhesional

SA.Tc.03 (Bib.290)

HB - 40(terphenyl), temperature = -6°C, distilled water

Adhesion (MPa)

	0.062	
	0.062	Most common break = adhesional
Average	0.062	

SA.Tc.04 (Bib.290)

Bis (phi - C5) glutarate temperature = -6°C, distilled water

Adhesion (MPa)

	0.007	
	0.000	Most common break = adhesional
Average	0.004	

SA.Tc.05 (Bib.290)

Isopropylbiphenyl, temperature = -6°C, distilled water

Adhesion (MPa)

	0.083	Most common break = adhesional
Average	0.083	

Other

SA.Ot.01 (Bib.290) T.F. Ford and O.D. Nichols (13.06.61)

(Sub.Ref. Freiburger and Lacks) Isopropylbiphenyl,
temperature = -12.2°C, distilled water

Substrate material	Adhesion (MPa)
--------------------	----------------

Stainless steel	0.79
Aluminium	0.62
Teflon	0.41 - 0.48

SA.Ot.02 (Bib.19)

Impact ice formed in Lucas Aerospace (Artington) Icing Wind Tunnel.
Various layers over 1.6 mm of natural sponge rubber

Substrate material Material	Adhesion (MPa) thickness (mm)	
Shim steel	0.076	0.044 +/- 0.025
Shim steel	0.127	0.058 +/- 0.022
Commercial copper	0.076	0.039 +/- 0.011
Hard copper	0.102	0.053 +/- 0.022
Copper beryllium (half hard)	0.076	0.054 +/- 0.020
Copper beryllium (half hard)	0.102	0.060 +/- 0.028
Phosphor bronze	0.152	0.068 +/- 0.037
Low density polyethylene	0.127	0.036 +/- 0.012
Low density polyethylene	0.254	0.026 +/- 0.007
Low density polyethylene	0.508	0.046 +/- 0.024
Nylon 6	0.254	0.062 +/- 0.029
Shim steel	0.076	0.044 +/- 0.017
Copper beryllium	0.076	0.048 +/- 0.015
Comercial copper on 3.2 mm of rubber	0.076	0.043 +/- 0.007

SA.Ot.03 (Bib.10)

Substrate thickness = 0.051 mm, temperature = -25°C,
bulk frozen water

Substrate material	Adhesion (MPa)
Hycar	1.034 - 1.103
GR - S	0.896
Thiokol FA	0.952
Koroseal	0.827
Polyethylene	1.103
Silicone rubber	0.310

SA.Ot.04 (Bib.10)

Various, pre-soaked in water for one hour at 70°C, then wiped dry,
bulk frozen water

Substrate material	Ratio of adhesion Dry/Pre-soaked
Pure gum rubber	0.83
Rubber plus 60 parts gastex	0.91
Neoprene compound	0.92
De-icer surface (B.F. Goodrich) neoprene inflatable boot	0.62

SA.Ot.05 (Bib.10)

Bulk frozen water Silane surface treatment on B.F. Goodrich inflatable neoprene de-icer

Concentration of C.Cl in silane liquid	4	Percentage of adhesion of untreated surface
4.5		31
9		33
17		22
28		16
33		23
50		18
100		12

SA.Ot.06 (Bib.10)

Bulk frozen water Silane surface treatment on B.F. Goodrich inflatable neoprene de-icer

Percentage of adhesion of untreated surface

Solvent in silane 30% solvent by vol. 50% solvent by vol.

Naphtha B	37	
C.Cl ₄	23	18
C ₄ H ₁₄	42	21
C ₂ H ₄ Cl ₂	33	15
C ₄ H ₄	33	9
C ₄ H ₄ Cl	49	36

SA.Ot.07 (Bib.10)

temperature = -25°C, bulk frozen water

Substrate material	Percentage of adhesion of untreated surface
Monomethyl trichlorsilane	12
Dimethyl trichlorsilane	20
Trimethyl monochlorsilane	23
Mostly diethyl dichlorsilane	2
Mostly dibutyl dichlorsilane	25
Mostly diphenyl dichlorsilane	25
Phenyl butyl dichlorsilane	17

SA.Ot.08 (Bib.10)

temperature = -25°C, bulk frozen water

Substrate	Method of applying silane surface treatment	Percentage of adhesion of untreated surface
Rubber	Vapour in closed container 50 mins.	51
Rubber	Vapour in closed container 100 mins.	30
Rubber	Soaked in water, 1 hr. at 70°C, then vapour for 90 mins.	40
Rubber	Equilibrium with room humidity, then vapour for 90 mins.	45
De-icer surface (neoprene)	Hung over liquid for 10 mins.	18
De-icer	Hung over liquid for 60 mins.	15
De-icer	Treated with liquid	12

SA.Ot.09 (Bib.10)

bulk frozen water De-Icer surface treated with silane

Silane	Percentage of adhesion of untreated surface
CH_3SiCl_3	>100
$(\text{CH}_3)_2\text{SiCl}_2$	41
$(\text{CH}_3)_3\text{SiCl}$	75

SA.Ot.10 (Bib.10)

temperature = -30°C, bulk frozen water

Surface roughness material	Percentage of adhesion of untreated surface
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Rough fabric	100
Holland cloth backed	50
by fabric Parchment paper	70
Holland cloth	60
Aluminium	65
Glass	25

SA.Ot.11 (Bib.1)

Bulk frozen water

Substrate material	Temperature slope of adhesion (Mpa.°C-1)
Steel	-0.051
Copper	-0.034
Aluminium	-0.061
Glass (96% silica)	-0.031
Polyethylene	-0.040
Rubber	-0.041
Silicone treated rubber	-0.028

Tensile Adhesion

Stainless Steel

TA.SS.01 (Bib.288)

Stainless steel (grade 304/A), Snow ice,
temperature = -5°C

Average adhesion (MPa)	Cross sectional area (sq.cm)
------------------------	------------------------------

0.534	1.54
0.540	3.14
0.522	4.91
0.531	6.61

Most common break = Adhesional

TA.SS.02 (Bib.146)

temperature = -4.5°C, snow ice, all adhesional breaks

Surface finish	Adhesion (MPa)
	average of 7

Polish (matt)	1.197
Polish (mirror)	0.971

TA.SS.03 (Bib.333)

temperature = -7.8°C

No.tests	Most common fracture	adhesion (MPa)
11	adhesional	0.392 - 1.745
10	adhesional/cohesional	0.424 - 2.095
10	cohesional	0.833 - 2.477

Steel

TA.St.01 (Bib.333)

temperature = -7.8°C

No.tests	Most common fracture	adhesion (MPa)
12	adhesional	0.631 - 2.222
7	adhesional/cohesional	1.034 - 2.212
2	cohesional	1.273 - 1.766

Aluminium

TA.Al.01 (Bib.333)

temperature = -7.8°C

No.tests	Most common fracture	adhesion (MPa)
2	adhesional	0.896 - 1.177
7	adhesional	0.392 - 1.782 (resaxed)
11	adhesional/cohesional	0.255 - 2.254
2	cohesional	1.002 - 2.668
14	cohesional	0.849 - 1.586 (anodised)
14	cohesional	0.610 - 2.731 (resaxed)

Brass

TA.Br.01 (Bib.333)

temperature = -7.8°C

No.tests	Most common fracture	adhesion (MPa)
12	cohesional	1.076 - 2.440
4	cohesional	0.907 - 1.517

Polystyrene

TA.Po.01 (Bib.288) Snow ice

Temperature (°C) Adhesion (MPa)

-2.0	0.237
-5.0	0.245
-10.0	0.4336
-18.0	0.463
-25.0	0.625

TA.Po.02 (Bib.288)

temperature = -5°C, snow ice, most common break = adhesional

Adhesion (MPa) Rate of stress application (Mpa.s⁻¹)

0.013 +/- 0.002	0.029
0.014 +/- 0.003	0.098

Polyethylene

TA.Pe.01 (Bib.333)

temperature = -7.8°C No.tests Most common fracture adhesion (MPa)

1	adhesional	0.223 - 0.255
12	adhesional/cohesional	0.143 - 1.596
2	cohesional	0.663 - 0.822

Teflon

TA.Te.01 (Bib.333)

temperature = -7.8°C

No.tests	Most common fracture	adhesion (MPa)
11	adhesional	0.477 - 0.780 (Black)
15	adhesional/cohesional	0.557 - 1.352 (Black)
10	adhesional	0.117 - 0.727 (White)
9	adhesional/cohesional	0.334 - 1.050 (White)

Lubricant on Brass

TA.Bc.01 (Bib.333)

temperature = -7.8°C

No.tests	Most common fracture	adhesion (MPa)
15	adhesional	0.265 - 1.257
2	adhesional/cohesional	0.546 - 1.406
1	cohesional	1.289 - 1.316

Other

TA.Ot.01 (Bib.333)

temperature = -17.8°C, substrate backing = Nitrocellulose

Substrate coating composition	Fracture	Adhesion (MPa)
1/2 sec. R.S.	ad/cohesional	0.032
+ 0.75% microcrystalline wax	adhesional	0.006
+ 0.75% carnuba wax	ad/cohesional	0.038
+ 60% alkyd (38% C.O. Mod.)	ad/cohesional	0.014
+ 1.1% M.C. wax		
60% alkyd (45% C.O. Mod.)	ad/cohesional	0.033
+ 1.1% M.C. wax		
+ 0.75% di-hydroxy stearic acid	ad/cohesional	0.055
+ 50% aluminium stearate	ad/cohesional	0.044
+ 60% alkyd (38% C.O.)	adhesional	0.014
+ 6.4% silicone oil		
DC-200(20) Dow Corning		
+ 60% alkyd (38% C.O. Mod)	adhesional	0.009
+ 6.4% silicone oil		
SF-96(40) General Electric		

substrate backing = Cellulose acetate

Substrate coating composition	Fracture	Adhesion (MPa)
+ 50% santicizer M-17 (monosanto)	adhesional	0.042

substrate backing = Pliolite 50 (Goodyear)

Substrate coating composition	Fracture	Adhesion (MPa)
+ 2% SF-96(40)	adhesional	0.007

Ta.Ot.02 (Bib.333)

Unstated metal coating employed on refrigerator evaporator

Temperature (°C)	Adhesion (MPa)
-18.3	0.075
-18.9	0.084
-19.4	0.094
-21.1	0.088
-21.1	0.082
-22.2	0.090

Ta.Ot.03 (Bib.333) temperature = -17.8°C, all adhesional breaks
substrate = 10 parts 1/2 sec. N.C. + following additives

Additive	Adhesion (MPa)
20 parts alkyd (coconut oil mod.)	0.207
20 parts alkyd (coconut oil mod.) + 0.55% M.C. wax	0.089
20 parts alkyd (coconut oil mod.) + 3.3 parts tricresyl phosphate (Mil-L-7178)	0.093
20 parts alkyd (coconut oil mod.) + 3.3 parts tricresyl phosphate (Mil-L-7178) + 0.55% M.C. wax	0.091
20 parts alkyd (coconut oil mod.) + 5 parts tricresyl phosphate	0.070
10 parts alkyd, 5 parts vinylite VYCC (Carbide and Carbon Chemical Co.) + 0.7% M.C. wax	0.072
20 parts alkyd (coconut oil mod.) + 5 parts tricresyl phosphate + 2% silicone oil SF-96(40) (General Electric)	0.037

Tensile Strength

TS.01 (Bib.299)

Commercial ice Shear force normal to long axis of prismatic crystals

Temperature (°C)	Tensile strength (MPa)
0	1.34
-5.0	1.43
-10.0	1.46
-20.0	1.58
-30.0	1.68
-40.0	1.83
-45.0	2.22
-50.0	2.41

TS.02 (Bib.335)

temperature = -6.7°C,
average tensile strength = 0.703 MPa

TS.03 (Bib.335) (Sub.Ref. G.G.Bell). Maine Society of Civil Engineers, No.1, 1911

Temperature (°C)	Tensile strength (MPa)		
-8.3	0.379	0.565	0.724
	0.724	0.758	0.772
	0.772	0.772	0.793
	0.814	0.814	0.827
	0.827	0.869	0.889
	0.896	0.931	0.931
	0.945	0.952	0.958
		1.000	1.296
-9.4	0.552	0.621	0.655
	0.690	0.800	0.979

TS.04 (Bib.305)

Clear fresh-water lake ice, sawn beams.

Temperature (°C)	Loading rate mm.s ⁻¹	No. tests	Strength (MPa)
-5	0.0051	5	1.193 - 1.386
	0.012	3	0.800 - 1.034
	0.027	2	1.179 - 1.310
	0.0023	2	1.138 - 1.165
	0.0051	5	1.000 - 1.551
	0.93	4	0.889 - 1.083
-20	0.0080	3	1.014 - 1.282
	0.0093	5	1.207 - 1.427
	1.7	4	1.303 - 1.675

TS.05 (Bib.305)

Clear fresh-water lake ice, sawn beams.

Author	Temperature (°C)	No. tests	Strength (MPa)	(average)
Brown (1)	-1.7	12	0.869 - 2.110	1.26
Horeth and Wilson (2)	-6.1	6	1.041 - 1.862	1.476
Hitch	-5.0	21	0.800 - 1.551	1.193
Brown (1)	-9.4	12	1.220 - 2.144	1.476
Hitch	-20.0	12	1.014 - 1.675	1.600

(1) Tests for the St.Lawrence Seaway project on ice cut from the St.Lawrence river. (2) Test for the U.S. Coast Guard on ice cut from Lake Michigan. The ice was tested aboard the Coast Guard cutter Makinaw (1948).

TS.06 (Bib.315) (Sub.Ref. Wilson and Horeth) Artificial ice.

Temperature (°C)	No. tests	Strength (MPa)	(average)
0	11	0.869 - 1.834	1.241
-22.8	9	1.558 - 2.041	1.765

Compressive Strength

CS.01 (Bib.299)

Clear lake ice, load applied normal to ice sheets

Temperature (°C)	Compressive strength (MPa)
0	1.98
-5.0	4.55
-10.0	5.06
-20.0	5.39
-30.0	6.23
-40.0	7.14
-50.0	8.08

CS.02 (Bib.299)

Clear lake ice, load applied parallel to ice sheets

Temperature (°C)	Compressive strength (MPa)
0	1.23
-5.0	2.78
-10.0	3.67
-20.0	4.29
-30.0	4.90
-40.0	5.95
-50.0	6.90

CS.03 (Bib.299)

Natural snow ice, load applied normal to stratification (normal to ice sheet)

Temperature (°C)	Compressive strength (MPa)
0	1.59
-5.0	2.90
-10.0	4.16
-20.0	3.52
-30.0	3.58
-40.0	3.22
-50.0	3.87

CS.04 (Bib.299)

Natural snow ice, load applied parallel to stratification (parallel to ice sheet)

Temperature (°C)	Compressive strength (MPa)
0	2.00
-5.0	2.82
-10.0	3.52
-20.0	3.40
-30.0	3.49
-40.0	3.05
-50.0	4.10

CS.05 (Bib.299)

Commercial ice, load applied normal to axis of prismatic crystals

Temperature (°C)	Compressive strength (MPa)
0	1.10
-5.0	3.33
-10.0	3.91
-20.0	4.56
-30.0	5.26
-40.0	6.34
-50.0	6.84

Shear Strength

SS.01 (Bib.290)

Temp. °C	Adhesion (MPa)	Temp. °C	Shear strength (Mpa)
-2	2.66	-11	3.21
-2	2.50	-11	2.78
-2	2.67	-11	3.56
-2	2.15	-11	2.96
-2	2.43	-11	2.09
Average	2.48 +/- 0.15	-11	2.19
		-11	2.40
-6	1.83	-11	2.18
-6	2.88	Average	2.68 +/- 0.46
-6	2.05		
-6	1.94	-16	2.46
-6	2.32	-16	2.44
-6	2.32	-16	3.74
-6	2.85	-16	3.14
-6	2.54	-16	2.44
-6	2.43	Average	2.84 +/- 0.48
-6	2.85		

Average	2.40 +/- 0.31	-21	2.94
		-21	3.06
		-21	2.76
		-21	3.32
		-21	3.20
		-21	3.04
Average	3.05 +/- 0.14		

SS.02 (Bib.335)

Temperature = -6.7°C, average shear strength = 0.745 MPa

SS.03 (Bib.315)

Ice	Temperature (°C)	No. tests	Strength (MPa)	(average)
Wilson and Horeth				
Artificial	0	10	0.283 - 1.110	0.648
Lake Michigan	-11.1 to -6.7	13	0.269 - 0.710	0.517
Artificial	-16.7	10	0.400 - 0.827	0.621
Artificial	-23.3	10	0.483 - 1.193	0.793
Finlayson				
River ice	-1.7	10	0.283 - 1.110	0.696
River ice	-2.2	10	0.283 - 1.110	0.703
River ice	-3.3	10	0.283 - 1.110	0.676
River ice	-13.3	13	0.269 - 0.710	0.683
River ice	-15.0	13	0.269 - 0.710	0.627
River ice	-15.5	13	0.269 - 0.710	0.648
River ice	-19.4	10	0.400 - 0.827	0.696

Torsional Shear Strength

ST.01 (Bib.299)

Clear lake ice, shear force parallel to sheet

Temperature (°C)	Shear strength (MPa)
0	0.78
-5.0	1.34
-10.0	1.52
-20.0	1.91
-30.0	2.08
-40.0	2.46
-50.0	2.81

ST.02 (Bib.299)

Clear lake ice, shear force normal to sheet

Temperature (°C)	Shear strength (MPa)
0	0.60
-5.0	0.80
-10.0	1.22
-20.0	1.39
-30.0	1.64
-40.0	1.82
-50.0	2.11

ST.03 (Bib.299)

Natural snow ice, shear force parallel to stratification (parallel to ice sheet)

Temperature (°C)	Shear strength (MPa)
0	0.79
-5.0	0.98
-10.0	1.10
-20.0	1.08
-30.0	1.13
-40.0	1.20
-50.0	1.34

ST.04 (Bib.299)

Natural snow ice, shear force normal to stratification (normal to ice sheet)

Temperature (°C)	Shear strength (MPa)
0	0.87
-5.0	0.95
-10.0	1.11
-30.0	1.17

ST.05 (Bib.299)

Commercial ice, shear force parallel to long axis of prismatic crystals

Temperature (°C)	Shear strength (MPa)
0	0.75
-5.0	0.87
-10.0	1.15
-20.0	1.31
-30.0	1.57
-40.0	1.68
-50.0	1.81

Modulus of Elasticity

ME.01 (Bib.305)

Clear fresh-water lake ice, sawn beams. Tested in the bending of beams.

Loading rate mm.s ⁻¹	Temperature °C	E GPa	average
0.0051	-5	2.675	2.444
0.012		2.337	
0.027		2.572	
0.0023		1.538	
0.0051		1.882	
0.93		3.358	
	-20	2.744	4.397
0.0080		2.841	
0.0093		4.061	
1.7		6.288	

16.4.4 Table 3 :Test Data Comparison Considerations

1. Water preparation.
 1. distillation
 2. passed through exchange resin
 3. supercooled
2. Ice preparation.
 1. sample from glacier
 2. sample from lake
 3. sample from sea
 4. compressed snow ice
 5. compressed sieved crystals
 6. bulk frozen water
3. Ice test specimen preparation.
 1. sawn from larger sample
 2. turned on a lathe
 3. chemically etched
 4. moulded
 5. water impregnated forged snow ice
 6. impact accretion
4. Substrate surface finish.
 1. mirror finish
 2. various polishing methods
 3. scored
 4. alumina blasted
 5. rubbed with emery paper "rough"

5. Substrate surface contamination.

1. boiled
2. washed in detergent
3. washed in solvent
4. sweated (baked)
5. electrolytically degreased
6. ultrasonically degreased
7. chemically etched
8. aqua-blasted
9. vapour blasted
10. grit blasted
11. machined

6. Test environment.

1. natural
2. deck of a ship
3. laboratory
4. cold room
5. icing research wind tunnel
6. constant temperature
7. constant pressure
8. liquid nitrogen cooled
9. vibration free

7. Test apparatus.

1. 'dead' weights
2. screw jack

3. hydraulic jack
4. gas pressure
5. liquid pressure
6. peeling
7. centrifugal rig
8. icing wind tunnel
9. non-rotating in-flight
10. rotating in-flight
11. aircraft propeller in flight
12. aircraft engine air intake duct lip in flight

8. Results manipulation.

1. averaging
2. moving average
3. smoothing
4. best fit straight line
5. best fit curve
6. gradient and intercept
7. gradient and assumed intercept

16.4.5 Table 4 :Example Propeller Blade Geometry

S blade cross section reference
r blade radius (mm)
 t_1 section thickness at 1% chord (mm)
 t_2 section thickness at 2% chord (mm)
 t_5 section thickness at 5% chord (mm)
 $t_{7.5}$ section thickness at 7.5% chord (mm)
 t_{10} section thickness at 10% chord (mm)
r(%) radius as a percentage of blade from shaft
 A_1 section leading edge area to 1% chord (sq.cm)
 A_2 section leading edge area to 2% chord (sq.cm)
 A_5 section leading edge area to 5% chord (sq.cm)
 $A_{7.5}$ section leading edge area to 7.5% chord (sq.cm)
 A_{10} section leading edge area to 10% chord (sq.cm)
c section chord (mm)
 l_1 section leading edge/unit radius to 1% chord (cm)
 l_2 section leading edge/unit radius to 2% chord (cm)
 l_5 section leading edge/unit radius to 5% chord (cm)
 $l_{7.5}$ section leading edge/unit radius to 7.5% chord (cm)
 l_{10} section leading edge/unit radius to 10% chord (cm)

S	r	t_1	t_2	t_5	$t_{7.5}$	t_{10}
	r(%)	$\frac{t_1}{2}$	$\frac{t_2}{2}$	$\frac{t_5}{2}$	$\frac{t_{7.5}}{2}$	$\frac{t_{10}}{2}$
	c	A_1	A_2	A_5	$A_{7.5}$	A_{10}
		l_1	l_2	l_5	$l_{7.5}$	l_{10}
B	279.40	38.23	53.34	80.81	95.36	105.95
	16.7	19.12	26.67	40.41	47.68	52.98
	279.40	0.53	1.81	7.44	13.59	20.62
		3.86	5.47	8.69	10.71	12.46
C	349.25	29.53	41.21	62.44	73.67	81.85
	20.8	14.77	20.61	31.22	36.84	40.93
	274.07	0.40	1.37	5.64	10.30	15.63
		3.00	4.29	6.98	8.75	10.35
D	419.10	25.41	35.45	53.72	63.38	70.43
	25.0	12.71	17.73	26.86	31.69	35.22
	268.73	0.34	1.16	4.75	8.69	13.18
		2.60	3.74	6.17	7.83	9.34

E	558.80	18.28	25.52	38.66	45.62	50.69
	33.3	9.14	12.76	19.33	22.81	25.35
	258.06	0.24	0.80	3.29	6.00	9.11
		1.90	2.79	4.82	6.29	6.67
F	698.50	14.30	19.86	29.62	34.54	37.94
	41.7	7.15	9.93	14.81	17.27	18.97
	247.40	0.18	0.60	2.44	4.42	6.66
		1.51	2.26	4.03	5.37	6.65
F'	749.30	12.23	16.94	25.06	28.99	31.61
	44.7	6.12	8.47	12.53	14.50	15.81
	252.22	0.15	0.52	2.11	3.82	5.73
		1.32	2.01	3.73	5.05	6.34
G	838.20	10.21	14.10	20.60	23.60	25.47
	50.0	5.11	7.05	10.30	11.80	12.74
	249.43	0.13	0.43	1.73	3.11	4.64
		1.14	1.77	3.40	4.68	5.94
H	977.90	8.24	11.56	19.19	19.82	21.42
	58.3	4.12	5.78	8.60	9.91	10.71
	249.96	0.10	0.35	1.43	2.58	3.87
		0.96	1.56	3.17	4.44	5.70
J	1117.60	7.06	9.91	14.63	16.74	19.97
	66.7	3.53	4.96	7.32	8.37	8.99
	248.45	0.09	0.30	1.21	2.19	3.27
		0.86	1.44	3.00	4.26	5.51
K	1257.30	5.57	7.86	11.64	13.31	14.26
	75.0	2.79	3.93	5.82	6.66	7.13
	240.26	0.07	0.23	0.93	1.68	2.51
		0.74	1.27	2.76	3.97	5.18
L	1397.00	3.82	5.49	8.28	9.53	10.22
	83.3	1.91	2.75	4.14	4.77	5.11
	209.75	0.04	0.14	0.57	1.04	1.56
		0.57	1.02	2.31	3.36	4.42
M	1536.70	2.40	3.40	5.12	5.85	6.26
	91.7	1.20	1.70	2.56	2.93	3.13
	149.40	0.02	0.06	0.25	0.46	0.68
		0.38	0.70	1.61	2.36	3.11

N	1606.55	1.79	2.38	3.54	4.05	4.34
	95.8	0.90	1.19	1.77	2.03	2.17
	109.04	0.01	0.03	0.13	0.23	0.35
		0.28	0.51	1.17	1.72	2.27
N'	1641.48	1.50	1.92	2.82	3.44	3.47
	97.9	0.75	0.96	1.41	1.72	1.74
	84.23	0.01	0.02	0.08	0.15	0.22
		0.23	0.40	0.91	1.34	1.76
T	1676.40	1.27	1.49	1.93	2.17	2.32
	100.0	0.64	0.75	0.97	1.09	1.16
	47.59	0.00	0.01	0.03	0.06	0.09
		0.16	0.26	0.55	0.78	1.02

16.4.6 Table 5 :Sample Ice Shape Co-Ordinates

y/mm									
thickness d (mm), along line of incidence fwd of l.e.									
<div>10</div> <div>20</div> <div>30</div>									
approximate mass density (kg.m ⁻³)									
x/mm	0.5	0.7	0.9	0.5	0.7	0.9	0.5	0.7	0.9
0	0	0	0	0	0	0	0	0	0
0.5	0.88	1.28	2.42	0.71	1.07	2.14	0.60	0.93	1.96
1.0	1.33	1.81	3.05	1.07	1.51	2.70	0.91	1.32	2.47
1.5	1.70	2.22	3.49	1.36	1.85	3.09	1.16	1.62	2.83
2.0	2.02	2.56	3.84	1.62	2.14	3.40	1.38	1.87	3.11
3.0	2.57	3.14	4.40	2.07	2.62	3.89	1.76	2.29	3.56
4.0	3.06	3.62	4.84	2.46	3.02	4.28	2.09	2.64	3.92
5.0	3.49	4.05	5.21	2.81	3.38	4.61	2.39	2.95	4.22
7.5	4.46	4.96	5.97	3.58	4.14	5.28	3.05	3.61	4.83
10.0	5.29	5.72	6.57	4.26	4.78	5.81	3.62	4.17	5.32
15.0	6.75	7.01	7.52	5.43	5.85	6.65	4.62	5.11	6.09
20.0	8.03	8.09	8.27	6.46	6.75	7.32	5.49	5.90	6.70
25.0				7.38	7.55	7.89	6.28	6.60	7.21
30.0				8.23	8.27	8.38	7.00	7.23	7.67
35.0							7.68	7.81	8.07
40.0							8.32	8.35	8.44

16.4.7 Table 6: Flight Test Data

C/M = Composite/Metal Temperature = Min./Max. (Average)
 Cycle = Time ON / Time OFF
 LWC = Min./Max. (Ave.) Droplet MVD = Min./Max. (Ave.)

Flight	Blade rad. C/M (m)	Temp. (°C)	IAS (kt)	Flow LWC ⁻³ (g.m ⁻³)
Test	Date	Cycle ON/OFF (s)	Ang. Vel. (rpm)	Droplet MVD (µm)
952	M 1.346	(-19)	175	(1.0)
952	04.06.84	70/70	1559	20/25
332	C 1.676	-5.8/-7.7	140	0.1/0.4 (0.24)
3517	27.02.85	90/90	1270	15/22 (18)
335	C 1.676	-6.1/-6.8	140	0.13/0.63 (0.4)
3527:1	01.03.85	30/30	1260	17/30 (25)
335	C 1.676	-9.1/-9.4	140	0.05/0.22
3527:3	01.03.85	60/60	1260	19/23
335	C 1.676	-10.9/-11.4	140	(0.15)
3527:4	01.03.85	30/30	1260	(19)
341	C 1.676	-3.8/-5.9	140	0.11/0.42
3533	13.03.85	24/72	1260	11/21
349	C 1.676	-5.7/-6.8	140	0.1/0.58
3534	20.03.85	unknown	1270	9/25
	C 1.676	-2.7/-3.1	140	0.1/0.5
3543:1	22.03.85	18/54	1260	12/22
	C 1.676	-6.8/-7.2	140	0.1/0.33
3550:2	26.03.85	12/36	1250	15/30
	C 1.676	-9.6/-14.6	140	0.1/0.5
3552:1	04.04.85	45/135	1250	13/36
	C 1.676	-4.3/-7.1	140	0.1/0.6
3552:2	04.04.85	12/84	1250	12/84

Additional Information

Flight 952 - Pressure altitude 23000 Ft. Icing
 encounter duration 20 minutes.
 Test 3517 - After 0.5 FAA icing encounters.
 Test 3527:1 - After 1.3 FAA icing encounters.
 Test 3527:4 - After 0.38 FAA icing encounters.

16.4.8 Table 7:Ice Specimen Categorisation

Table 7(a) :Ice Specimen Categorisation

Note: Some figures present several ice accretion specimens on one or more blades. Radially long accretions are split into several specimens as would be the actual case during shedding.

N = Near blade F = Far blade (in photograph)

Case No.	Fig. No.	Flight No.	Test No.	Blade No.	Specimen No.	Radius (mm) from to
1	F1		952	1	1	761 - 1008
2				4	2	770 - 1020
3	F2		952	2	1	654 - 730
4				2	2	753 - 890
5				2	3	943 - 1026
6				2	4	1085 - 1156
7				1	5	760 - 900
8	F3		952	1	1	750 - 894
9				1	2	894 - 1038
10	F4		952	3	1	635 - 795
11				3	2	795 - 956
12				3	3	956 - 1116
13	F5		952	1	1	770 - 992
14	F6		952	4	1	750 - 862
15				4	2	862 - 974
16	F7		952	2	1	681 - 825
17				2	2	825 - 969
18	F8		952	1	1	755 - 891
19				1	2	891 - 1027
20	F9		952	3	1	745 - 859
21				3	2	859 - 973
22				2	3	765 - 1050
23	F10		952	1	1	765 - 968
24	F11		952	3	1	735 - 840
25				3	2	840 - 945
26				2	3	760 - 1050
27	F12	332	3517	N	1	940 - 1034
28				N	2	1034 - 1128
29				F	3	860 - 1150
30	F13	332	3517	N	1	960 - 1075
31				N	2	1075 - 1190
32				F	3	865 - 1040
33	F14	332	3517	N	1	947 - 1000
34				N	2	1006 - 1066
35				F	3	940 - 1060

Case No.	Fig. No.	Flight No.	Test No.	Blade No.	Specimen No.	Radius (mm) from to
36	F15	332	3517	2	1	865 - 945
37				2	2	945 - 1084
38				2	3	1084 - 1223
39	F16	332	3517	N	1	950 - 1030
40				F	2	860 - 1005
41				F	3	1005 - 1150
42	F17	332	3517	2	1	860 - 935
43				2	2	955 - 1250
44				4	1	1010 - 1100
45	F18	332	3517	4	2	1100 - 1190
46				F	3	855 - 1005
47				F	4	1005 - 1155
48	F19	332	3517		1	860 - 1005
49					2	1005 - 1150
50	F25	335	3527:4		1	852 - 1111
51					2	1111 - 1371
52	F26	335	3527:3		1	846 - 1062
53					2	1062 - 1278
54	F27	335	3527:3	N	1	850 - 991
55				N	2	991 - 1123
56				N	3	1123 - 1273
57				F	4	820 - 1012
58				F	5	1012 - 1203
59	F28	335	3527:4	3	1	887 - 1078
60	F29	335	3527:4	N	1	854 - 978
61				N	2	978 - 1102
62				2	3	860 - 935
63	F30	335	3527:4	4	1	833 - 945
64				4	2	945 - 1057
65				4	3	1057 - 1169
66				4	4	1221 - 1268
67				4	5	1268 - 1330
68				4	6	1330 - 1381
69				4	1	290 - 520
70	F32	335	3527:4	3	1	910 - 997
71				3	2	997 - 1083
72	F37	349	3550:2	2	1	840 - 1033
73				2	2	1033 - 1227
74	F38	349	3550:2	3	1	885 - 945
75	F39	349	3550:2	1	1	873 - 931
76				1	2	931 - 988
77	F40	349	3550:2	3	1	870 - 1010

Case No.	Fig. No.	Flight No.	Test No.	Blade No.	Specimen No.	Radius (mm) from to
78	F41	349	3550:2	2	1	875 - 1048
79				2	2	1048 - 1220
80				3	3	812 - 1031
81	F45	349	3550:2	2	1	880 - 1058
82				2	2	1058 - 1236
83				3	3	819 - 1021
84	F46	349	3550:2	4	1	874 - 946
85	F47	349	3550:2	1	1	798 - 1008
86				1	2	1008 - 1219
87	F48	349	3550:2	N	1	870 - 1000
88	F49	349	3552:1	3	1	221 - 340
89				3	2	880 - 1017
90	F50	349	3552:2	3	3	1017 - 1153
91				3	4	1153 - 1290
92				1	1	857 - 1035
93	F51	349	3552:1	2	2	855 - 950
94				2	1	290 - 636
95				2	2	786 - 960
96	F52	349	3552:1	2	1	308 - 629
97				2	2	802 - 950
98	F53	349	3552:1	4	1	863 - 967

Table 7(b) :Ice Specimen Categorisation

Note: d = Ice accretion thickness forward of the blade leading edge.

x = Ice accretion thickness forward and aft of the leading edge, ie. total accretion chord.

i_c = ice thickness nondimensionalised with respect to blade chord.

Case No.	Temperature °C	Density kg.m ⁻³	d mm	x mm	i_c %c
1	-19	500	32	40	2.9
2			25	36	4.0
3			30	50	7.2
4	-19	700	12	15	1.1
5			11	14	1.1
6			7	10	1.3
7	-19	700	19	22	1.1
8			12	23	4.0
9			11	19	2.9
10	-19	500	16	28	4.3
11			13	22	3.3
12			9	12	1.2
13	-19	500	19	23	1.4
14	-19	700	18	25	2.5
15	-19	500	10	18	2.9
16			22	35	4.7
17			15	21	2.2
18	-19	700	10	20	3.6
19			10	19	3.3
20	-19	500	15	25	3.6
21			11	18	2.6
22			12	28	5.8
23	-19	500	12	21	3.3
24	-19	500	17	25	2.9
25	-5.8/-7.7	900	10	16	2.2
26			15	23	2.9
27			6	10	1.4
28			6	10	1.5
29			8	12	1.4

Case No.	Temperature °C	Density kg.m ⁻³	d mm	x mm	i _c %c
30	-5.8/-7.7	900	5	10	1.8
31			7	10	1.1
32			7	10	1.1
33	-5.8/-7.7	900	7	10	1.1
34			7	10	1.1
35			7	11	1.4
36	-5.8/-7.7	900	7	21	5.1
37			7	10	1.1
38			7	10	1.1
39	-5.8/-7.7	900	5	11	2.2
40			4	7	1.1
41			4	7	1.1
42	-5.8/-7.7	900	13	20	2.5
43			5	12	2.5
44	-5.8/-7.7	900	5	11	2.2
45			5	11	2.2
46			6	11	1.8
47	-5.8/-7.7	900	6	11	1.8
48			7	10	1.1
49			7	10	1.1
50	-10.9/-11.4	900	9	12	1.1
51			9	13	1.5
52	-9.1/-9.4	900	8	16	2.9
53			8	16	2.9
54	-9.1/-9.4	900	7	15	2.9
55			7	15	2.9
56			7	16	3.3
57	-10.9/-11.4	900	4	10	2.2
58			4	10	2.2
59			12	21	3.3
60	-10.9/-11.4	900	8	15	2.5
61			10	13	1.1
62			8	13	1.8
63	-10.9/-11.4	900	10	20	3.6
64			10	15	1.8
65			10	12	0.7
66	-10.9/-11.4	900	5	6	0.4
67			10	13	1.2
68			5	6	0.4
69	-10.9/-11.4	900	7	30	7.7

Case	Temperature	Density	d	x	i _c
No.	°C	kg.m ⁻³	mm	mm	%c
70	-10.9/-11.4	900	11	18	2.5
71			6	9	1.1
72	-6.8/-7.2	900	9	14	1.8
73			14	17	1.1
74	-6.8/-7.2	900	14	21	2.5
75	-6.8/-7.2	900	14	18	1.4
76			14	18	1.4
77	-6.8/-7.2	900	14	17	1.1
78	-6.8/-7.2	900	6	12	2.2
79			8	14	2.2
80			11	17	2.2
81	-6.8/-7.2	900	7	13	2.2
82			13	16	1.1
83			13	22	3.3
84	-6.8/-7.2	900	12	18	2.2
85	-6.8/-7.2	900	12	20	2.9
86			12	20	2.9
87	-6.8/-7.2	900	10	16	2.2
88	-9.6/-14.6	700	6	17	4.0
89			10	21	4.0
90			5	11	2.2
91			5	12	2.6
92	-4.3/-7.1	900	7	16	3.3
93			9	13	1.4
94	-9.6/-14.6	700	5	28	7.9
95			6	11	1.8
96	-9.6/-14.6	700	3	15	4.1
97			4	11	2.5
98	-4.3/-7.1	700	11	13	0.7

Table 7(c) :Ice Specimen Categorisation

Note: $t/2$, A_1 , p from Fig.7(a) $\omega = 1559$ rpm (Cases 1 - 26)
 k from Fig.13 1331 rpm (Cases 27 - 98)
Ice adhesion from Fig.29 H = Ice adhesion

Case No	$t/2$ mm	A_1 cm ²	p cm	k	$A_1 + A_1$ cm ²	A_i cm ²	$A - p$ mm	H MPa
1	6.9	1.1	3.0	0.40	12.07	11.0	37	0.436
2	9.2	2.0	4.3	0.58	14.78	12.8	30	0.358
3	14.2	6.9	8.7	0.89	29.67	22.8	26	0.336
4	4.2	0.15	1.2	0.49	2.68	2.5	21	0.322
5	2.6	0.10	1.0	0.30	1.48	1.4	14	0.257
6	3.0	0.2	0.7	0.37	1.10	0.9	13	0.272
7	4.0	0.15	1.2	0.38	3.70	3.5	30	0.465
8	9.0	2.4	4.4	0.88	9.15	6.8	15	0.230
9	2.9	0.8	2.8	0.29	2.26	1.5	5	0.090
10	11.3	3.3	5.0	0.36	6.14	2.8	6	0.057
11	7.1	1.5	4.7	0.40	4.64	3.1	7	0.082
12	2.2	0.05	0.9	0.28	1.23	1.2	13	0.179
13	3.9	0.1	1.3	0.36	4.48	4.4	34	0.399
14	7.0	0.8	2.5	0.64	7.54	6.7	27	0.406
15	7.3	1.0	2.9	0.76	5.47	4.5	15	0.257
16	10.9	3.4	5.5	0.68	16.57	13.2	24	0.241
17	5.0	0.4	1.7	0.43	4.63	4.2	25	0.299
18	8.6	2.0	4.8	0.85	7.17	5.2	11	0.169
19	6.2	1.2	3.3	0.60	4.68	3.5	11	0.197
20	9.0	2.0	3.9	0.73	10.38	8.4	21	0.224
21	5.9	0.7	2.4	0.53	4.46	3.8	16	0.195
22	9.1	3.7	6.4	0.65	11.08	7.4	12	0.145
23	8.1	1.5	3.5	0.85	9.15	7.6	22	0.254
24	8.1	1.3	3.1	0.63	8.96	7.7	25	0.263
25	5.0	0.4	1.7	0.50	3.48	3.1	18	0.214
26	6.4	1.9	2.9	0.49	6.10	4.2	14	0.169
27	4.9	0.2	1.3	0.74	1.90	1.7	13	0.224
28	4.1	0.2	1.3	0.67	1.72	1.5	12	0.227
29	4.6	0.15	1.3	0.66	2.16	2.0	15	0.264
30	5.1	0.2	1.5	0.81	2.08	1.9	13	0.231
31	3.1	0.1	1.0	0.43	1.10	1.0	10	0.198
32	4.9	0.15	1.2	0.76	1.95	1.8	15	0.250
33	4.4	0.15	1.2	0.71	1.82	1.7	14	0.238
34	4.0	0.15	1.1	0.65	1.67	1.5	14	0.254
35	4.7	0.1	1.3	0.73	2.13	2.0	16	0.280
36	12.0	4.4	6.0	1.53	10.55	6.1	10	0.158

Case No	t — 2 mm	A ₁ cm ²	p cm	k	A _i + A ₁ cm ²	A _i cm ²	A — p mm	H MPa
37	4.1	0.1	1.2	0.69	1.77	1.8	15	0.266
38	3.1	0.05	1.0	0.50	1.28	1.2	12	0.242
39	6.3	0.5	1.8	0.93	2.71	2.2	12	0.208
40	4.9	0.1	1.3	0.85	1.35	1.3	10	0.163
41	3.8	0.05	1.0	0.65	1.04	1.0	10	0.188
42	8.0	0.9	2.6	1.00	6.46	6.5	25	0.393
43	6.0	0.7	2.3	0.83	2.71	2.0	9	0.174
44	5.5	0.5	1.9	0.81	2.36	1.9	10	0.184
45	4.8	0.4	1.6	0.73	2.13	1.7	11	0.220
46	6.2	0.2	1.5	0.93	2.71	2.7	18	0.293
47	4.7	0.2	1.5	0.73	2.13	1.9	13	0.245
48	4.8	0.15	1.3	0.77	1.97	1.8	14	0.228
49	3.9	0.1	1.0	0.64	1.64	1.5	15	0.283
50	4.5	0.1	1.2	0.66	2.16	2.1	17	0.292
51	3.0	0.1	1.1	0.43	1.56	1.5	13	0.282
52	8.6	1.3	3.2	1.18	5.66	4.4	14	0.234
53	6.1	0.9	2.8	0.79	3.79	2.9	10	0.205
54	9.0	1.3	3.2	1.29	5.68	4.4	14	0.225
55	7.1	1.2	3.0	0.96	4.23	3.0	10	0.185
56	6.4	1.2	3.3	0.82	3.93	2.7	8	0.168
57	7.0	0.5	2.0	1.14	2.92	2.4	12	0.192
58	5.0	0.4	1.8	0.79	2.03	1.6	9	0.174
59	8.9	1.8	3.6	1.51	10.41	8.6	24	0.412
60	8.0	0.9	2.5	1.10	4.84	3.9	16	0.256
61	4.0	0.1	1.1	0.62	2.26	2.2	20	0.364
62	6.5	0.2	1.6	0.91	3.31	3.1	19	0.298
63	10.7	2.4	4.0	1.34	8.66	6.3	16	0.249
64	5.3	0.3	1.5	0.71	3.13	2.8	19	0.333
65	2.7	0.05	0.8	0.38	1.24	1.2	15	0.292
66	1.0	0.05	0.3	0.17	0.22	0.2	6	0.131
67	2.1	0.05	0.9	0.32	1.16	1.1	12	0.273
68	0.9	0.0	0.3	0.17	0.22	0.2	7	0.166
69	39.5	26.7	14.1	2.79	30.94	4.2	3	0.021
70	7.5	0.8	2.5	0.96	5.39	4.6	18	0.300
71	4.0	0.1	1.1	0.71	1.58	1.5	13	0.236
72	6.0	0.2	1.6	0.79	3.17	3.0	19	0.311
73	3.2	0.1	1.0	0.92	4.79	4.7	47	0.929
74	8.0	0.9	2.5	0.95	6.55	5.6	23	0.368
75	5.7	0.2	1.3	0.72	4.04	3.8	30	0.473
76	5.0	0.2	1.3	0.65	3.65	3.4	27	0.453
77	4.9	0.15	1.3	0.62	3.23	3.1	24	0.394

Case No	t — 2 mm	A ₁ cm ²	p cm	k	A _i + A ₁ cm ²	A _i cm ²	A — p mm	H MPa
78	6.6	0.5	1.9	0.91	2.98	2.5	13	0.219
79	5.0	0.4	1.8	0.69	2.77	2.4	13	0.258
80	6.9	0.7	2.0	0.89	4.63	3.9	20	0.322
81	6.3	1.0	1.9	0.87	3.16	2.2	11	0.186
82	3.1	1.3	1.0	0.37	1.78	0.5	5	0.100
83	9.9	0.2	3.7	1.20	8.80	8.6	23	0.370
84	6.2	1.9	2.0	0.80	4.49	2.6	13	0.207
85	9.2	1.4	3.2	1.16	7.49	6.1	19	0.300
86	6.9	1.1	3.0	0.86	5.56	4.5	15	0.292
87	6.7	0.5	1.9	1.56	7.48	7.0	37	0.605
88	46.0	13.1	10.9	4.99	32.98	19.9	18	0.069
89	10.2	2.7	4.5	1.47	13.34	10.6	24	0.310
90	5.1	0.4	1.9	0.56	1.93	1.5	8	0.118
91	5.0	0.7	2.4	0.65	2.55	1.8	8	0.133
92	9.2	1.8	3.6	1.28	6.14	4.3	12	0.198
93	5.4	0.2	1.4	0.75	2.73	2.5	18	0.284
94	33.9	24.5	7.3	2.87	40.09	15.6	21	0.132
95	6.9	0.3	1.7	0.92	3.16	2.9	17	0.202
96	28.9	7.9	7.4	3.34	18.29	10.4	14	0.089
97	8.7	1.0	2.6	1.17	4.02	3.0	12	0.143
98	3.8	0.05	0.8	0.47	2.08	2.0	25	0.311

16.4.9 Table 8 :Overall Ice Shear Adhesion Envelope

Literature Survey and Tests Using the Research Programme Test Rig

(Figs.33,L31)

Absolute maximum shear adhesion = 1.63 MPa (236 psi)

Stainless steel (Bib.288), Table 2, Fig.L1

initial slope = $0.138 \text{ MPa} \cdot ^\circ\text{C}^{-1}$ drop in temperature
($20 \text{ psi} \cdot ^\circ\text{C}^{-1}$) below 0°C

Flight Test Photograph Shear Adhesion Envelope (Fig.40)

Absolute maximum shear adhesion = 0.929 MPa (135 psi)

Composite blade leading edge erosion shield (stainless steel or nickel), Table 7(c), Case 73, Fig.F37

initial slope = $0.076 \text{ MPa} \cdot ^\circ\text{C}^{-1}$ drop in temperature
($11 \text{ psi} \cdot ^\circ\text{C}^{-1}$) below 0°C

16.5 Ice Freezing Stresses

Primarily, a computational theoretical approach was envisaged, but on more detailed analysis of the associated criteria, a practical physical approach to the problem was considered a more feasible alternative.

The case of thermal expansion of a simple parallel metal cylinder or tube (ie. open at both ends) is relatively easy to calculate in terms of the new dimensions at a different temperature. A compound tube consisting of three concentric cylinders is however, a more complex problem requiring a finite element approach of many iterations to achieve meaningful results on this scale. Additional complexities are created when the outer cylinder is open at both ends, the inner cylinder is solid, and the intermediate cylinder is prevented from any longitudinal movement at one end and open at the other end. To this is added the fact that the intermediate cylinder consists of water, becoming ice as the temperature falls, with the associated phenomena of contraction followed by expansion followed by contraction. There is a dependence on temperature, pressure, freezing rate, the heat capacity and diffusivity of the boundary walls, and the air bubble content, bubble size, location and orientation within the ice. It can soon be realised that an accurate computational analysis of the system is not a viable proposition and the problem becomes further more complex when the flexible neoprene layer is introduced to the interface.

However, considering the dynamic situation as the water freezes, the outer free surface of the water being one of the last areas to solidify, it can be seen that the bulk of the internal pressure which would be generated in a fully dimensionally restricted situation will be released through this surface. The final frozen cross section of the ice at the free surface provides evidence of this pressure release in that the surface is considerably convexed to allow for the increased volume of the ice above that of the water.

The trapped bubble formations within the ice which display a definite movement of the entrapped air from the bulk of the water to the free surface (Fig.17), which was itself restricted in the last stages of freezing, indicates a possible source for internal pressure as the ice initially expands. When water at a temperature of 0°C (or slightly above), is applied to the rig which is at a temperature of say -20°C , there is a reasonably rapid freezing of the water in direct contact with the flat base of the breech forming a flat circular disc of ice extending from the substrate at its inner radius to the barrel at its outer radius. As the ice in this disc expands, it could exert a pressure on the substrate, but being a relatively thin disc, with a large free surface to the water, the pressure exerted would probably be of negligible value.

An alternative approach would be to use the bond shear adhesion strength acquired from tests recording the nitrogen pressure, with a knowledge of the coefficient of friction of ice on the various substrate materials, to calculate the radial force. However, the

presence of stiction, and the variation of the coefficient of friction with many of the parameters render this type of calculation totally inaccurate. Thus a practical, approach was considered to be the most feasible option.

It is only necessary to measure the radial force at the interface if it is of a significant non-zero value. Therefore, it may be possible to simply, and at a low cost, assess whether this force exists to any considerable extent before employing expenditure and design time on a detailed method of measuring the stress, assuming it to exist. A simple procedure for establishing whether a significant stress exists, is to replace the bullet with a thin walled tube of relatively soft material (e.g. copper), with a thin slit in its wall along its length parallel to its longitudinal axis. A slit of approximately 1 mm in width is filled with silicone grease and placed within the barrel on top of the breech base, to replace the bullet, but not held in position. Water is introduced into the barrel around the copper tube and prevented from entering the tube by the silicone grease. After freezing of the water has taken place, the slit in the tube is observed to assess if it has opened or closed to any reasonable extent. Obviously, the thermal contraction of the copper tube must be allowed for in the results. The magnitude of this allowance is determined at 0°C by observing (or possibly measuring) the gap in the tube before introducing the water. Thus, if the gap is observably reduced during freezing of the water, then a radial stress exists at the interface and steps may be taken to measure it. Initial calculation of the order of magnitude of the gap change with a representative temperature change will ascertain whether the difference in gap size will in actual fact, be observable, and define the level of iteration to achieve the most suitable tube wall thickness required to produce reasonable results.

If an observable gap change does occur during freezing or thereafter during a subsequent temperature fall, it will then be necessary to measure the stress exerted on the interface. This may be done by modifying the copper tube, adding strain gauges (more than one for redundant value checking), to the surface of the tube, either on the inner or outer radius, or preferably both. The stress in the tube is determined from the recorded strain, from which the pressure on the ice/substrate interface bond is calculated.

16.6 Adhesion/Cohesion Bond Strength Calculation (Sup.4)

If the interface bond is broken entirely adhesively (Fig.12), then the bond strength is easily derived from the required gas pressure. If some form of totally cohesive debonding takes place (Fig.13), then the cohesive strength may be derived from a knowledge of the fracture surface area and orientation. Should the most likely case occur when a combination of debonding in adhesion and cohesion takes place (Fig.14), then from a knowledge of the cohesive strength (acquired in cases of total cohesive debonding), and the bond strength in mixed conditions, the bond strength of the adhesional area may be derived. Obviously, the fracture surface area is not easily measured and a much simpler approach is to effect a sufficient number

of tests such that only the results from totally adhesional debonding need be utilised.

16.7 Analysis of Flight Test Data

(Sup.5 - 5.2.2)

Observing (Fig.40) of the shear adhesion results from the flight test photographic recordings (Figs.F1-F53), it can be seen that, although there is considerable scatter, the results fall into a definite band, with only two exceptions out of the 98 cases. The statistical trend is generally toward a value of shear adhesion of approximately 0.45 MPa (65 psi) for all values of temperature, since there is no data at higher values of temperature (-5 to 0°C). The data are plotted against outside air temperature as, although the substrate surface temperature is derivable, the accuracy of such a derivation would render the results less accurate than if the OAT were employed.

As detailed earlier, the extraction of data from such small scale photographs can easily lead to large inaccuracies which, if not controlled, may render the results meaningless, as the error band exceeds the typical absolute value by a large margin. There are five parameters to extract from the photographs. The local blade radius "r" from the centre of rotation (propeller shaft) at which the accretion is situated, ie. both inboard and outboard limits of the accretion "r_i" and "r". This is a simple measurement of length, scaled accordingly. The scale was assessed from a knowledge of the blade geometry (Table 4), such as the blade chord at some recognisable radial feature, e.g. the pitch adjustment line situated at radial station "J" (Table 4), which appears as a chordwise white line with two short perpendicular branches on the photographs. Alternatively, the blade radial length from the spinner to station "J", or station "J" to the tip may be used depending on the 'window' of the photograph. However, in many cases the blade was not parallel to the plane of the photograph, introducing a perspective element in the radial sense (blade pitch angle and twist always causes perspective scaling in the chordwise sense), which considerably complicated the scaling method.

Similarly scaled from the photographs, was the chordwise extent of the accretion. This was measured both forward of the leading edge "d", (loosely termed "ice thickness"), and the extent aft of the blade leading edge "X-d". This latter measurement was simplified by measuring the total chordwise dimension "X" of the accretion from its leading edge to its trailing edge. In most cases the trailing edge of the accretion fluctuated considerably in its chordwise aft extent along its radial coverage of the blade. Thus an average value was estimated so as to exclude thin extremities which bear virtually no influence on the adhesional strength of the main ice accretion. The remaining two parameters are much more difficult to determine and introduce a much greater error band. Firstly, the mass density of the ice accretion. Most leading edge ice accretions vary somewhat in density throughout their volume depending upon prevailing ambient and local conditions. A glaze ice will generally be reasonably homogeneous

whereas a rime ice will often tend to increase in density towards the substrate leading edge, ie. aft, or, downstream. This is due mainly to four reasons. The rime ice of low density and high air content with well separated ice crystals is compacted by the 'pounding' influence of impacting, accreting ice. The thermally insulating and wind protective subsequent layers of accreting ice bring about a temperature gradient in the ice accretion, increasing toward the substrate (leading edge) causing re-crystallisation in a denser form, more acquainted with the higher temperatures. Any meltwater produced by residual heat in the substrate from a previous de-icing cycle formed at the leading edge and re-freezing, will increase the density (and adhesional strength) in the vicinity of the substrate leading edge. Additionally, meltwater produced at the leading edge of the ice accretion due to kinetic heating, around the stagnation point, will be forced aft through the porous underlying rime ice by the action of impacting droplets and airflow.

After observation of over two thousand flight photographs, and from knowledge gained in the extensive Literature Survey, the ice density was estimated from its appearance in the photographs. It was decided to categorise the accretions into three density categories, as any finer categorisation was not feasibly definable from the figures.

1. Rime ice - density 500 kg.m^{-3} . An accretion fell into this category if it appeared brilliant white in the photograph (subject to the influence of shadow or the illumination effects of the prevailing sky tone). There must be no hint of transparency, and the accretion cross-sectional profile must be compatible with those generally associated with rime ice. The accretion will be relatively sharp pointed at its leading edge (dependent on substrate leading edge thickness), relatively thick (forward of the leading edge), and there should be no evidence of runback ice (explained shortly - (Figs.F20-F24, F33, F42-F44)). To support this assessment, the ambient temperature should be of a relatively low value (e.g. below -15°C), (see Table 6 for example cases).
2. Mixed rime/glaze ice - density 700 kg.m^{-3} . This accretion generally appears opaque white having a small degree of transparency. The profile is blunter than that of the rime ice and sharper than that of the glaze ice. Typical ambient temperatures would be in the range -12°C to -7°C , with one or two exceptions, (see Table 6 for examples).
3. Glaze ice - density 900 kg.m^{-3} . This accretion is strongly transparent which often leads to visibility problems in the photographs. The air content is low and usually renders the substrate beneath the ice accretion visible through the ice. The accretion profile is blunt, usually more fluctuating in shape than the lighter rime ice and more likely to be associated with runback ice at the higher ambient temperatures of typically -5°C to 0°C .

Although ambient temperatures are used as a guideline here due to the variation of total temperature around the leading edge it is clearly the local total temperature which actually influences the ice density. Thus a high speed substrate in a low ambient temperature flow, may exhibit glaze ice accretion at its leading edge.

It was realised that, by employing only three values of ice density, a considerable error is introduced into the assessment, but it was not considered feasible to make a more accurate ice density assessment from the figures. Photographic enlargements were employed in developing the technique and the adopted density values.

The last parameter for assessment from the figures was the ice accretion cross-sectional area, required in addition to its density to assess its mass. In order to determine cross-sectional area, some idea of shape or profile is necessary. This presented the most difficult parameter to derive from the photographs. Photographic enlargements provided a slight improvement but, on the whole, were of little help and failed to justify the cost that would be involved in enlarging all of the figures. The cross-section of the accretions is rarely evident in a plain view in the figures. After many trials and testing of various techniques, an empirical approach was adopted. This involved the development of simple formulae to produce realistic profile curves from the available input parameters of density and the various dimensions already mentioned. Eventually a single simple formula evolved, able to predict ice accretion profiles of realistic appearance over the whole range of density, blade radius and ice accretion thickness, (Figs.41, 67-81):

$$y = k(5X)^a$$

Where "x" and "y" represent the abscissa and ordinate of the curve respectively (Fig.85), "k" is a constant introduced to allow for variation in blade thickness along its radius (explained later), and "a" is an ice density term such that it has three values corresponding to the three values of ice density as follows:-

density (kg.m ⁻³)	"a"
500	0.6
700	0.5
900	0.333

By reflecting this curve about the x-axis, the generic ice accretion profile is produced. Actual ice accretions are not symmetrical in this way due to the asymmetry of the aerofoil section leading edges employed about their chordlines, and the angle of incidence of the aerofoil to the oncoming air flow. However, the use of a symmetrical ice accretion profile is reasonably representative for the purpose of these estimations, (Figs.67-81). This renders the development of two formulae for separate prediction of the upper and lower areas of the accretion, or a single much more sophisticated formula for prediction of a complete asymmetric accretion profile, unnecessary. To align the accretion x-axis with the chord, results in

an unrealistically high location of the accretion on the leading edge. Similarly to follow the extended camber line of the aerofoil, results in an unrealistically low accretion location. Thus a compromise position is employed, judged by experience and appearance, (Fig.65). However, the mathematics of the subsequent calculations effectively align the accretion x-axis with the blade chord, but the error induced in the resulting value of accretion cross-sectional area by doing this is negligible. A set of typical such generic profile co-ordinates appears in Table 5. From a knowledge of all the previously mentioned parameters, the ice accretion cross-sectional area is calculated and employed in the calculation of adhesion strength of the ice. The procedure is as follows.

16.8 Sample Calculations

$$1. \quad i_c = \frac{(X - d) \times 0.9 \times 100}{c}$$

$$2. \quad k = \frac{y}{(5X)^a}$$

$$3. \quad A_i + A_1 = 2 \cdot \int_0^X y \cdot dX$$

$$= 2 \times 5^a \times k \int_0^X X^a \cdot dX$$

$$= 2 \times 5^a \times k \left[\frac{X^{(a+1)}}{(a+1)} \right]_0^X$$

$$= \frac{2 \times 5^a \times k \times X^{(a+1)}}{a+1}$$

$$4. \quad A_i = (A_i + A_1) - A_1$$

5. Centrifugal force acting on ice accretion

$$C_f = m \cdot r \cdot \omega^2$$

mass of accretion

$$m = A_i \times (r_o - r_i) \times r$$

effective adhesion contact area

$$A_c = p (r_o - r_i)$$

adhesive strength

$$H = \frac{h}{A_c}$$

at shedding

$$h = C_f \quad (r = \text{mean radius})$$

$$H = \frac{A_i \cdot (r_o - r_i) \cdot r \cdot \omega^2}{p \cdot (r_o - r_i)}$$

$$= \frac{A_i \cdot r \cdot \omega^2}{p} \cdot r$$

6. scaling factor

$$= \frac{1676.40}{1332.20}$$

$$= \frac{1.2584}{1}$$

16.9 Empirical Adhesion Derivation (Sup.5 - 5.2.3)

In order to make the assumption that an ice accretion or part thereof may be about to shed from the propeller blade, it must be apparent that a neighbouring accretion has done just that, ie. there appears in the figure an area or several areas where ice has been shed from the leading edge of the blade. Thus the final values of derived adhesion strength are actually minima, beyond which it is reasonable to assume that the accretion is likely to shed. Several of the figures contain examples of more than one such accretion and thus it was decided to categorise each accretion both for reference, and to maintain control of the data (Table 7(a)). The radial limits of each accretion and the accretion thicknesses (d and x) were scaled as previously detailed from the figures using the blade geometry (Table 4), (Fig.66) to provide scaling factors. The ice mass density was categorised as detailed earlier, aided by a knowledge of the ambient temperature and droplet diameter (Table 6). The area of the blade leading edge beneath the ice accretion was determined subject to the afore-mentioned approximations introduced by aligning the accretion line of symmetry (x -axis) with the blade aerofoil chord. This was effected from a knowledge of the blade surface co-ordinates which were used to produce (Fig.83), from whence the blade leading edge thickness " t ", cross-sectional area " A_1 " and skin perimeter " l " are obtained (Table 7(c)). Although Cases 1 - 26 (Figs.F1-F11) deal with a metal blade of tip radius 1332.20 mm compared with 1676.40 mm for the composite blade of Cases 27 - 98 (Figs.F12-F33, F37-F53), the blade shape distribution is sufficiently similar for these purposes, if scaled according to blade radius (sample calculation 6) to arrive at a larger radius for use in (Fig.83). This was preferable to producing a figure equivalent to (Fig.83) for the metal blade in question due to the large amount of data processing and time required in the production of such a figure.

In order to account for the manner in which shedding of the ice from the blade takes place, ie. fracture through the ice occurs once the ratio of areas of adhesive bonding to the substrate compared to cohesive bonding within the ice is preferential to cohesive fracture. This means that the ice in the thin aft extremities of the accretion on the blade, will remain on the blade in the majority of cases (where a de-icing or anti-icing system is not fitted under these areas), after shedding of the bulk of the ice accretion has taken place, (Fig.65). This phenomenon is rather variable in nature regarding the dimensional relationship between the shedding and non-shedding parts of the ice accretion, but is approximately allowed for in the manner in which the effective percentage chordwise extent of the accretion is calculated (sample calculation 1, Table 7(b)), and it is this value that is employed when using (Fig.83).

Using the value of ice mass density, the appropriate part of (Fig.82) is located and from a knowledge of " x " and " y " (y equal to $t/2$ at the effective aft extremity of the ice accretion on the blade), a value for the constant " k " may be calculated from the formula (Appendix A, sample calculation 2) or interpolated from (Fig.82).

Hence the cross-sectional area of the ice accretion together with the part of the blade leading edge to which it is effectively adhered may be calculated by integration of the respective formula (Appendix A, sample calculation 3). The cross-sectional area of the ice accretion alone is then a simple subtraction of the blade leading edge area " A_1 " from the combined area " $A_1 + A_1$ ", to leave the accretion area " A_1 ".

(Appendix A, sample calculation 4).

The adhesive strength of the ice to the blade when the accretion is about to be shed from the blade is equal to the sum of the forces attempting to remove it. Thus the shear adhesion of the accretion is equal to the centrifugal force on that accretion per unit of effective contact area, to a good degree of accuracy, (ie. the sum of all other force components acting in that direction is negligible). This assumption ignores the influence of peeling as covered previously in this report and assumes that a pure shear fracture occurs. A mean radius (blade radius) for the accretion is used in this calculation and the length of radial coverage of the accretion is eliminated in the derivation (Appendix A, sample calculation 5). Another major assumption in this method, is that the adhesion of the ice accretion which varies in thickness measured perpendicular to the interface with the substrate (ie. the blade leading edge perimeter), may be taken to be effectively equal to that of an accretion of constant thickness adhered to a flat surface. The influence of areas of ice accretion at a more inboard radius and thus under less bond releasing centrifugal force, on a neighbouring more outboard accretion, by aiding its retention on the substrate, is also ignored. It is of negligible effect unless accretions of large radial blade coverage are treated as a single case, employing a single mean radius for calculation of centrifugal force. The calculation of adhesion strength is also dealt with graphically in (Fig.41). The angular velocity of the propeller blades in a cruise configuration which is approximately the case for the flight tests in question (Table 6) is stated in Table 7(c).

16.9.1 Table 8(a) : Summary of Procedure (Sup.5 - 5.2.4)

Procedure	Figures	Tables	Sample calcs.
Scale blade (if necessary)		6(c)	6
Collect data ($x, d, r_i, r_o, \text{density}$)	F1 - F53	3,5,6(a)	
Determine blade leading edge geometry ($t/2, A_i, l, i_c$)	7(a), (b)	6	
Determine profile curve (a,k)	13	6(c)	2
Determine ice accretion cross-sectional area (A_i)		6(c)	3,4
Determine ice adhesion (H)	29	6(c)	5
Results	30	6	

17 One-Dimensional Thermodynamic Analysis

17.1 Case Descriptions

In all cases an aircraft cruise speed of 272 kt (140 ms^{-1}) and propeller rotational speed of 1331 rpm (140 rad.s^{-1}) are employed. This represents cruise conditions for the S340. Altitude is not considered a variable and thus sea level values of the pressure related parameters are applicable. The ambient free stream outside air temperature is 253 K (-20°C) in all cases, and in all but Case 1.5 the de-icer/ice interface temperature is 273 K (0°C). In Case 1.5 the ruling temperature is the blade surface aft of the de-icer where the heat energy is assumed to exit the blade. This temperature is assumed to be 273 K (0°C) in Case 1.5. As in practice a steady true stagnation point is never achievable on a rotating propeller blade, the heat transfer coefficient in leading edge cases is calculated 1 mm aft of the leading edge.

The de-icing system geometry is the same for all cases at sections where the de-icer exists.

Case 1 : Metal Blade

Case 1.1

A point on the leading edge at a blade radius of 890 mm (53% span) under 5 mm of ice. The thermal path taken by heat energy flowing from the heater into the blade and then out of the blade metal surface aft of the de-icer and 50 mm aft of the blade leading edge is 66 mm.

Case 1.2

A point 15 mm aft of the leading edge at a blade radius of 890mm, within the laminar flow boundary layer, and under 5 mm of ice. The thermal path length within the blade metal from the heater to the aft exit point 50 mm aft of the blade leading edge is 60 mm.

Case 1.3

A point 5 mm aft of the stagnation point where a stagnation temperature rise of 10 K (10°C) is assumed, ie. the effective t_{∞} forward is 263 K. The ice accretion thickness is 2 mm and the internal thermal path length is 60 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 1.4

A point 5 mm aft of the stagnation point where a stagnation temperature rise of 10 K (10°C) is assumed, ie. the effective t_{∞} forward is 263 K. The ice accretion thickness is 10 mm and the internal thermal path length is 60 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 1.5

A point on the de-icer 40 mm aft of the blade leading edge in the turbulent boundary layer, ie. near the trailing edge of the de-icer, under 5 mm of ice in a situation where heat energy passes through the blade and exits aft of the de-icer such that the blade metal surface temperature is 273 K (0°C). The blade internal thermal track length is 25 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 2 : Composite Blade

Case 2.1

A point on the leading edge at the spanwise tip of the de-icing boot (890 mm blade radius - section G), (ie. no polyurethane foam cuff), under 5 mm of ice. The carbon spar does not exist at this blade radius. The overall blade (ie. excluding the de-icer inner neoprene layer), internal thermal track length is 53.8 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 2.1.1

A point on the leading edge at the spanwise tip of the polyurethane foam cuff (749 mm blade radius - section F'), under 5 mm of ice. The carbon spar does not exist at this radius, and the blade internal thermal track length (excluding the de-icer neoprene layer) is 58.3 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 2.1.2

A point on the leading edge at the spanwise tip of the polyurethane foam cuff (749 mm blade radius - section F'), but with the foam cuff removed. The ice accretion thickness is 5 mm and the carbon spar does not exist at this radius. The blade internal thermal track length (excluding the de-icer neoprene layer) is 57.3 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 2.2

A point 15 mm aft of the blade leading edge at the spanwise tip of the polyurethane foam cuff (blade radius 749 mm - section F'), under 5 mm of ice. The carbon spar does not exist at this blade radius, and the internal thermal path length (excluding neoprene) is 57.3 mm to a heat exit point 50 mm aft of the blade leading edge.

Case 2.3

A point 5 mm aft of the blade leading edge where the stagnation temperature rise is assumed to be 10 K (10°C), at the spanwise tip of the polyurethane foam cuff (blade radius 749 mm - section F'), under 5 mm of ice. The carbon spar has zero thickness and the internal thermal track length within the blade is 57.3 mm to the heat exit point 50 mm aft of the blade leading edge.

Case 2.4

A point 5 mm aft of the blade leading edge where the stagnation temperature rise is assumed to be 10 K (10°C), at the spanwise tip of the polyurethane foam cuff (blade radius 749 mm - section F'), under 10 mm of ice. The carbon spar has zero thickness and the internal thermal track length within the blade is 57.3 mm to the heat exit point 50 mm aft of the blade leading edge.

Case 2.5

A point on the leading edge of the blade at section C (349 mm radius), under 5 mm of ice. The carbon spar does not exist at the leading edge, but is over 8 mm thick 90 mm aft of the leading edge where the heat exit point is taken to be.

Case 2.5.1

A point on the de-icer upper surface within the laminar flow boundary layer 15 mm aft of the leading edge, having an ice accretion thickness of 5 mm and at a radial station of 349 mm (section C).

Case 2.5.2

A point on the de-icer within the laminar flow boundary layer situated 5 mm aft of the leading edge, having an ice accretion thickness of 5 mm and at a blade radial station of 349 mm (Section C). A stagnation temperature rise of 10 K (10°C) is assumed.

Case 2.5.3

A point on the de-icer within the laminar flow boundary layer situated 5 mm aft of the leading edge, having an ice accretion thickness of 10 mm and at a radial station of 349 mm (section C). A stagnation temperature rise of 10 K (10°C) is assumed.

Sample Calculation Results

- (Fig.91) : Reynolds number
- (Fig.92) : Heat transfer coefficient
- (Fig.93) : Overall thermal conductivity
- (Fig.94) : Heat output ratio
- (Fig.95) : Heat transfer rate
- (Fig.96) : Heater temperature
- (Fig.97) : Ice/Air interface temperature
- (Fig.98) : De-Icer/blade interface temperature
- (Fig.99) : Aft blade/air interface heat exit temperature

17.1.1 Table 9 : Summary of Sample Calculations Results

r	= blade radial station of section under study	(mm)
OAT	= outside air temperature	(K)
$t_{\infty.fwd}$	= effective ambient temperature (with stagnation rise)	(K)
$t_{\infty.aft}$	= effective ambient temperature (no stagnation rise)	(K)
k_i	= thermal conductivity - ice	(Wm ⁻¹ K ⁻¹)
k_{air}	= thermal conductivity - air	(Wm ⁻¹ K ⁻¹)
k_n	= thermal conductivity - neoprene	(Wm ⁻¹ K ⁻¹)
k_a	= thermal conductivity - aluminium	(Wm ⁻¹ K ⁻¹)
k_p	= thermal conductivity - polyurethane paint	(Wm ⁻¹ K ⁻¹)
k_f	= thermal conductivity - polyurethane foam	(Wm ⁻¹ K ⁻¹)
k_g	= thermal conductivity - glass/resin	(Wm ⁻¹ K ⁻¹)
k_c	= thermal conductivity - carbon/resin	(Wm ⁻¹ K ⁻¹)
k_{gf}	= thermal conductivity - glass fibres	(Wm ⁻¹ K ⁻¹)
k_{cf}	= thermal conductivity - carbon fibres	(Wm ⁻¹ K ⁻¹)
x_i	= thickness of ice	(mm)
$x_{n.o}$	= thickness of neoprene over heater	(mm)
$x_{n.in}$	= thickness of neoprene under heater	(mm)
x_a	= thickness of aluminium	(mm)
x_p	= thickness of polyurethane paint	(mm)
x_f	= thickness of polyurethane foam	(mm)
x_g	= thickness of glass/resin layer	(mm)
x_c	= thickness of carbon/resin	(mm)
x_{gf}	= distance travelled in glass fibres	(mm)
x_{cf}	= distance travelled in carbon fibres	(mm)
x_{g1}	= travel to mid-thickness plane - glass/resin	(mm)
x_{c1}	= travel to mid-thickness plane - carbon/resin	(mm)

Interface Temperatures

$t_{i/a}$	= ice/air (fwd - out)	(K)
$t_{n/i}$	= neoprene/ice (fwd - out)	(K)
t_h	= heater	(K)
$t_{n/al}$	= neoprene/aluminium (aft - in)	(K)
$t_{al/a}$	= aluminium/air (aft)	(K)
$t_{n/p}$	= neoprene/polyurethane paint (aft - in)	(K)
$t_{p/f}$	= polyurethane paint/polyurethane foam (aft - in)	(K)
$t_{p/g}$	= polyurethane paint/glass-resin (aft - in)	(K)
$t_{f/g}$	= polyurethane foam/glass-resin (aft - in)	(K)
$t_{g/c}$	= glass-resin/carbon-resin (aft - in)	(K)
$t_{g/gf}$	= glass-resin/glass-fibres (aft - in)	(K)
$t_{c/cf}$	= carbon-resin/carbon-fibres (aft - in)	(K)
$t_{cf/c}$	= carbon-fibres/carbon-resin (aft)	(K)
$t_{gf/g}$	= glass-fibres/glass-resin (aft)	(K)
$t_{c/g}$	= carbon-resin/glass-resin (aft)	(K)
$t_{g/f}$	= glass-resin/polyurethane foam (aft)	(K)
$t_{g/p}$	= glass-resin/polyurethane paint (aft)	(K)
$t_{f/p}$	= polyurethane foam/polyurethane paint (aft)	(K)
$t_{p/a}$	= polyurethane paint/air (aft)	(K)
x_o	= heat out (fwd) point distance from blade leading edge measured over surface	(mm)
x_{in}	= heat in (aft) exit point distance from leading edge measured over surface	(mm)
v_{∞}	= ambient velocity	(ms ⁻¹)
$R_{ex.o}$	= Reynolds number at fwd. heat out point	$\times 10^5$
$R_{ex.in}$	= Reynolds number at aft heat exit point	$\times 10^5$
h_o	= heat transfer coefficient at fwd point	(Wm ⁻² K ⁻¹)

h_{in} = heat transfer coefficient at aft point ($Wm^{-2}K^{-1}$)
 U_o = overall thermal conductivity fwd of heater ($Wm^{-1}K^{-1}$)
 U_{in} = overall thermal conductivity aft of heater ($Wm^{-1}K^{-1}$)
 q_o = rate of heat energy transfer fwd of heater (Wm^{-2})
 q_{in} = rate of heat energy transfer aft of heater (Wm^{-2})
 q_h = total rate of heat output from heater (Wm^{-2})
 R_q = ratio of heat fwd to total heater output -

Constants

OAT = 253 K (-20°C)

$t_{n/i}$ = 273 K (0°C), except Case 1.5 where $t_{n/i}$ = 270.8 K (-2.2°C)

$x_{n.o}$ = 1.800 mm

$x_{n.in}$ = 1.016 mm $k_g = 0.34 Wm^{-1}K^{-1}$ $k_c = 1.00 Wm^{-1}K^{-1}$

$k_i = 2.30 Wm^{-1}K^{-1}$ $k_a = 18.00 Wm^{-1}K^{-1}$ $k_{gf} = 1.00 Wm^{-1}K^{-1}$

$k_{air} = 0.026 Wm^{-1}K^{-1}$ $k_p = 1.09 Wm^{-1}K^{-1}$ $k_{cf} = 5.00 Wm^{-1}K^{-1}$

$k_n = 0.15 Wm^{-1}K^{-1}$ $k_f = 0.03 Wm^{-1}K^{-1}$

$Pr = 0.689$ $C = 1.2256 kgm^{-3}$

$\mu = 1.783 \times 10^{-5} mskg^{-1}$

Case	$R_{ex.o}$	U_o	x_i	x_c	$t_{\infty fwd}$	$t_{n/p}$	$t_{g/gf}$	$t_{g/f}$
r	$R_{ex.in}$	U_{in}	x_a	x_{gf}	$t_{i/a}$	$t_{p/f}$	$t_{c/cf}$	$t_{g/p}$
x_o	h_o	q_o	x_p	x_{cf}	t_h	$t_{f/g}$	$t_{gf/g}$	$t_{f/p}$
x_{in}	h_{in}	q_{in}	x_f	x_{gl}	$t_{n/al}$	$t_{p/g}$	$t_{cf/c}$	$t_{p/a}$
v	R_q	q_h	x_g	x_{cl}	$t_{al/a}$	$t_{g/c}$	$t_{c/g}$	
1.1	0.128	65.23	5.0	-	-3.0	-	-	-
890	6.427	49.07	65.0	-	-2.0	-	-	-
0.0	864.4	901	-	-	10.8	-	-	-
50.0	100.0	1511	-	-	0.6	-	-	-
187.0	0.37	2412	-	-	-4.9	-	-	-

Case	$R_{ex.o}$	U_o	x_i	x_c	$t_{\infty fwd}$	$t_{n/p}$	$t_{g/gf}$	$t_{g/f}$
r	$R_{ex.in}$	U_{in}	x_a	x_{gf}	$t_{i/a}$	$t_{p/f}$	$t_{c/cf}$	$t_{g/p}$
x_o	h_o	q_o	x_p	x_{cf}	t_h	$t_{f/g}$	$t_{cf/c}$	$t_{f/p}$
x_{in}	h_{in}	q_{in}	x_f	x_{gl}	$t_{n/al}$	$t_{p/g}$	$t_{gf/g}$	$t_{p/a}$
v	R_q	q_h	x_g	x_{cl}	$t_{al/a}$	$t_{g/c}$	$t_{c/g}$	
1.2	1.928	53.61	5.0	-	-20.0	-	-	-
890	6.427	49.75	60.0	-	-5.9	-	-	-
15.0	223.2	3006	-	-	36.1	-	-	-
50.0	100.0	2791	-	-	17.2	-	-	-
187.0	0.52	5797	-	-	7.9	-	-	-
1.3	0.487	58.32	2.0	-	-20.0	-	-	-
890	6.427	49.75	60.0	-	-4.2	-	-	-
5.0	336.5	1942	-	-	23.3	-	-	-
50.0	100.0	1657	-	-	12.1	-	-	-
141.7	0.54	3599	-	-	6.6	-	-	-
1.4	0.487	51.76	10.0	-	-20.0	-	-	-
890	6.427	49.75	60.0	-	-5.9	-	-	-
5.0	336.5	1366	-	-	16.4	-	-	-
50.0	100.0	1313	-	-	7.5	-	-	-
141.7	0.51	2679	-	-	3.1	-	-	-
1.5	5.142	42.18	5.0	-	-20.0	-	-	-
890	6.427	55.07	25.0	-	-5.4	-	-	-
40.0	104.9	1531	-	-	16.3	-	-	-
50.0	100.0	2001	-	-	2.8	-	-	-
141.7	0.43	3532	-	-	0.0	-	-	-
2.1	0.128	65.23	5.0	0.0	-3.0	8.0	4.4	-
890	6.427	13.36	-	40.0	-2.0	-	-	-15.9
1.0	864.4	901	0.381	-	10.8	-	-	-
50.0	100.0	416	0.0	2.951	-	8.0	-12.3	-16.0
187.0	0.69	1312	3.56	-	-	-	-	-
2.1.1	0.120	53.22	5.0	0.0	-5.0	3.8	-6.2	-
749	6.015	8.82	-	40.0	-1.0	3.7	-	-17.6
1.0	216.7	442	0.381	-	5.3	-3.7	-	-
50.0	94.9	223	1.00	3.75	-	-	-15.1	-17.6
175.0	0.66	665	4.52	-	-	-	-	-

Case	$R_{ex.o}$	U_o	x_i	x_c	$t_{\infty fwd}$	$t_{n/p}$	$t_{g/gf}$	$t_{g/c}$
r	$R_{ex.in}$	U_{in}	x_a	x_{gf}	$t_{i/a}$	$t_{p/f}$	$t_{c/cf}$	$t_{g/p}$
x_o	h_o	q_o	x_p	x_{cf}	t_h	$t_{f/g}$	$t_{cf/c}$	$t_{f/p}$
x_{in}	h_{in}	q_{in}	x_f	x_{g1}	$t_{n/al}$	$t_{g/c}$	$t_{gf/g}$	$t_{p/a}$
v	R_q	q_h	x_g	x_{c1}	$t_{al/a}$	$t_{g/gf}$	$t_{c/g}$	
2.1.2	0.120	53.22	5.0	0.0	-5.0	3.2	-0.4	-
749	6.015	12.49	-	40.0	-1.0	-	-	-16.6
1.0	216.7	442	0.381	-	5.3	-	-	-
50.0	94.9	316	0.0	3.75	-	3.0	-13.1	-16.7
175.0	0.58	758	4.52	-	-	-	-	-
2.2	1.804	53.18	5.0	0.0	-20.0	30.5	22.7	-
749	6.015	12.49	-	40.0	-6.4	-	-	-12.5
15.0	215.9	2937	0.381	-	36.1	-	-	-
50.0	94.9	689	0.0	3.75	-	30.3	-4.9	-12.7
175.0	0.81	3628	4.52	-	-	-	-	-
2.3	0.487	58.32	5.0	0.0	-10.0	19.6	13.5	-
749	6.015	12.49	-	40.0	-4.8	-	-	-14.1
5.0	336.5	1943	0.381	-	23.3	-	-	-
50.0	94.9	541	0.0	3.75	-	19.4	-8.2	-14.3
141.7	0.78	2484	4.52	-	-	-	-	-
2.4	0.487	51.76	10.0	0.0	-10.0	13.3	8.9	-
749	6.015	12.49	-	40.0	-5.9	-	-	-15.1
5.0	336.5	1366	0.381	-	16.4	-	-	-
50.0	94.9	455	0.0	3.75	-	13.2	-10.1	-15.2
141.7	0.75	1821	4.52	-	-	-	-	-
2.5	0.120	70.55	5.0	0.0	-9.0	31.6	-13.7	-
349	6.015	1.48	-	60.0	-5.8	31.6	-	-19.2
1.0	769.0	2677	0.381	-	32.1	-13.0	-	-
90.0	94.9	77	17.2	3.324	-	-	-18.4	-19.2
148.0	0.97	2754	4.01	-	-	-	-	-
2.5.1	1.526	52.06	5.0	8.6	-20.0	32.5	-	-
349	9.157	2.27	-	-	-6.0	32.4	-14.8	-18.6
15.0	198.6	2774	0.381	17.91	33.1	-11.5	-15.2	-
90.0	73.48	121	10.8	3.324	-	-	-	-18.6
148.0	0.96	2895	4.01	8.11	-	-13.9	-16.2	-

Case	$R_{ex.o}$	U_o	x_i	x_c	$t_{\omega fwd}$	$t_{n/p}$	$t_{g/gf}$	$t_{g/c}$
r	$R_{ex.in}$	U_{in}	x_a	x_{gf}	$t_{i/a}$	$t_{p/f}$	$t_{c/cf}$	$t_{g/p}$
x_o	h_o	q_o	x_p	x_{cf}	t_h	$t_{f/g}$	$t_{cf/c}$	$t_{f/p}$
x_{in}	h_{in}	q_{in}	x_f	x_{g1}	$t_{n/al}$	$t_{g/c}$	$t_{gf/g}$	$t_{p/a}$
v	R_q	q_h	x_g	x_{c1}	$t_{al/a}$	$t_{g/gf}$	$t_{c/g}$	
2.5.2	0.487	58.32	5.0	8.6	-10.0	22.8	-	-
349	9.157	1.72	-	-	-4.8	22.8	-16.9	-19.2
5.0	336.5	1943	0.381	13.61	23.3	-16.8	-17.1	-
90.0	73.48	74	15.1	3.324	-	-	-	-19.2
148.0	0.96	2017	4.01	8.11	-	-16.3	-17.7	
2.5.3	0.487	51.76	10.0	8.6	-10.0	16.0	-	-
349	9.157	1.72	-	-	-6.1	15.9	-17.4	-19.4
5.0	336.5	1366	0.381	13.61	16.4	-15.7	-17.5	-
90.0	73.48	62	15.1	3.324	-	-	-	-19.4
148.0	0.96	1428	4.01	8.11	-	-16.9	-18.1	

17.2 Discussion

Observing Case 1.1. A blade radius of 890 mm was chosen to co-incide with the spanwise tip of the de-icer (allowing a few millimetres for edge effects), in order to allow comparison with the non-metallic composite blade. At similar radii on the composite blade (so far as the aerofoil section is concerned), are the de-icer spanwise tip (890 mm) and the polyurethane foam cuff tip (749 mm). The resultant airspeed at this radius (890 mm) for the standard aircraft cruise speed and cruise rpm applied is 187 ms^{-1} . At a static temperature of 253 K (-20°C), sonic speed is 318.8 ms^{-1} and thus the Mach number at 890 mm is 0.59. Case 1.1 investigates a point on the leading edge of the blade where the stagnation temperature rise is 17K resulting in a total temperature of 270 K (-3°C).

Thus it can be seen that although there is a quite significant fall in temperature aft, (through the blade to the air flow over the blade aft of the de-icing system), the temperature fall forward at the leading edge is much less. A 273 K (0°C) de-icer/ice interface temperature is assumed in order to model the situation where the ice adhesive bond is about to fail due to a phase change from ice to water at the interface. This is the reason for assuming no shedding due to centrifugal loading occurs.

As described earlier, the heat transfer coefficient at the leading edge is actually calculated at a position 1 mm downstream. Theoretically, at the stagnation point (on the leading edge) the air flow speed over the surface is zero. If this were the actual case then the heat transfer coefficient would be that due only to thermal conduction and radiation into stationary air from the ice. Natural convection would not occur as this would be a case of forced 'non-convection' (stagnation). However, as explained earlier, a true steady stagnation point is not achievable in a real situation of flow over a rotating propeller blade section and hence the 1 mm offset.

At a distance of 1 mm aft the flow is considered laminar and the laminar heat transfer coefficient is calculated to be $864.4 \text{ Wm}^{-2}\text{K}^{-1}$. This results in an overall thermal conductivity forward from the heater element (theoretically infinitely thin), through the outer neoprene layer (1.8 mm), 5 mm of ice and the laminar boundary layer of $65.23 \text{ Wm}^{-2}\text{K}^{-1}$. At the point where the heat energy travelling aft through the blade is assumed to leave the blade into the air flow (50 mm aft of the leading edge, measured over the curved section surface), a smaller heat transfer coefficient of $100.0 \text{ Wm}^{-2}\text{K}^{-1}$, in the thicker, turbulent boundary layer, applies. This yields an overall thermal conductivity aft, from the heater through 1.016 mm of neoprene, 65 mm of aluminium alloy and the turbulent boundary layer of

$49.07 \text{ Wm}^{-2}\text{K}^{-1}$. Hence the overall thermal conductivities forward and aft are of approximately similar magnitudes (Fig.93).

In order to effect the desired 273 K de-icer surface temperature a heater temperature of 283.3 K (10.3°C) is required, resulting in

heat transfer rates forward and aft of 0.901 kWm^{-2} and 1.511 kWm^{-2} respectively (Fig.95). Thus it can be seen that only 37% of the heat energy output from the heater element is actually applied to melting the ice at the ice/de-icer interface. It is interesting to note that the blade metal surface aft of the de-icing system, at the point where the heat energy is considered in this case to exit the blade, is calculated to be 268.1 K (-4.9°C). Thus, in this case, runback water would be allowed to freeze aft of the de-icer. However, once that runback water had frozen it would considerably reduce the thermal conductivity aft, thereby raising the aft metal/runback ice interface temperature, possibly as far as 273 K and hence go on to melt the ice interface causing shedding of the runback ice accumulation.

Hence in Case 1.1, the overall power efficiency of the de-icing system is low (37%), the majority of the heat energy produced being lost to the blade and airflow aft.

The leading edge is a somewhat particular case due to the stagnation temperature rise and thus Case 1.2 is concerned with a point on the de-icer surface 15 mm aft of the blade leading edge, outside the main stagnation area. All other dimensions are as in the previous case except that the thermal path taken through the aluminium alloy has been reduced from 65 mm to 60 mm due to the movement of the heat initiation point. The forward (out) Reynolds number is seen to increase from 1.285×10^4 of Case 1.1 to 1.928×10^5 , which with the change in distance from the leading edge, applying the Prandtl number of 0.689, results in a forward laminar heat transfer coefficient of

$223.2 \text{ Wm}^{-2}\text{K}^{-1}$. Therefore there is a reduction in heat transfer coefficient of 74% from the leading edge of Case 1.1. However it could be argued that it would be more realistic to apply a part of the stagnation velocity reduction (and temperature rise) at the point 1 mm aft which would in turn reduce the forward heat transfer coefficient of Case 1.1. For instance, if it were assumed that 50% of the stagnation temperature rise was applicable, this would yield a velocity of 93.5 ms^{-1} , leading to a Reynolds number of 6.425×10^3 and a heat transfer coefficient of $611.1 \text{ Wm}^{-2}\text{K}^{-1}$. However, to calculate the fraction of the stagnation temperature rise and velocity reduction applicable would considerably increase the sophistication of these calculations beyond the level to which they are intended, and beyond that inherent in other assumptions imposed. Therefore it was decided to maintain a constant approach of applying the full ambient velocity at the 1 mm aft point. The aft dimensions for Case 1.2 are the same as in Case 1.1, therefore the aft heat transfer coefficient is equal at

$100.0 \text{ Wm}^{-2}\text{K}^{-1}$. The overall forward thermal conductivity in this case is $53.61 \text{ Wm}^{-2}\text{K}^{-1}$ representing an 18% decrease from Case 1.1 as a direct result of the decreased forward heat transfer coefficient. The aft overall thermal conductivity has only changed slightly from Case 1.1 to $49.75 \text{ Wm}^{-2}\text{K}^{-1}$ due to the 5 mm reduction in thermal path length in the aluminium alloy.

The heater temperature of Case 1.2, due to the lack of stagnation temperature rise, is much higher than that of Case 1.1, being 36.1°C as opposed to 10.8°C . This is necessary to maintain the 0°C de-icer surface temperature despite the colder air temperature. It is worth noting here that the ice outer surface temperature is calculated to be -5.9°C in Case 1.2 compared with -2.0°C in Case 1.1. The overall effect is to raise the heat flow forward by 234% from Case 1.1 to 3.006 kWm^{-2} . Consequently as there is still only a 52% power efficiency applicable, the aft heat flow rate has risen by 85% from Case 1.1 to 2.791 kWm^{-2} . Hence although a heater power output of only 2.41 kWm^{-2} is required when considering the leading edge of Case 1.1, a heater power of 5.80 kWm^{-2} is necessary for areas not influenced by leading edge velocity stagnation. This comparison highlights the recent design reasoning for the reduced power output of the spraymat heater element band applied at the leading edges of de-icing systems compared with its adjacent bands.

Case 1.2 is an interesting Case because the blade aft heat exit point surface temperature is calculated to be positive at 7.9°C . This would indicate that in a runback situation (ie. melt-water running back over the aft blade surface), the heat escaping aft through the blade would provide a secondary de-icing system to prevent that water from freezing and causing undesirable runback ice formations. Thus it could be postulated that, in this case, the heat energy flowing aft is not in fact lost, but on the contrary is put to effective use, and hence the de-icing system efficiency is a misleader in such cases when calculated in the applied manner.

In Case 1.3 a partial stagnation temperature rise of 10°C is assumed at a distance of 5 mm from the blade leading edge. The case arose as a direct result of the considerations mentioned in Case 1.2 for applying a fraction of the stagnation temperature rise. Thus a new Mach number of 0.445 and hence velocity of 141.7 ms^{-1} were determined. The forward Reynolds number emerged at 4.870×10^4 , yielding a forward, laminar heat transfer coefficient of $336.5 \text{ Wm}^{-2}\text{K}^{-1}$. This is situated between the values determined in Cases 1.1 and 1.2 as would be expected. Due to common geometry the aft, heat transfer coefficient

50 mm aft of the blade leading edge remains at $100.0 \text{ Wm}^{-2}\text{K}^{-1}$ (Fig.92), and the aft overall thermal conductivity is constant at $49.75 \text{ Wm}^{-2}\text{K}^{-1}$ (Fig.93). The forward overall thermal conductivity of $58.32 \text{ Wm}^{-2}\text{K}^{-1}$ also lies between the values for Cases 1.1 and 1.2, representing an increase of 9% above Case 1.2 and decrease of 11% below Case 1.1 due solely to the corresponding changes in heat transfer coefficient (Fig.93).

The partial stagnation temperature rise is reflected in the heater temperature of 23.3°C (Fig.96). This lies between the lower value of 10.8°C in Case 1.1 where a full stagnation temperature rise reduces the demand on the heater to raise the de-icer surface temperature to 0°C , and the higher value of 36.1°C in Case 1.2 where no stagnation temperature rise exists. Correspondingly the forward heat transfer rate of Case 1.3 is 1.942 kWm^{-2} and the aft value is

1.657 kWm^{-2} . These values bear no surprises, following the trend set by the forward temperatures (Fig.95). The heater system power forward efficiency of 54% is marginally higher than that of Case 1.2. The forward ice surface temperature in Case 1.3 is calculated to be -4.2°C indicating that the 10°C rise in effective forward ambient temperature is not simply transferable to the ice surface due to the boundary layer effects. In a similar manner to Case 1.2, Case 1.3 also exhibits a positive aft blade surface temperature (6.6°C) with the same ramifications regarding runback ice as its predecessor.

At this point an investigation into the effect of ice thickness was initiated, or rather an increase in forward thermal insulation due to an increased ice thickness. Therefore the dimensions (with the exception of ice thickness, which was increased from 5 mm to 10 mm), and many of the variable parameters, take the same values in case 1.4 as in Case 1.3. Thus the values of forward and aft heat transfer coefficient, and aft overall thermal conductivity are taken from Case 1.3. As expected there is a decrease in the forward overall thermal conductivity from $58.32 \text{ Wm}^{-2}\text{K}^{-1}$ to $51.76 \text{ Wm}^{-2}\text{K}^{-1}$ (Fig.93). This

results in a forward heat transfer rate of 1.366 kWm^{-2} and heater temperature of 16.4°C . Thus it can be seen that, as it is the de-icer/ice interface temperature of 0°C which must be maintained, and not the ice surface temperature, then the effect of the increased thermal insulation is beneficial in reducing the required heater temperature (Fig.96). This is because the ice layer in question lies on the opposite side of the point of consideration (0°C interface) to that of the heat energy transmitter (heater element).

The lower heater temperature results in a reduced heat loss aft of 1.313 kWm^{-2} (Fig.95), leading to an aft blade surface temperature of 3.1°C . Hence, provided the blade aerodynamic qualities are not significantly impaired, its structural integrity put at risk, or unacceptable vibration levels produced, then 10 mm appears to be an

almost ideal ice thickness to allow to accrete between forced shedding cycles. This is because the aft blade surface temperature reaches a positive value with a reasonable margin (Fig.99) to remove runback ice formations, whilst overall electrical energy consumption (Fig.95) is minimised by the effective increased thermal insulation of the ice layer (Fig.93). The system efficiency forward of 51% shows a slight reduction from Case 1.3 and considerable improvement over Case 1.1 (Fig.94). It may be considered rather low, but the benefits of the apparent lost energy aft in combating the undesirable runback ice must be accounted for.

It was next decided to study the effects of considering a point near the trailing edge of the de-icing system in such a position as to be close to the aft blade surface through which the heat energy is assumed to escape. Thus the internal thermal path length within the aluminium alloy is reduced to 25 mm. At this location (40 mm aft of the blade leading edge), the flow was considered turbulent and therefore the turbulent heat transfer coefficient was determined at $104.9 \text{ Wm}^{-2}\text{K}^{-1}$. With a standard 5 mm of ice, this yielded a reduced forward overall thermal conductivity of $42.18 \text{ Wm}^{-2}\text{K}^{-1}$. Due to the much reduced distance of heat energy travel from the heater element to the blade aft surface of 26.016 mm, there is a relatively large increase in aft overall thermal conductivity to $55.07 \text{ Wm}^{-2}\text{K}^{-1}$, representing a 11% increase from Case 1.3 (Fig.93), where the path length aft is 61.016 mm.

As would therefore be expected, there is a decrease in the forward heat transfer rate from Case 1.3 to Case 1.5 (Fig.95), and a relatively small increase in the aft heat transfer rate and consequent decrease in overall heater power output rate (Fig.94). Therefore the forward value increases 28%, the aft 11%, and the overall 25%. This leads to a local system efficiency change from 50% in Case 1.3 to 43% in Case 1.5. The heater temperature is very similar to that of Case 1.3 being 22.6°C compared with 23.3°C (Fig.96). This is brought about by the case similarities and the fact that it is the de-icer forward surface temperature which governs. The aft blade surface temperature in this case was determined to be 0.0°C indicating the transition point between the capability to remove runback ice and being incapable.

It was then decided to investigate several cases employing the non-metallic composite blade. Case 2.1 considers a section in the same conditions and at the same radius as that of Case 1.1 (890 mm), and of course of the same geometrical profile (Fig.66). Therefore the forward and aft heat transfer coefficients are exactly the same as in Case 1.1 (Fig.92). Also equal are the forward overall thermal conductivity, heat transfer rate, heater temperature and ice surface temperature (Figs.93, 94, 96 and 97), because the same de-icing boot is applied to both blades. However the inner composition of the blade is different in thermal terms from the aluminium alloy of the metal blade, rendering an overall aft thermal conductivity and heat transfer rate

of $13.36 \text{ Wm}^{-2}\text{K}^{-1}$ and 416 Wm^{-2} respectively. This is compared with $49.07 \text{ Wm}^{-2}\text{K}^{-1}$ and 1511 Wm^{-2} for the metal blade (Figs.93 and 94). This represents a heat loss aft of only 27% of that of the metal blade due to a four fold increase in thermal insulation. Thus the total heater power is 1.312 kWm^{-2} (half that of Case 1.1), and the de-icing system power efficiency is 69% compared with 37% of Case 1.1.

The large increase in thermal insulation offered by the composite blade over the metal blade is reflected in the reduced aft blade surface temperature of -16.0°C compared with -4.9°C (Fig.99). The internal layer interface temperatures within the blade were determined for comparison of the thermal effectiveness of the various layers and materials involved (Table 9). It can be seen that the 0.381 mm thick polyurethane paint layer has a negligible effect on the heat flow, whereas 3 mm of glass/resin reduces the flow temperature by 3.6°C . Along the glass fibres there is a further reduction of 16.7°C over a distance of 40 mm, and a further 3.8°C on returning through the glass/resin from the layer mid-thickness.

Case 2.1.1 was introduced to study the effects of the presence of the polyurethane foam cuff. A section at the spanwise tip of the cuff was chosen in order to present a section as close in geometry to that of Case 2.1 as possible. The blade radius at this section, where the foam cuff is 1 mm thick, is 749 mm. Hence there is an ambient velocity reduction of 6.4% from Case 2.1 to 175 ms^{-2} , yielding forward and aft heat transfer coefficient reductions of 75% to $216.7 \text{ Wm}^{-2}\text{K}^{-1}$ and 5% to $94.9 \text{ Wm}^{-2}\text{K}^{-1}$ respectively. Again, as the geometry forward of the cuff is the same as in the previous case, then the forward overall thermal conductivity is the same. However there is an 18% reduction in forward heat transfer rate due to the reduced heat transfer coefficient at the lower air speed.

The heater temperature also reflects this slightly reduced heat transfer, being 5.3°C in this case as opposed to 10.8°C in the previous case. However there is a marked reduction in the aft overall thermal conductivity of 34% from $13.36 \text{ Wm}^{-2}\text{K}^{-1}$ to $8.82 \text{ Wm}^{-2}\text{K}^{-1}$ due to the presence of the cuff (Fig.93). This results in a 34% reduced heat transfer rate aft to only 223 Wm^{-2} (416 Wm^{-2} in Case 2.1), and 11%

reduction in total heater power to 0.665 kWm^{-2} (Fig.95). The combined effect is to reduce the aft blade surface temperature by 1.6°C to -17.6°C and produce a system efficiency reduction from 69% to 66% (Fig.94).

In comparing the results of the previous two cases it is not a simple task to separate the effects of the presence of the 1 mm thick polyurethane foam cuff from those of the material layer thickness changes and the reduced airspeed. Therefore Case 2.1.2 was introduced,

being a hypothetical case taken from Case 2.1.1 but with the foam cuff removed. All other conditions and dimensions remain unchanged such that the airspeed and other layer thicknesses are the same as in the previous case. Hence the heat transfer coefficients, forward overall thermal conductivity, forward heat transfer rate, ice surface temperature and heater temperature remain unchanged. Removal of the foam cuff is noted in the new value of aft overall thermal conductivity increase by 42% to $12.49 \text{ Wm}^{-2}\text{K}^{-1}$, 42% increase in heat transfer rate aft to 316 Wm^{-2} and 14% increase in total heater power to 758 Wm^{-2} (Figs.93 and 95). The blade aft surface is equal as a result at -16.7°C . Hence these figures represent the quite considerable effects of the presence of the 1 mm thick polyurethane foam cuff.

As applied to the the metal blade in Cases 1.1 and 1.2, comparing a leading edge and 15 mm aft heat transmission points, Case 2.2 considers a point 15 mm aft on the composite blade at 749 mm radius for comparison with Case 2.1.1. The aft, turbulent heat transfer coefficient is taken from Case 2.1.1 and a new forward, laminar heat transfer coefficient is calculated 15 mm aft of the blade leading edge at 749 mm blade radius, ($215.9 \text{ Wm}^{-2}\text{K}^{-1}$). This yielded a forward overall thermal conductivity of $53.18 \text{ Wm}^{-2}\text{K}^{-1}$ at an airspeed of 175 ms^{-1} , compared with $53.61 \text{ Wm}^{-2}\text{K}^{-1}$ in Case 1.2 at a blade radius of 890 mm and consequent airspeed of 187 ms^{-1} (Fig.93). This resulted in the same heater temperature as Case 1.2 of 36.1°C and a forward heat transfer rate of 2.937 kWm^{-2} compared with 3.006 kWm^{-2} . As the heat energy is considered to flow over the major part of its path along the glass fibres within the glass/resin layer, the actual path length is of a similar magnitude to that taken through the blade from the leading edge in the previous case. Thus for comparison purposes it is advantageous to employ the same path length and hence the same value of $12.49 \text{ Wm}^{-2}\text{K}^{-1}$ for the overall aft thermal conductivity.

Because of the large difference in forward effective ambient temperature from Cases 2.1.1 and 2.1.2 to Case 2.2 (ie. -5°C and -5°C to -20°C), there is a large increase in the required forward heat transfer rate from 0.44 kWm^{-2} to 2.94 kWm^{-2} , (568%). This shows that the 15°C fall in effective OAT far outweighs the decrease in forward overall thermal conductivity caused by the decrease in forward heat transfer coefficient. The aft heat transfer rate has increased above that of the previous case by 118% with the same overall aft thermal conductivity due to the relatively large increase in heater temperature from 5.3°C to 36.1°C (Figs.93, 95 and 96). Hence the

increases in both forward and aft heat transfer rate yield an overall increase of 382% in the total required heater power output from 0.76 kWm^{-2} to 3.62 kWm^{-2} . Although more power is required in this case compared with the previous two cases, the ratio of 'useful' heat energy transmitted forward to that 'lost' aft has improved from 58% in Case 2.1.2 to 81% in Case 2.2 (Fig.94). The resulting effect of the reduced effective ambient temperature is to lower the ice/air interface temperature from -1.0°C in Case 2.1.2 to -6.4°C in this case (Fig.97). The aft blade surface temperature remains similar at -12.7°C compared with -16.7°C of the previous case (Fig.99).

In comparison with the metal blade of Case 1.2, it can be seen, as expected, that the Reynolds numbers (Fig.91), forward and aft heat transfer coefficients (Fig.92), and forward overall thermal conductivity (Fig.93), are similar. The large decrease in aft overall thermal conductivity due to the thermal characteristics of the non-metallic composite materials (Fig.93) is responsible for the equally large decrease in aft heat transfer rate (Fig.95) producing the greatly reduced aft blade surface temperature (Fig.99).

For direct comparison with Case 1.3, (except for a minor geometry change due to slightly reduced blade radius), Case 2.3 considers a heat transmission point 5 mm aft of the blade leading edge, where a 10°C stagnation temperature rise is effective. Thus the heat transfer coefficients are the same as in Case 1.3 (except for a 5% reduction in aft, turbulent heat transfer coefficient due to the minor section difference mentioned above). Also equal, as would be expected, are the forward thermal conductivity (Fig.93) and forward heat transfer rate (Fig.95). The greatly increased thermal insulation of the non-metallic composite layers in comparison with the solid aluminium are again reflected in the reduced aft overall thermal conductivity from $49.75 \text{ Wm}^{-2}\text{K}^{-1}$ of Case 1.3 to $12.49 \text{ Wm}^{-2}\text{K}^{-1}$ of Case 2.3, the latter being only 25% of the former. Thus the heat loss aft is reduced from 1.66 kWm^{-2} to 0.54 kWm^{-2} , a reduction of 67% (Fig.95), producing a reduction in required heater output power of 1.15 kWm^{-2} from 3.60 kWm^{-2} to 2.48 kWm^{-2} (Fig.95) and thereby increasing the heater output efficiency by 24% to 78% (Fig.94).

Comparing Case 2.3 with Case 2.2, it can be seen that moving the heat transmission point forward 10 mm has the effect of increasing the forward heat transfer coefficient from $215.9 \text{ Wm}^{-2}\text{K}^{-1}$ to $336.5 \text{ Wm}^{-2}\text{K}^{-1}$ (Fig.92). This would produce an increase in forward heat transfer rate were it not for the reduction in heater temperature (Figs.95 and 96). There is little change in heater power output efficiency (3% fall) and the forward ice surface and aft blade surface temperatures are similar in both cases (Table 9 and Figs.97 and 99). However the reduction in required heater temperature is relevant when considering material

properties with respect to temperature, as is the 1 kWm^{-2} reduction in forward heat flow rate.

Case 2.4 was introduced for comparison with Cases 2.3 and 1.4. The comparison with Case 2.3 highlights the effects of increasing the ice thickness from 5 mm to 10 mm, and the comparison with Case 1.4 is to compare the differences between the metal and composite blades in similar circumstances.

As the geometry of Case 2.4 is identical to that of Case 2.3, except for the increase in ice thickness, the Reynolds numbers (Fig.91), heat transfer coefficients (Fig.92) and aft overall thermal conductivity (Fig.93) are the same as in the previous case. There is an 11% reduction in forward overall thermal conductivity from $58.32 \text{ Wm}^{-2}\text{K}^{-1}$ to $51.76 \text{ Wm}^{-2}\text{K}^{-1}$. This has the effect of decreasing the required heat energy flow rate forward (Fig.95), to produce a blade surface temperature of 0°C . The secondary effect is a decrease in heater temperature (Fig.96) to the value of 16.4°C necessary to yield the reduced heat flow of 1.366 kWm^{-2} . Due to the 6.9°C reduction in heater temperature, there is a small reduction (16%) in the aft heat transfer rate. The result of the combined decreases in both forward and aft heat flow rates is to reduce the total heater power required by 27% to 1.82 kWm^{-2} (Fig.95). The extra thermal insulation provided by the additional 5 mm of ice causes a 1.1°C decrease in the ice surface temperature (Fig.97), and there is a 0.9°C decrease in the aft blade surface temperature due to the reduced heater temperature and hence reduced heat flow aft.

In comparison with the metal blade (Case 1.4), the heat transfer coefficients, forward thermal conductivity and heater temperature are the same as the metal blade case, but there is a marked reduction of 65% in the aft heat flow rate (Fig.95) due to the greatly reduced thermal conductivity aft of $12.49 \text{ Wm}^{-2}\text{K}^{-1}$ compared with $49.75 \text{ Wm}^{-2}\text{K}^{-1}$ of the metal blade (Fig.93). Consequently the required heater output power falls by 0.86 kWm^{-2} , improving the heater efficiency from 51% to 75% (Fig.94). The remaining difference of notable magnitude is that in the blade aft surface temperature, being 3.1°C in the metal blade case, ie. above zero and capable of removing runback ice, and -15.2°C in the composite blade case, definitely well below zero and incapable of removing runback ice.

Case 2.5 is not directly comparable with Case 1.5, but is a separate group of cases (2.5 - 2.5.3) studying a section of the composite blade where the polyurethane foam cuff is relatively thick (17.2 mm at the leading edge). If Case 2.5 is compared with Case 2.1.2, (the closest in terms of external conditions), then the presence of the foam cuff is immediately recognisable in the reduction in aft thermal conductivity from $12.49 \text{ Wm}^{-2}\text{K}^{-1}$ to only $1.48 \text{ Wm}^{-2}\text{K}^{-1}$.

This results in a large improvement in heater efficiency from 58% to 97% (Fig.94), as heat flow aft is a definite loss if it is not possible to remove runback ice. The change in section geometry and thence overall thermal characteristics, leads to an ice surface temperature of -5.8°C (Fig.97) and blade aft surface temperature of -19.2°C (Fig.99). By comparing the layer interface temperatures at either face of the polyurethane foam cuff ($t_{p/f}$ and $t_{f/g}$ - Table 9) it can be seen that 87% of the temperature decrease aft takes place within the polyurethane foam cuff. Thus the blade structure under the cuff is almost rendered irrelevant when the cuff is relatively thick, as in this case, at the leading edge.

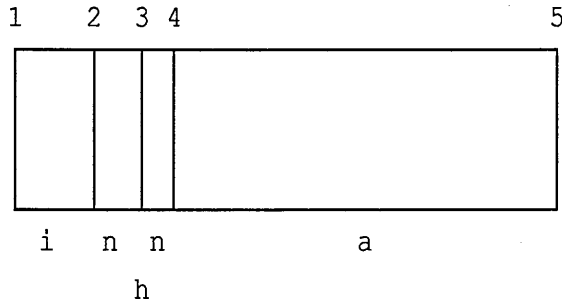
Case 2.5.1 considers the same section as Case 2.5, at 349 mm blade radius, but investigates a heat transmission point 15 mm aft of the blade leading edge. Hence there are changes in the heat flow rates and temperatures. However, due to the low absolute value of aft thermal conductivity and therefore aft heat transfer rate, the changes are not large in absolute terms, from the values of the previous case (Figs. 93, 95, 96, 97, 98 and 99). From Case 2.5 to Case 2.5.1 there is a 3.6% increase in forward heat transfer rate to 2.77 kWm^{-2} and a 43 Wm^{-2} increase in aft heat transfer rate to 121 Wm^{-2} , leading to a 142 Wm^{-2} increase in required heater power of 2.90 kWm^{-2} and thence a 1% reduction in heater power output efficiency. The heater temperature increases by just 1°C to 33.1°C , the forward ice surface temperature only changes by 0.2°C to -6°C from -5.8°C , and the aft blade surface temperature rises by 0.6°C to -18.6°C . Therefore it can be seen that the presence of the thick foam cuff, with its low thermal conductivity, practically obliterates the thermal effects of the other layers. Hence the marked changes between the results of Cases 1.1 and 1.2 with the metal blade, brought about by moving the heat transmission point 15 mm aft from the leading edge are not so apparent in the composite blade cases, where the cuff is relatively thick.

Cases 2.5.2 and 2.5.3 consider identical geometry and external conditions except for an increased ice thickness in the latter case of 10 mm compared with 5 mm of ice in the former case. Thus these two cases were established to consider the effects of ice thickness in conjunction with a relatively thick (15.1 mm) foam cuff. The results (Table 9) show a reduction in forward overall thermal conductivity, as would be expected, due to the extra 5 mm of ice, of 11% from $58.32 \text{ Wm}^{-2}\text{K}^{-1}$ to $51.76 \text{ Wm}^{-2}\text{K}^{-1}$ (Fig.93). This has the effect of reducing the heat flow forward necessary to produce the blade/ice interface temperature of 0°C by 30% from 1.94 kWm^{-2} to 1.37 kWm^{-2} (Fig.95). Hence the necessary heater temperature to promote that heat flow rate is reduced by 6.9°C from 23.3°C to 16.4°C (Fig.96). As to be expected, there is little change in the blade aft surface temperature (0.2°C increase). The overall effect on total required heater output

is a 29% decrease from 2.02 kWm^{-2} to 1.43 kWm^{-2} (Fig.95) with the same heater output efficiency (Fig.94), the heat loss aft having decreased by 16% from $74 \text{ Wm}^{-2}\text{K}^{-1}$ to $62 \text{ Wm}^{-2}\text{K}^{-1}$ (Fig.95). Thus the effects of the extra ice thickness are visible but much diminished by the presence of the thick foam cuff.

17.3 Theory

CASE 1: Metal Propeller Blade



(Fig.84)

i = ice n = neoprene h = heater a = aluminium

Stations

1. Ice/air interface.
2. Ice/neoprene interface.
3. Electric heater matrix.
4. Neoprene/aluminium alloy interface.
5. Aluminium alloy/air interface.

Constants

$$k_{23} = k_{34} = k_n$$

$$t_1 < t_2 < t_3 \quad t_3 > t_4 > t_5$$

$$k_{12} = k_i = 2.30 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_a = 18.00 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_n = 0.15 \text{ Wm}^{-1}\text{K}^{-1}$$

$$x_{n.in} = 1.016 \text{ mm}$$

$$T_2 = 273 \text{ K } (0^\circ\text{C})$$

$$x_{n.o} = 1.800 \text{ mm}$$

<u>Variables</u>	<u>Resultants</u>
t_1	q_h
x_i	t_3
x_a	t_4
	t_5

Formulae

Laminar heat transfer coefficient

$$h_{lx} = 0.332 \frac{k}{x} Pr^{1/3} R_{ex}^{1/2}$$

Turbulent heat transfer coefficient

$$h_{tx} = 0.0073 R_{ex}^{-0.211} C_p e^{U_\infty}$$

Prandtl number

Reynolds number

$$Pr = \frac{C_p \mu}{k}$$

$$R_{ex} = \frac{U_\infty x}{\mu}$$

Heat flow out of blade from heater

$$q_o = - h_{lx} (t_\infty - t_1) \quad (1) \quad (\text{Ref.15}) \text{pp.477}$$

Heat flow into blade from heater then out of blade aft of de-icer

$$q_{in} = - h_{tx} (t_\infty - t_5) \quad (2)$$

Overall heat transfer coefficient out of blade from heater

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{x_i}{k_i} + \frac{x_{n.o}}{k_n}$$

$$U_o = \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \quad (3)$$

Overall heat transfer coefficient into blade then out of blade aft of de-icer

$$U_{in} = \frac{h_{in} k_a k_n}{k_a k_n + x_a h_{in} k_n + x_{n.in} h_{in} k_a} \quad (4)$$

where h_{in} is the convective heat transfer coefficient aft, ie. when the heat energy emitted from the heater into the blade re-emerges out of the blade aft of the de-icer.

Using:

$$\begin{aligned} q &= -k \frac{dt}{dx} \\ q_o &= -\frac{k_i}{x_i} (t_1 - t_2) \\ t_1 &= t_2 - q_o \frac{x_i}{k_i} \end{aligned} \quad (5)$$

Similarly:

$$t_3 = t_2 + q_o \frac{x_{n.o}}{k_n} \quad (6)$$

Heat in:

$$\begin{aligned} q_{in} &= -\frac{k_n}{x_{n.in}} (t_4 - t_3) \\ t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \end{aligned} \quad (7)$$

Similarly:

$$t_5 = t_4 - q_{in} \frac{x_a}{k_a} \quad (8)$$

Total heater power output

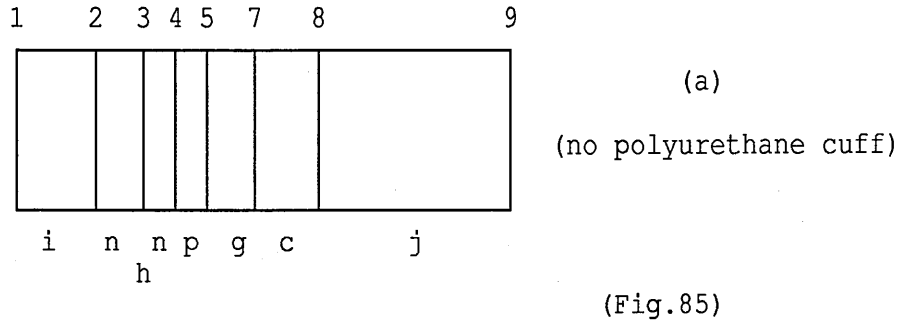
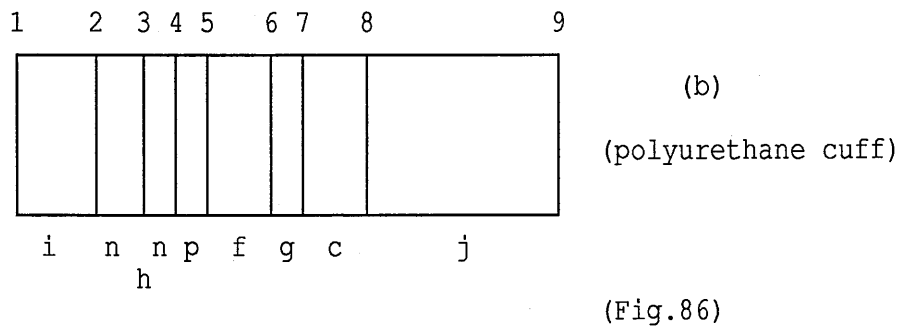
$$q_h = q_o + q_{in} \quad (9)$$

Ratio of heat out to heat in ie. measure of heater system power efficiency.

$$R_q = \frac{q_o}{q_h} \quad (10)$$

Case 2: Composite Propeller Blade

Blade Composition



i = ice n = neoprene h = heater p = polyurethane paint
 f = foam cuff g = glass/resin c = carbon/resin
 j = foam core

(Fig.85) shows the construction of the sample composite blade as it exists between radii 750 mm and 890 mm. In this area the blade does not possess the polyurethane foam cuff, as is the case inboard of 750 mm. The cuff is fitted to the blade between the glass fibre and spray polyurethane layers, as in (Fig.86). The composite blade is fitted with a standard neoprene de-icing boot similar to that used on the metal blade.

Stations

1. Ice/air interface.
2. Ice/neoprene interface.
3. Electric heater matrix.
4. Neoprene/polyurethane interface.
5. (a). Polyurethane/glass fibre-epoxy resin interface.
 (b). Polyurethane/polyurethane foam cuff interface.
6. Polyurethane foam cuff/glass fibre-epoxy resin interface.

7. Glass fibre-epoxy resin/carbon fibre-epoxy resin interface.
8. Carbon fibre-epoxy resin/polyurethane foam core interface.
9. Polyurethane foam core centre.

gf = glass fibres cf = carbon fibres

g/r = glass fibre matrix resin

c/r = carbon fibre matrix resin

Constants

$$k_{23} = k_{34} = k_n$$

$$t_1 < t_2 < t_3 \quad t_3 > t_4 > t_5 > t_6 > t_7 > t_8 > t_9$$

$$k_n = 0.15 \text{ Wm}^{-1}\text{K}^{-1}$$

$$x_{n.in} = 1.016 \text{ mm}$$

$$x_{n.o} = 1.800 \text{ mm}$$

$$k_i = 2.30 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_g = 0.34 \text{ Wm}^{-1}\text{K}^{-1}$$

$$x_p = 0.381 \text{ mm}$$

$$k_f = 0.03 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_c = 1.00 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_{gf} = 1.0 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_p = 1.09 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_j = 0.02 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_{cf} = 5.0 \text{ Wm}^{-1}\text{K}^{-1}$$

$$t_2 = 273 \text{ K } (0^\circ\text{C})$$

$$k_{g/r} = 0.515 \text{ Wm}^{-1}\text{K}^{-1}$$

$$k_{c/r} = 1.25 \text{ Wm}^{-1}\text{K}^{-1}$$

Formulae

Formulae (1)-(3), (5)-(7), (9) and (10) are as for the metal blade, whereas (4) and (8) differ according to the individual case characteristics.

From Case 1

$$q_o = - h_{lx} (t_\infty - t_1) \quad (1)$$

$$q_{in} = - h_{tx} (t_\infty - t_9) \quad (2)$$

$$U_o = \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \quad (3)$$

$$t_1 = t_2 - q_o \frac{x_i}{k_i} \quad (5)$$

$$t_3 = t_2 + q_o \frac{x_{n.o}}{k_n} \quad (6)$$

$$t_4 = t_3 - q_{in} \frac{x_{n.in}}{k_n} \quad (7)$$

$$q_h = q_o + q_{in} \quad (9)$$

$$R_q = \frac{q_o}{q_{in}} \quad (10)$$

$$\theta = \tan^{-1} \left[\frac{k_1}{k_2} \right] \quad (11)$$

The value of U_{in} is dependent on the blade composition beneath the de-icer heater matrix and the path taken by the heat energy flow. If a state of equilibrium is to be assumed, as it is for the purposes of these estimative calculations, then it must be assumed that within each two-dimensional blade section all heat energy transmitted from the de-icer into the blade leaves the blade into the airflow. Thus it follows that the heat energy flowing from the de-icer, as in the metal blade case, must deviate in direction to eventually follow a path which takes it out of the blade. Considering the blade section geometry with the de-icing system wrapped around the leading edge, as on the metal blade, the heat energy must flow aft to areas of lower temperature and hence also not cross the core foam body.

A second influence on the heat energy to flow aft within a laminate layer as mentioned earlier is the anisotropic thermal properties of the fibre/resin layers, having a greater value of thermal conductivity along the fibres than across them perpendicular to the laminate. For the purposes of this simplistic approach, only the line representing the mean streamline of the heat flow is considered, ie. no consideration of diffusivity is made.

Considering heat energy transmitted from the de-icer element into the blade at points not very close to the de-icer element trailing edge, ie. upstream of the de-icer trailing edge, then due to the surrounding presence of the de-icer, this energy will be encouraged to flow initially perpendicularly into the blade. This path will then be able to deviate according to the relative thermal properties of the materials, as described above. Once sufficiently clear of the de-icer, then the differential temperature will dictate the direction of flow. This will take an aftward course.

17.4 Sample Calculations

Case 1 : Metal Propeller Blade

Case 1.1

A point on the leading edge at the spanwise tip of the de-icer under 5.0 mm of ice.

$$OAT = 253K \text{ } (-20^{\circ}C)$$

$$Radius = 890 \text{ mm } (53\%)$$

$$t_2 = 273K \text{ } (0^{\circ}C)$$

$$x_i = 5.0 \text{ mm}$$

$$k_A = 0.026 \text{ Wm}^{-1}\text{K}^{-1}$$

$$x_a = 65.0 \text{ mm}$$

$$\mu = 1.783 \times 10^{-5} \text{ kgm}^{-1}\text{s}^{-1}$$

$$\rho = 1.2256 \text{ kgm}^{-3}$$

$$v = (s^2 + \frac{(2.\pi.r.\omega)}{3600})^{0.5} \quad (12)$$

$$= \left[140^2 + \frac{(2.\pi \times 0.890 \times 1331)^2}{3600} \right]^{0.5} \text{ ms}^{-1}$$

$$= \underline{187 \text{ ms}^{-1}}$$

$$a = (R.T.T)^{0.5} \quad (13)$$

$$= (287 \times 1.4 \times 253)^{0.5} \text{ ms}^{-1}$$

$$= \underline{318.8 \text{ ms}^{-1}}$$

$$M = \frac{v}{a} \quad (14)$$

$$= \frac{187}{318.8}$$

$$= \underline{0.59}$$

$$T = t \left[1 + \frac{(\tau - 1)M^2}{2} \right] \quad (15)$$

$$= 253 \left[1 + \frac{(1.4 - 1) \times 0.59^2}{2} \right] \text{ K}$$

$$= \underline{270 \text{ K } (-3^\circ\text{C})} \quad (T_{\infty, \text{fwd}})$$

As a true stagnation is not constantly achieved,
assume $x = 1.0 \text{ mm}$ for calculation of h_{1x}

$$\begin{aligned} R_{\text{ex}} &= \frac{1.2256 \times 187 \times 1.0 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 1.0 \text{ mm}) \\ &= \underline{1.285 \times 10^4} \quad (R_{\text{ex.o}}) \end{aligned}$$

$$\begin{aligned} h_{1x} &= 0.332 \times \frac{k}{x} \times \text{Pr}^{1/3} \times R_{\text{ex}}^{0.5} \\ &= 0.332 \times \frac{2.6 \times 10^{-2}}{1.0 \times 10^{-3}} \times 0.689^{1/3} \times (1.285 \times 10^4)^{0.5} \\ &= \underline{864.4 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o) \end{aligned}$$

$$\begin{aligned} (3) \quad U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\ &= \frac{864.4 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 864.4 \times 0.15 + 0.0018 \times 864.4 \times 2.30} \\ &= \underline{65.23 \text{ Wm}^{-2}\text{K}^{-1}} \end{aligned}$$

At point where heat energy leaves blade assume $x = 50 \text{ mm}$ ie. aft of de-icer trailing edge.

$$\begin{aligned} R_{\text{ex}} &= \frac{1.2256 \times 187.0 \times 50 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 50.0 \text{ mm}) \\ &= \underline{6.427 \times 10^5} \quad (R_{\text{ex.in}}) \end{aligned}$$

$$h_{tx} = 0.0073 R_{\text{ex}}^{-0.211} C_p e^V$$

$$h_{tx} = 0.0073 \times (6.427 \times 10^5)^{-0.211} \times 1005 \times 1.2256 \times 187$$

$$= \underline{100.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{in})$$

from (4)

$$U_{in} = \frac{h_{in} k_a k_n}{k_a k_n + x_a h_{in} k_n + x_{n.in} h_{in} k_a}$$

$$= \frac{100.0 \times 18.00 \times 0.15}{18.0 \times 0.15 + 0.065 \times 100.0 \times 0.15 + 0.001016 \times 100.0 \times 18.0}$$

$$= \underline{49.07 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$t_3 = \frac{U_o t_{\infty} x_{n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}}$$

$$= \frac{65.23 \times 270.0 \times 1.8 \times 10^{-3} - 273 \times 0.15}{65.23 \times 1.8 \times 10^{-3} - 0.15} \text{ K}$$

$$= \underline{283.3 \text{ K (10.3}^\circ\text{C)}} \quad (t_h)$$

$$q_o = - U_o (t_{\infty} - t_3)$$

$$= - 65.23 (270.0 - 283.3) \text{ Wm}^{-2}$$

$$= \underline{0.901 \text{ kWm}^{-2}}$$

$$t_1 = t_2 - q_o \frac{x_i}{k_i}$$

$$= 273 - 900.7 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K}$$

$$= \underline{271.0 \text{ K (-2.0}^\circ\text{C)}} \quad (t_{i/a})$$

$$q_{in} = - U_{in} (t_{\infty} - t_3)$$

$$= - 49.07 (253 - 283.8) \text{ Wm}^{-2}$$

$$= \underline{1.511 \text{ kWm}^{-2}}$$

therefore

$$\begin{aligned}q_h &= 0.901 + 1.511 \text{ kWm}^{-2} \\&= \underline{2.412 \text{ kWm}^{-2}}\end{aligned}$$

and

$$\begin{aligned}R_q &= \frac{0.901}{2.412} \\&= \underline{0.37}\end{aligned}$$

$$\begin{aligned}t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\&= 283.8 - 1.511 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\&= \underline{273.6 \text{ K } (0.6^\circ\text{C})} \quad (t_{n/al})\end{aligned}$$

Surface temperature

$$\begin{aligned}t_5 &= t_4 - q_{in} \frac{x_a}{k_a} \\&= 273.6 - 1.511 \times 10^3 \times \frac{65.0 \times 10^{-3}}{18.00} \\&= \underline{268.1 \text{ K } (-4.9^\circ\text{C})} \quad (t_{al/a})\end{aligned}$$

Check

$$\begin{aligned}h_{tx} &= - \frac{q_{in}}{(t_\infty - t_5)} \\&= \frac{1.511 \times 10^3}{253 - 268.1} \text{ Wm}^{-2}\text{K}^{-1} \\&= \underline{100.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{in})\end{aligned}$$

Case 1.2

A point on the de-icer upper surface within the laminar flow boundary layer 15.0 mm aft of the leading edge, having an ice accretion thickness of 5.0 mm.

Assume the path within the metal is 60.0 mm to a point on the upper blade surface 50.0 mm aft of the leading edge.

$$\text{OAT} = 253 \text{ K} \quad (-20^\circ\text{C}) \quad x_i = 5.0 \text{ mm}$$

$$t_2 = 273 \text{ K} \quad (0^\circ\text{C}) \quad x_a = 60.0 \text{ mm}$$

$$r = 890 \text{ mm}$$

$$R_{\text{ex}} = \frac{\rho U_\infty x}{\mu}$$

at $x = 15.0 \text{ mm}$

$$\begin{aligned} R_{\text{ex}} &= \frac{1.2256 \times 187.0 \times 15.0 \times 10^{-3}}{1.783 \times 10^{-5}} \\ &= \underline{1.928 \times 10^5} \end{aligned} \quad (R_{\text{ex.o}})$$

$$\begin{aligned} \text{Pr} &= \frac{C_{pu}}{k} \\ &= \frac{1.005 \times 10^3 \times 1.783 \times 10^{-5}}{2.6 \times 10^{-2}} \\ &= \underline{0.689} \end{aligned}$$

$$\begin{aligned} h_{lx} &= 0.332 \frac{k}{x} \text{Pr}^{1/3} R_{\text{ex}}^{0.5} \\ &= 0.332 \times \frac{2.6 \times 10^{-2}}{15.0 \times 10^{-3}} \times 0.689^{1/3} \times (1.928 \times 10^5)^{0.5} \\ &= \underline{223.2 \text{ Wm}^{-2}\text{K}^{-1}} \end{aligned} \quad (h_o)$$

at $x = 50.0 \text{ mm}$

$$h_{tx} = \underline{100.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (\text{from Case 1.1}) \quad (h_{in})$$

from (3)

$$U_o = \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i}$$

$$U_o = \frac{223.2 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 223.2 \times 0.15 + 0.00180 \times 223.2 \times 2.30}$$
$$= \underline{53.61 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$q_o = - U_o (t_\infty - t_3)$$

but

$$q_o = - \frac{k_{n.o}}{x_{n.o}} (t_2 - t_3)$$

therefore

$$U_o (t_3 - t_\infty) = \frac{k_{n.o}}{x_{n.o}} (t_3 - t_2)$$

$$t_3 \left[U_o - \frac{k_{n.o}}{x_{n.o}} \right] = \frac{U_o t_\infty - t_2 \frac{k_{n.o}}{x_{n.o}}}{U_o - \frac{k_{n.o}}{x_{n.o}}}$$

$$t_3 = \frac{U_o t_\infty x_{n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}}$$

$$= \frac{53.61 \times 253 \times 1.8 \times 10^{-3} - 273 \times 0.15}{53.61 \times 1.8 \times 10^{-3} - 0.15} \text{ K}$$

$$= \underline{309.1 \text{ K (36.1 } ^\circ\text{C)}} \quad (t_h)$$

$$q_o = - U_o (t_\infty - t_3)$$

$$= - 53.61 (253 - 309.1) \text{ Wm}^{-2}$$

$$= \underline{3.006 \text{ kWm}^{-2}}$$

$$(5) \quad t_1 = t_2 - q_o \frac{x_i}{k_i}$$

$$= 273 - 3.006 \times 10^3 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K}$$

$$= \underline{266.5 \text{ K (-6.5} ^\circ\text{C)}} \quad (t_{i/a})$$

Check

$$\begin{aligned} q_o &= - h_o (t_\infty - t_1) \\ &= - 223.2 (253 - 266.5) \text{ Wm}^{-2} \\ &= \underline{3.010 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (4) \quad U_{in} &= \frac{h_{in} k_a k_n}{k_a k_n + x_a h_{in} k_n + x_{n.in} h_{in} k_a} \\ &= \frac{100.0 \times 18.00 \times 0.15}{18.00 \times 0.15 + 0.060 \times 100.0 \times 0.15 + 0.001016 \times 100.0 \times 18.00} \\ &= \underline{49.75 \text{ Wm}^{-2} \text{K}^{-1}} \end{aligned}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_\infty - t_3) \\ &= 49.75 (253 - 309.1) \\ &= \underline{2.791 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 309.1 - 2.791 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{290.2 \text{ K (17.2}^\circ\text{C)}} \quad (t_{n/al}) \end{aligned}$$

$$\begin{aligned} (8) \quad t_5 &= t_4 - q_{in} \frac{x_a}{k_a} \\ &= 290.2 - 2.791 \times 10^3 \times \frac{60.0 \times 10^{-3}}{18.00} \text{ K} \\ &= \underline{280.9 \text{ K (7.9}^\circ\text{C)}} \quad (t_{al/a}) \end{aligned}$$

$$\begin{aligned} (9) \quad q_h &= 3.006 + 2.791 \text{ kWm}^{-2} \\ &= \underline{5.797 \text{ kWm}^{-2}} \end{aligned}$$

$$(10) \quad R_q = \frac{q_o}{q_h}$$

$$R_q = \frac{3.006}{5.797}$$

$$= \underline{0.52}$$

Case 1.3

A point close to the stagnation point (5.0 mm aft) where a stagnation temperature rise of 10 K (10°C) is assumed, ie. effective t_{∞} forward is 263 K, having accreted 2.0 mm of ice.

$$\text{OAT} = 253 \text{ K} \quad (-20^{\circ}\text{C}) \quad x_a = 60.0 \text{ mm}$$

$$t_{\infty} = 263 \text{ K} \quad (-10^{\circ}\text{C}) \quad x_i = 2.0 \text{ mm}$$

$$t_2 = 273 \text{ K} \quad (0^{\circ}\text{C}) \quad r = 890 \text{ mm}$$

$$(15) \quad T = t \left[1 + \frac{(\tau - 1)}{2} M^2 \right]$$

$$M = \left[\frac{2}{(\tau - 1)} \left[\frac{T}{t} - 1 \right] \right]^{0.5}$$

$$= \left[\frac{2}{1.4 - 1} \left[\frac{263}{253} - 1 \right] \right]^{0.5}$$

$$= \underline{0.445}$$

$$(13) \quad a = (R\tau T)^{0.5}$$

$$= \underline{318.8 \text{ ms}^{-1}} \quad (\text{from Case 1.1})$$

therefore

$$v = 318.8 \times 0.445 \text{ ms}^{-1}$$

$$= \underline{141.7 \text{ ms}^{-1}}$$

$$R_{ex} = \frac{\rho U_{\infty x}}{\mu}$$

$$= \frac{1.2256 \times 141.7 \times 5.0 \times 10^{-3}}{1.783 \times 10^{-5}}$$

$$= \underline{4.870 \times 10^4}$$

($R_{ex.o}$)

$$\begin{aligned} \text{Pr} &= \frac{C_{pu}}{k} \\ &= \underline{0.689} \quad (\text{from Case 1.2}) \end{aligned}$$

$$\begin{aligned} h_{lx} &= 0.332 \frac{k}{x} \text{Pr}^{1/3} \text{Re}_x^{0.5} \\ &= 0.332 \times \frac{2.6 \times 10^{-2}}{5.0 \times 10^{-3}} \times 0.689^{1/3} \times (4.870 \times 10^4)^{0.5} \\ &= \underline{336.5 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o) \end{aligned}$$

at $x = 50.0 \text{ mm}$

$$\underline{h_{tx} = 100.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (\text{from Case 1.1}) \quad (h_{in})$$

$$\begin{aligned} (3) \quad U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\ &= \frac{336.5 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 336.5 \times 0.15 + 0.0018 \times 336.5 \times 2.30} \\ &= \underline{58.32 \text{ Wm}^{-2}\text{K}^{-1}} \end{aligned}$$

$$\begin{aligned} (4) \quad U_{in} &= \frac{h_{in} k_a k_n}{k_a k_n + x_a h_{in} k_n + x_{n.in} h_{in} k_a} \\ &= \frac{100.0 \times 18.00 \times 0.15}{18.00 \times 0.15 + 0.060 \times 100.0 \times 0.15 + 0.001016 \times 100.0 \times 18.00} \\ &= \underline{49.75 \text{ Wm}^{-2}\text{K}^{-1}} \end{aligned}$$

$$\begin{aligned} t_3 &= \frac{U_o t_{\infty n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \quad (\text{from Case 1.2}) \\ &= \frac{58.32 \times 263.0 \times 1.8 \times 10^{-3} - 273 \times 0.15}{58.32 \times 1.8 \times 10^{-3} - 0.15} \\ &= \underline{296.3 \text{ K } (23.3^\circ\text{C})} \quad (t_h) \end{aligned}$$

$$\begin{aligned} q_o &= - U_o (t_\infty - t_3) \\ &= - 58.32 (263 - 296.3) \text{ Wm}^{-2} \\ &= \underline{1.942 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_\infty - t_3) \\ &= - 49.75 (263 - 296.3) \text{ Wm}^{-2} \\ &= \underline{1.657 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 296.3 - 1.657 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \\ &= \underline{285.1 \text{ K } (12.1^\circ\text{C})} \quad (t_{n/al}) \end{aligned}$$

$$\begin{aligned} (8) \quad t_5 &= t_4 - q_{in} \frac{x_a}{k_a} \\ &= 285.1 - 1.657 \times 10^3 \times \frac{60.0 \times 10^{-3}}{18.00} \text{ K} \\ &= \underline{279.6 \text{ K } (6.6^\circ\text{C})} \quad (t_{al/a}) \end{aligned}$$

$$\begin{aligned} (9) \quad q_h &= 1.942 + 1.657 \text{ kWm}^{-2} \\ &= \underline{3.599 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (10) \quad R_q &= \frac{q_o}{q_h} \\ &= \frac{1.942}{3.599} \\ &= \underline{0.54} \end{aligned}$$

$$\begin{aligned} t_1 &= t_2 - q_o \frac{x_i}{k_i} \\ &= 273 - 1.942 \times 10^3 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K} \\ &= \underline{268.8 \text{ K } (-4.2^\circ\text{C})} \quad (t_{i/a}) \end{aligned}$$

Case 1.4

As case 1.3 but with 10.0 mm of ice.

from Case 1.3

$$t_{\infty} = 263 \text{ K } (-10^{\circ}\text{C}) \quad x_a = 60.0 \text{ mm}$$

$$t_2 = 273 \text{ K } (0^{\circ}\text{C}) \quad x_i = 10.0 \text{ mm}$$

$$r = 890 \text{ mm}$$

$$\underline{v = 141.7 \text{ ms}^{-1}}$$

$$\underline{R_{ex} = 4.870 \times 10^5} \quad (R_{ex.o})$$

$$\underline{Pr = 0.689}$$

$$\underline{h_{lx} = 336.5 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o)$$

$$\underline{h_{tx} = 100.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{in})$$

$$\underline{U_{in} = 49.75 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$(3) \quad U_o = \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i}$$

$$= \frac{336.5 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.010 \times 336.5 \times 0.15 + 0.0018 \times 336.5 \times 2.30}$$

$$= \underline{51.76 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$t_3 = \frac{U_o t_{\infty} x_{n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}}$$

$$= \frac{51.76 \times 263.0 \times 1.8 \times 10^{-3} - 273 \times 0.15}{51.76 \times 1.8 \times 10^{-3} - 0.15} \text{ K}$$

$$= \underline{289.4 \text{ K } (16.4^{\circ}\text{C})} \quad (t_h)$$

$$\begin{aligned}q_o &= - (t_\infty - t_3) \\&= - 51.76 (263 - 289.4) \text{ Wm}^{-2} \\&= \underline{1.366 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}q_{in} &= - U_{in} (t_\infty - t_3) \\&= - 49.75 (263 - 289.4) \text{ Wm}^{-2} \\&= \underline{1.313 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}(7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\&= 289.4 - 1.313 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\&= \underline{280.5 \text{ K (7.5}^\circ\text{C)}} \quad (t_{n/al})\end{aligned}$$

$$\begin{aligned}(8) \quad t_5 &= t_4 - q_{in} \frac{x_a}{k_a} \\&= 280.5 - 1.313 \times 10^3 \times \frac{60.0 \times 10^{-3}}{18.00} \text{ K} \\&= \underline{276.1 \text{ K (3.1}^\circ\text{C)}} \quad (t_{al/a})\end{aligned}$$

$$\begin{aligned}q_h &= 1.366 + 1.313 \text{ kWm}^{-2} \\&= \underline{2.679 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}R_q &= \frac{q_o}{q_h} \\&= \frac{1.366}{2.679} \\&= \underline{0.51}\end{aligned}$$

$$\begin{aligned}t_1 &= t_2 - q_o \frac{x_i}{k_i} \\&= 273 - 1.366 \times 10^3 \times \frac{10.0 \times 10^{-3}}{2.30} \text{ K} \\&= \underline{267.1 \text{ K (-5.9}^\circ\text{C)}} \quad (t_{i/a})\end{aligned}$$

Case 1.5

A point on the de-icer in the turbulent boundary layer, ie. near the trailing edge of the de-icer, under 5.0 mm of ice in a situation where heat energy passes through the blade and exits aft of the de-icer such that the blade metal surface temperature is 0°C.

Assume the point is 40.0 mm downstream of the leading edge over the upper surface, and the thermal track within the blade metal is 25.0 mm.

$$\begin{aligned} \text{OAT} &= 253 \text{ K } (-20^\circ\text{C}) & x_a &= 25.0 \text{ mm} & r &= 890 \text{ mm} \\ & & x_i &= 5.0 \text{ mm} & t_5 &= 273 \text{ K } (0^\circ\text{C}) \\ & \text{(at } x = 40.0 \text{ mm)} & & & & \end{aligned}$$

$$\begin{aligned} R_{\text{ex}} &= \frac{\rho U_\infty x}{\mu} \\ &= \frac{1.2256 \times 187.0 \times 40.0 \times 10^{-3}}{1.783 \times 10^{-5}} \\ &= 5.142 \times 10^5 \quad (R_{\text{ex.o}}) \end{aligned}$$

$$\begin{aligned} \text{(out)} \quad h_{\text{tx}} &= 0.0073 R_{\text{ex}}^{-0.211} C_p \rho^v \\ &= 0.0073 \times (5.142 \times 10^5)^{-0.211} \times 1005 \times 1.2256 \times 187 \\ &= 104.9 \text{ Wm}^{-2}\text{K}^{-1} \quad (h_o) \end{aligned}$$

from Case 1.1

$$\text{(in)} \quad \underline{h_{\text{tx}} = 100.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{\text{in}})$$

$$\begin{aligned} \text{(3)} \quad U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\ &= \frac{104.9 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 104.9 \times 0.15 + 0.0018 \times 104.9 \times 2.30} \\ &= 42.18 \text{ Wm}^{-2}\text{K}^{-1} \end{aligned}$$

$$\text{(4)} \quad U_{\text{in}} = \frac{h_{\text{in}} k_a k_n}{k_a k_n + x_a h_{\text{in}} k_n + x_{n.\text{in}} h_{\text{in}} k_a}$$

$$U_{in} = \frac{100.0 \times 18.00 \times 0.15}{18.00 \times 0.15 + 0.025 \times 100.0 \times 0.15 + 0.001016 \times 100.0 \times 18.00}$$
$$= \underline{55.07 \text{ W m}^{-2} \text{K}^{-1}}$$

$$q_{in} = - h_{in} (t_{\infty} - t_5)$$
$$= - 100.0 (253 - 273) \text{ Wm}^{-2}$$
$$= \underline{2.001 \text{ kWm}^{-2}}$$

$$q_{in} = - U_{in} (t_{\infty} - t_3)$$

$$t_3 = \frac{q_{in}}{U_{in}} + t_{\infty}$$
$$= \frac{2.001 \times 10^3}{55.07} + 253$$
$$= \underline{289.3 \text{ K (16.3}^{\circ}\text{C)}} \quad (t_h)$$

$$t_4 = t_3 - q_{in} \frac{x_{n.in}}{k_n}$$
$$= 289.3 - 2.001 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15}$$
$$= \underline{275.8 \text{ K (2.8}^{\circ}\text{C)}} \quad (t_{n/al})$$

$$(8) \quad t_5 = t_4 - q_{in} \frac{x_a}{k_a}$$
$$= 275.8 - 2.001 \times 10^3 \times \frac{25.0 \times 10^{-3}}{18.00} \text{ K}$$
$$= \underline{273.0 \text{ K (0.0}^{\circ}\text{C)}} \quad (t_{al/a})$$

$$q_o = - U_o (t_{\infty} - t_3)$$
$$= - 42.18 (253 - 289.3) \text{ Wm}^{-2}$$
$$= \underline{1.531 \text{ kWm}^{-2}}$$

$$\begin{aligned} q_h &= q_o + q_{in} \\ &= 1.531 + 2.001 \text{ kWm}^{-2} \\ &= \underline{3.532 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} R_q &= \frac{q_o}{q_h} \\ &= \frac{1.531}{3.532} \\ &= \underline{0.43} \end{aligned}$$

$$\begin{aligned} t_2 &= t_3 - q_o \frac{x_{n.o}}{k_{n.o}} \\ &= 289.3 - 1.531 \times 10^3 \times \frac{1.8 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{270.9 \text{ K } (-2.1 \text{ } ^\circ\text{C})} \quad (t_{n/i}) \end{aligned}$$

$$\begin{aligned} t_1 &= \frac{q_o}{h_o} + t_\infty \\ &= \frac{1.531 \times 10^3}{104.9} + 253 \text{ K} \\ &= \underline{267.6 \text{ K } (-5.4 \text{ } ^\circ\text{C})} \quad (t_{i/a}) \end{aligned}$$

$$\begin{aligned} \text{(out)} \quad h_{tx} &= - \frac{q_o}{(t_\infty - t_1)} \\ &= - \frac{1.531 \times 10^3}{(253 - 267.6)} \text{ Wm}^{-2}\text{K}^{-1} \\ &= \underline{104.9 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o) \end{aligned}$$

Composite Propeller Blade

Case 2

The value of U_{in} is dependent on the path taken by the heat energy from the heater, through the blade, to the blade upper surface aft of the de-icer. The thermal conductivity of the expanded polyurethane foam core is very much less than that of the carbon/resin spar :-

$$\frac{k_f}{k_c} = 0.03$$

therefore it is reasonable to assume that the magnitude of heat energy transmitted into the foam core from the heater is negligible. Hence it is assumed that any heat energy entering the carbon spar from the overlying glass/resin layer is conducted within the carbon layer and thence back into the overlying layers. In cases at radial stations where the carbon spar does not exist it is assumed that the heat energy is conducted away in the glass/resin layer as:

$$\frac{k_f}{k_g} = 0.08$$

As no account is taken of thermal diffusion in these estimations, it is assumed that the heat energy either passes through a layer or is conducted within it, ie. it is not shared between layers.

As mentioned earlier for a general case possessing a carbon spar, within the carbon/resin and glass/resin layers the thermal conductivity within the fibres is greater than across the fibres and resin.

using:

$$\Theta = \tan^{-1} \left[\frac{k_1}{k_2} \right]$$

for the glass/resin layer

$$\begin{aligned} k_1 &= k_{gf} \\ &= \underline{1.0 \text{ Wm}^{-1}\text{K}^{-1}} \end{aligned}$$

fill ratio of glass to resin = 50%

therefore

$$\begin{aligned} k_2 &= \frac{k_{gf} + k_{g/r}}{2} \\ &= \underline{\underline{\frac{1.0 + 0.515}{2} \text{ Wm}^{-1}\text{K}^{-1}}} \end{aligned}$$

$$= \underline{0.758 \text{ Wm}^{-1}\text{K}^{-1}}$$

therefore

$$\theta_{g/r} = \underline{52.9^\circ}$$

for carbon/resin layer

$$\begin{aligned} k_1 &= k_{cf} \\ &= \underline{5.0 \text{ Wm}^{-1}\text{K}^{-1}} \end{aligned}$$

therefore

$$\begin{aligned} k_2 &= \frac{5.0 + 1.25}{2} \text{ Wm}^{-1}\text{K}^{-1} \\ &= \underline{3.125 \text{ Wm}^{-1}\text{K}^{-1}} \end{aligned}$$

therefore

$$\theta_{c/r} = \underline{58.0^\circ}$$

Thus it can be seen that in a simplistic approach using a single streamline to represent the heat flow, the streamline will deviate from the normal to the layer by 53° for the glass/resin layer and 58° for the carbon/resin layer. Therefore, considering the glass/resin and carbon/resin layers together, the previous assumption that the heat flow into foam core is negligible is further justified.

From this approach, in all cases involving sections at blade radii where the carbon spar exists, heat energy flowing from the heater into the blade was assumed to flow perpendicularly through the layers as far as the mid thickness of the glass/resin layer. Thence it flows within the glass fibres of the glass/resin layer aft. It is then assumed to change direction to flow perpendicularly through the overlying layers toward the blade upper surface, to emerge out of the blade aft of the de-icer, aft of the blade leading edge.

Cases where the carbon fibre spar exists take a similar approach except that the heat energy is assumed to flow at an angle $\theta_{g/r}$

through the glass/resin layer followed by $\theta_{c/r}$ through the

carbon/resin layer as far as the layer mid thickness plane, whence it flows aft within the carbon fibres of the carbon/resin layer and eventually turns to flow perpendicularly out of the blade.

Case 2.1

A point on the leading edge at the spanwise tip of the de-icing boot, (ie. no polyurethane foam cuff), under 5.0 mm of ice. The carbon spar does not exist at this blade radius.

$$\begin{aligned} \text{OAT} &= 253 \text{ K } (-20^{\circ}\text{C}) & x_i &= 5.0 \text{ mm} \\ t_2 &= 273 \text{ K } (0^{\circ}\text{C}) & x_p &= 0.381 \text{ mm} \\ x_f &= 0.0 \text{ mm} & x_g &= 3.56 \text{ mm} \\ x_c &= 0.0 \text{ mm} & r &= 890 \text{ mm} \end{aligned}$$

Section G (Fig.94(a))

From 1.1

$$\underline{t_1 = 271.0 \text{ K } (-2.0^{\circ}\text{C})} \quad (t_{i/a})$$

and

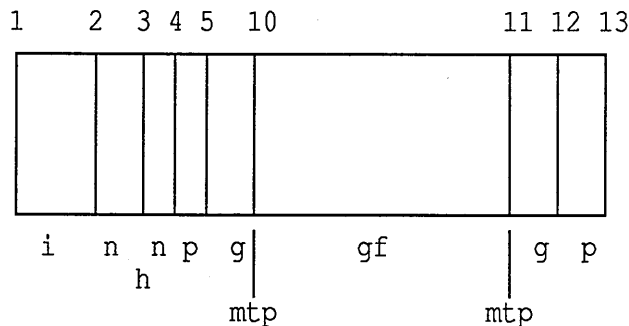
$$\underline{U_o = 65.23 \text{ Wm}^{-2}\text{K}^{-1}}$$

Assume as in Case 1.1 $x_{in} = 50.0 \text{ mm}$, ie. the heat energy leaves the blade at a point 50.0 mm aft of the blade leading edge at a point just aft of the de-icer trailing edge.

from Case 1.1

$$\begin{aligned} \underline{R_{ex} = 1.285 \times 10^4} & \quad (\text{at } x = 1.0 \text{ mm}) & (R_{ex.o}) \\ \underline{h_{1x} = 864.4 \text{ Wm}^{-2}\text{K}^{-1}} & \quad (\text{at } x = 1.0 \text{ mm}) & (h_o) \\ \underline{R_{ex} = 6.427 \times 10^5} & \quad (\text{at } x = 50.0 \text{ mm}) & (R_{ex.in}) \\ \underline{h_{tx} = 100.0 \text{ Wm}^{-2}\text{K}^{-1}} & \quad (\text{at } x = 50.0 \text{ mm}) & (h_{in}) \\ \underline{q_o = 0.901 \text{ kWm}^{-2}} & & \\ \underline{t_3 = 283.8 \text{ K } (10.8^{\circ}\text{C})} & & (t_h) \end{aligned}$$

mtp = mid thickness plane



(Fig.85(a))

Thermal path length travelled within glass/resin layer to the layer mid thickness plane at angle 53° to the normal.

$$x_{g1} = \frac{x_g}{2 \cos 52.9^\circ} \text{ m}$$

$$= \underline{2.951 \text{ mm}}$$

therefore

$$\frac{1}{U_{in}} = \frac{x_{n.in}}{k_n} + 2 \frac{x_p}{k_p} + 2 \frac{x_{g1}}{k_g} + \frac{40.0 \times 10^{-3}}{k_{gf}} + \frac{1}{h_{tx}}$$

$$= \frac{0.001016}{0.15} + 2 \times \frac{0.000381}{1.09} + 2 \times \frac{0.002951}{0.34} + \frac{0.040}{1.0} + \frac{1}{100.0}$$

$$= 0.075 \text{ W}^{-1} \text{ m}^2 \text{ K}$$

$$\underline{U_{in} = 13.36 \text{ Wm}^{-2} \text{ K}^{-1}}$$

$$q_{in} = - U_{in} (t_\infty - t_3)$$

$$= - 13.36 (253 - 283.8) \text{ Wm}^{-2}$$

$$= \underline{0.416 \text{ kWm}^{-2}}$$

$$q_h = q_o + q_{in}$$

$$= 0.416 + 0.901 \text{ kWm}^{-2}$$

$$= \underline{1.312 \text{ kWm}^{-2}}$$

$$R_q = \frac{q_o}{q_h}$$

$$= \frac{0.901}{1.312}$$

$$= \underline{0.69}$$

$$(7) \quad t_4 = t_3 - q_{in} \frac{x_{n.in}}{k_n}$$

$$= 283.8 - 416 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K}$$

$$\underline{t_4 = 281.0 \text{ K } (8.0^\circ\text{C})} \quad (t_{n/p})$$

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 281.0 - 416 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{281.0 \text{ K } (8.0^\circ\text{C})} \quad (t_{p/f}) \end{aligned}$$

$$\begin{aligned} t_{10} &= t_5 - q_{in} \frac{x_{g1}}{k_g} \\ &= 281.0 - 416 \times \frac{2.951 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{277.4 \text{ K } (4.4^\circ\text{C})} \quad (t_{g/gf}) \end{aligned}$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 277.4 - 416 \times \frac{40.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{260.7 \text{ K } (-12.3^\circ\text{C})} \quad (t_{gf/g}) \end{aligned}$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_{g1}}{k_g} \\ &= 260.7 - 416 \times \frac{2.951 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{257.1 \text{ K } (-15.9^\circ\text{C})} \quad (t_{g/p}) \end{aligned}$$

$$\begin{aligned} t_{13} &= t_{12} - q_{in} \frac{x_p}{k_p} \\ &= 257.1 - 416 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{257.0 \text{ K } (-16.0^\circ\text{C})} \quad (t_{p/a}) \end{aligned}$$

Check

$$\begin{aligned} t_{13} &= t_{\infty} + \frac{q_{in}}{h_{in}} \\ &= 253 + \frac{0.416 \times 10^3}{100.0} \text{ K} \\ &= \underline{257.1 \text{ K } (-15.9^{\circ}\text{C})} \end{aligned} \quad (t_{p/a})$$

Case 2.1.1

A point on the leading edge at the spanwise tip of the polyurethane foam cuff, under 5.0 mm of ice. The carbon spar does not exist at this radius.

$$OAT = 253 \text{ K } (-20^{\circ}\text{C})$$

$$x_i = 5.0 \text{ mm}$$

$$t_2 = 273 \text{ K } (0^{\circ}\text{C})$$

$$x_f = 1.00 \text{ mm}$$

$$r = 749 \text{ mm (Section F') (Fig.94(b))}$$

$$x_c = 0.0 \text{ mm}$$

$$x_g = 4.52 \text{ mm}$$

$$x_p = 0.381 \text{ mm}$$

$$(15) \quad v = \left[140^2 + \frac{(2.\pi \times 0.749 \times 1331)^2}{3600} \right]^{0.5} \text{ ms}^{-1}$$

$$= \underline{175 \text{ ms}^{-1}}$$

$$\text{From 1.1} \quad \underline{a = 318.8 \text{ ms}^{-1}}$$

$$(17) \quad M = \frac{175}{318.8}$$

$$= \underline{0.55}$$

$$(18) \quad T = 253 \left[1 + \frac{(1.4 - 1) \times 0.55^2}{2} \right] \text{ K}$$

$$= \underline{268 \text{ K } (-5^{\circ}\text{C})} \quad (t_{\infty.\text{fwd}})$$

$$R_{\text{ex}} = \frac{1.2256 \times 175 \times 1.0 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 1.0 \text{ mm})$$

$$= \underline{1.203 \times 10^4} \quad (R_{\text{ex.o}})$$

$$\begin{aligned}
 h_{tx} &= 0.0073 R_{ex}^{-0.211} C_p c^v \\
 &= 0.0073 \times (1.203 \times 10^4)^{-0.211} \times 1005 \times 1.2256 \times 175 \\
 &= \underline{216.7 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o)
 \end{aligned}$$

$$\begin{aligned}
 R_{ex} &= \frac{1.2256 \times 175 \times 50 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 50.0 \text{ mm}) \\
 &= \underline{6.015 \times 10^5} \quad (R_{ex.in})
 \end{aligned}$$

$$\begin{aligned}
 h_{tx} &= 0.0073 R_{ex}^{-0.211} C_p c^v \\
 &= 0.0073 \times (6.015 \times 10^5)^{-0.211} \times 1005 \times 1.2256 \times 175 \\
 &= \underline{94.9 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{in})
 \end{aligned}$$

$$\begin{aligned}
 U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\
 &= \frac{216.7 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 216.7 \times 0.15 + 0.0018 \times 216.7 \times 2.30} \\
 &= \underline{53.22 \text{ Wm}^{-2}\text{K}^{-1}}
 \end{aligned}$$

$$\begin{aligned}
 t_3 &= \frac{U_o t_{\infty n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \\
 &= \frac{53.22 \times 270.0 \times 1.8 \times 10^{-3} - 273 \times 0.15}{53.22 \times 1.8 \times 10^{-3} - 0.15} \\
 &= \underline{278.3 \text{ K } (5.3^\circ\text{C})} \quad (t_h)
 \end{aligned}$$

$$\begin{aligned}
 q_o &= - U_o (t_{\infty} - t_3) \\
 &= - 53.22 (270.0 - 278.3) \text{ Wm}^{-2} \\
 &= \underline{0.442 \text{ kWm}^{-2}}
 \end{aligned}$$

$$\begin{aligned}q_{in} &= - U_{in} (t_{\infty} - t_3) \\&= - 8.82 (253 - 278.3) \text{ Wm}^{-2} \\&= \underline{0.223 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}q_h &= q_o + q_{in} \\&= 0.442 + 0.223 \text{ kWm}^{-2} \\&= \underline{0.665 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}R_q &= \frac{q_o}{q_h} \\&= \frac{0.442}{0.665} \\&= \underline{0.66}\end{aligned}$$

$$\begin{aligned}(7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\&= 278.3 - 223 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\&= \underline{276.8 \text{ K (3.8}^\circ\text{C)}} \quad (t_{n/p})\end{aligned}$$

$$\begin{aligned}t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\&= 276.8 - 223 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\&= \underline{276.7 \text{ K (3.7}^\circ\text{C)}} \quad (t_{p/f})\end{aligned}$$

$$\begin{aligned}t_6 &= t_5 - q_{in} \frac{x_f}{k_f} \\&= 276.7 - 223 \times \frac{1.00 \times 10^{-3}}{0.03} \text{ K} \\&= \underline{269.3 \text{ K (-3.7}^\circ\text{C)}} \quad (t_{f/g})\end{aligned}$$

$$t_{10} = t_6 - q_{in} \frac{x_{g1}}{k_g}$$

$$\begin{aligned} t_{10} &= 269.3 - 223 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{266.8 \text{ K } (-6.2^{\circ}\text{C})} \end{aligned} \quad (t_{g/gf})$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 266.8 - 223 \times \frac{40.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{257.9 \text{ K } (-15.1^{\circ}\text{C})} \end{aligned} \quad (t_{gf/g})$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_g}{k_g} \\ &= 257.9 - 223 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{255.4 \text{ K } (-17.6^{\circ}\text{C})} \end{aligned} \quad (t_{g/p})$$

$$\begin{aligned} t_{13} &= t_{12} - q_{in} \frac{x_p}{k_p} \\ &= 255.4 - 223 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{255.4 \text{ K } (-17.6^{\circ}\text{C})} \end{aligned} \quad (t_{p/a})$$

Check

$$\begin{aligned} t_{13} &= t_{\infty} + \frac{q_{in}}{h_{in}} \\ &= 253 + \frac{0.223 \times 10^3}{94.9} \text{ K} \\ &= \underline{255.4 \text{ K } (-17.6^{\circ}\text{C})} \end{aligned} \quad (t_{p/a})$$

$$\frac{1}{U_{in}} = 0.080 \text{ W}^{-1}\text{m}^2\text{K}$$

$$U_{in} = 12.49 \text{ Wm}^{-2}\text{K}^{-1}$$

from (6)

$$t_3 = t_2 + q_o \frac{x_{n.o}}{k_n}$$

from Case 2.1.1 therefore

$$t_3 = 278.3 \text{ K (5.3}^\circ\text{C)}$$

$$\begin{aligned} q_{in} &= -U_{in} (t_\infty - t_3) \\ &= -12.49 (253 - 278.3) \text{ Wm}^{-2} \\ &= 0.316 \text{ kWm}^{-2} \end{aligned}$$

$$\begin{aligned} q_h &= q_o + q_{in} \\ &= 0.442 + 0.316 \text{ kWm}^{-2} \\ &= 0.758 \text{ kWm}^{-2} \end{aligned}$$

$$\begin{aligned} R_q &= \frac{q_o}{q_h} \\ &= \frac{0.442}{0.758} \\ &= 0.58 \end{aligned}$$

(7)

$$\begin{aligned} t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 278.3 - 316 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= 276.2 \text{ K (3.2}^\circ\text{C)} \end{aligned}$$

($t_{n/p}$)

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 276.2 - 316 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \end{aligned}$$

$$\underline{t_5 = 276.0 \text{ K } (3.0^\circ\text{C})} \quad (t_{p/g})$$

$$\begin{aligned} t_{10} &= t_5 - q_{in} \frac{x_{g1}}{k_g} \\ &= 276.0 - 316 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{272.6 \text{ K } (-0.4^\circ\text{C})} \quad (t_{g/gf}) \end{aligned}$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 272.6 - 316 \times \frac{40.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{259.9 \text{ K } (-13.1^\circ\text{C})} \quad (t_{gf/g}) \end{aligned}$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_g}{k_g} \\ &= 259.9 - 316 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{256.4 \text{ K } (-16.6^\circ\text{C})} \quad (t_{g/p}) \end{aligned}$$

$$\begin{aligned} t_{13} &= t_{12} - q_{in} \frac{x_p}{k_p} \\ &= 256.4 - 316 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{256.3 \text{ K } (-16.7^\circ\text{C})} \quad (t_{p/a}) \end{aligned}$$

Check

$$\begin{aligned} t_{13} &= t_\infty + \frac{q_{in}}{h_{in}} \\ t_{13} &= 253 + \frac{0.316 \times 10^3}{94.9} \text{ K} \\ &= \underline{256.3 \text{ K } (-16.7^\circ\text{C})} \quad (t_{p/a}) \end{aligned}$$

Case 2.2

A point 15.0 mm aft of the blade leading edge at the spanwise tip of the polyurethane foam cuff, under 5.0 mm of ice. The carbon spar does not exist at this blade radius.

$$\begin{array}{ll}
 \text{OAT} = 253 \text{ K } (-20^{\circ}\text{C}) & x_i = 5.0 \text{ mm} \\
 t_2 = 273 \text{ K } (0^{\circ}\text{C}) & x_p = 0.381 \text{ mm} \\
 x_f = 0.0 \text{ mm} & x_g = 4.52 \text{ mm} \\
 x_c = 0.00 \text{ mm} & r = 749 \text{ mm} \quad (\text{Section F'}) \\
 & (\text{Fig.94(b)})
 \end{array}$$

from Case 2.1.1

$$\begin{aligned}
 v &= 175 \text{ ms}^{-1} \\
 R_{\text{ex}} &= \frac{1.2256 \times 175 \times 15.0 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 15.0 \text{ mm}) \\
 &= \frac{1.804 \times 10^5}{(R_{\text{ex.o}})}
 \end{aligned}$$

from Case 1.2

$$\begin{aligned}
 \text{Pr} &= 0.689 \\
 h_{1x} &= 0.332 \times \frac{k}{x} \text{Pr}^{1/3} R_{\text{ex}}^{0.5} \\
 &= 0.332 \times \frac{2.6 \times 10^{-2}}{15.0 \times 10^{-3}} \times 0.689^{1/3} \times (1.804 \times 10^5)^{0.5} \\
 &= \frac{215.9 \text{ Wm}^{-2}\text{K}^{-1}}{(h_o)}
 \end{aligned}$$

from Case 2.1.1 at $x = 50.0 \text{ mm}$

$$h_{tx} = \frac{94.9 \text{ Wm}^{-2}\text{K}^{-1}}{(h_{in})}$$

$$\begin{aligned}
 U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\
 &= \frac{215.9 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 215.9 \times 0.15 + 0.00180 \times 215.9 \times 2.30} \\
 &= \frac{53.18 \text{ Wm}^{-2}\text{K}^{-1}}{}
 \end{aligned}$$

from case 1.2

$$\begin{aligned}
 t_3 &= \frac{U_o t_{\infty} x_{n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \\
 &= \frac{53.18 \times 253 \times 1.8 \times 10^{-3} - 273 \times 0.15}{53.18 \times 1.8 \times 10^{-3} - 0.15} \text{ K} \\
 &= \underline{308.2 \text{ K (36.1 } ^\circ\text{C)}} \quad (t_h)
 \end{aligned}$$

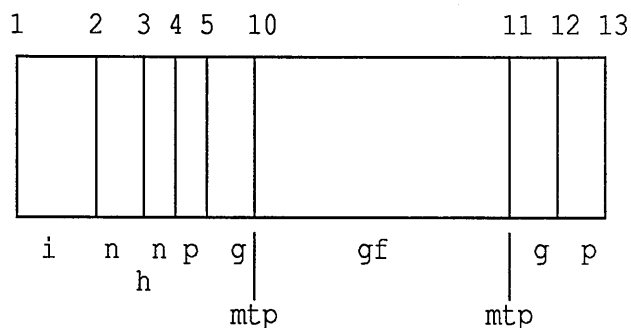
$$\begin{aligned}
 q_o &= - U_o (t_{\infty} - t_3) \\
 &= - 53.18 (253 - 308.2) \text{ Wm}^{-2} \\
 &= \underline{2.937 \text{ kWm}^{-2}}
 \end{aligned}$$

$$\begin{aligned}
 (5) \quad t_1 &= t_2 - q_o \frac{x_i}{k_i} \\
 &= 273 - 2.937 \times 10^3 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K} \\
 &= \underline{266.6 \text{ K (-6.4} ^\circ\text{C)}} \quad (t_{i/a})
 \end{aligned}$$

Check

$$\begin{aligned}
 q_o &= - h_o (t_{\infty} - t_1) \\
 &= - 215.9 (253 - 266.6) \text{ Wm}^{-2} \\
 &= \underline{2.939 \text{ kWm}^{-2}}
 \end{aligned}$$

mtp = mid thickness plane



(Fig.85(a))

from Case 2.1

$$x_{g1} = \underline{3.75 \times 10^{-3} \text{ m}}$$

$$U_{in} = \underline{12.49 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_{\infty} - t_3) \\ &= 12.49 (253 - 308.2) \\ &= \underline{0.689 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (9) \quad q_h &= 2.939 + 0.689 \text{ kWm}^{-2} \\ &= \underline{3.628 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (10) \quad R_q &= \frac{q_o}{q_h} \\ &= \frac{2.939}{3.628} \\ &= \underline{0.81} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 308.2 - 0.689 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{303.5 \text{ K (30.5}^\circ\text{C)}} \quad (t_{n/p}) \end{aligned}$$

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 303.5 - 689 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ \underline{t_5} &= \underline{303.3 \text{ K (30.3}^\circ\text{C)}} \quad (t_{p/g}) \end{aligned}$$

$$\begin{aligned} t_{10} &= t_5 - q_{in} \frac{x_{g1}}{k_g} \\ &= 303.3 - 689 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \end{aligned}$$

$$\underline{t_{10} = 295.7 \text{ K } (22.7^\circ\text{C})} \quad (t_{g/gf})$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 295.7 - 689 \times \frac{40.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{268.1 \text{ K } (-4.9^\circ\text{C})} \quad (t_{gf/g}) \end{aligned}$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_g}{k_g} \\ &= 268.1 - 689 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{260.5 \text{ K } (-12.5^\circ\text{C})} \quad (t_{g/p}) \end{aligned}$$

$$\begin{aligned} t_{13} &= t_{12} - q_{in} \frac{x_p}{k_p} \\ &= 260.5 - 689 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{260.3 \text{ K } (-12.7^\circ\text{C})} \quad (t_{p/a}) \end{aligned}$$

Check

$$\begin{aligned} t_{13} &= t_\infty + \frac{q_{in}}{h_{in}} \\ t_{13} &= 253 + \frac{0.689 \times 10^3}{94.9} \text{ K} \\ &= \underline{260.3 \text{ K } (-12.7^\circ\text{C})} \quad (t_{p/a}) \end{aligned}$$

Case 2.3

A point 5.0 mm aft of the blade leading edge where the stagnation temperature rise is assumed to be 10.0 K, at the spanwise tip of the polyurethane foam cuff, under 5.0 mm of ice.

$$\begin{array}{ll} \text{OAT} = 263 \text{ K } (-20^{\circ}\text{C}) & x_i = 5.0 \text{ mm} \\ t_2 = 273 \text{ K } (0^{\circ}\text{C}) & x_p = 0.381 \text{ mm} \\ x_f = 0.0 \text{ mm} & x_g = 4.52 \text{ mm} \\ x_c = 0.00 \text{ mm} & r = 749 \text{ mm} \quad (\text{Section F'}) \\ & (\text{Fig.94(b)}) \end{array}$$

from Case 1.3

$$\underline{v = 141.7 \text{ ms}^{-1}}$$

$$\begin{aligned} R_{\text{ex}} &= \frac{1.2256 \times 141.7 \times 5.0 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 5.0 \text{ mm}) \\ &= \underline{4.870 \times 10^4} \quad (R_{\text{ex.o}}) \end{aligned}$$

from Case 1.2

$$\begin{aligned} \underline{\text{Pr} = 0.689} \\ h_{1x} &= 0.332 \times \frac{k}{x} \text{Pr}^{1/3} R_{\text{ex}}^{0.5} \\ &= 0.332 \times \frac{2.6 \times 10^{-2}}{5.0 \times 10^{-3}} \times 0.689^{1/3} \times (4.870 \times 10^4)^{0.5} \\ &= \underline{336.5 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o) \end{aligned}$$

from Case 2.1.1 at $x = 50.0 \text{ mm}$

$$\underline{h_{tx} = 94.9 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{in})$$

$$\begin{aligned} U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\ &= \frac{336.5 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 336.5 \times 0.15 + 0.00180 \times 336.5 \times 2.30} \\ &= \underline{58.32 \text{ Wm}^{-2}\text{K}^{-1}} \end{aligned}$$

from case 1.2

$$\begin{aligned}
 t_3 &= \frac{U_o t_{\infty} x_{n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \\
 &= \frac{58.32 \times 263 \times 1.8 \times 10^{-3} - 273 \times 0.15}{58.32 \times 1.8 \times 10^{-3} - 0.15} \text{ K} \\
 &= \underline{296.3 \text{ K (23.3 } ^\circ\text{C)}} \quad (t_h)
 \end{aligned}$$

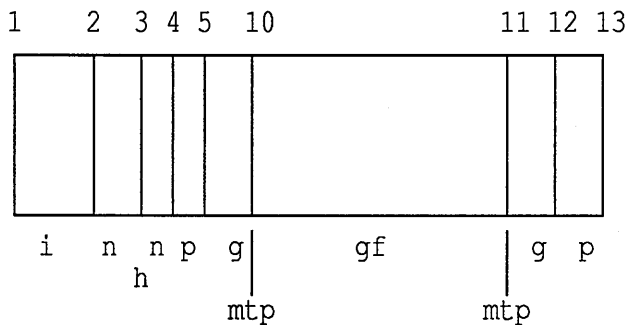
$$\begin{aligned}
 q_o &= - U_o (t_{\infty} - t_3) \\
 &= - 58.32 (263 - 296.3) \text{ Wm}^{-2} \\
 &= \underline{1.943 \text{ kWm}^{-2}}
 \end{aligned}$$

$$\begin{aligned}
 (5) \quad t_1 &= t_2 - q_o \frac{x_i}{k_i} \\
 &= 273 - 1.943 \times 10^3 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K} \\
 &= \underline{268.8 \text{ K (-4.8} ^\circ\text{C)}} \quad (t_{i/a})
 \end{aligned}$$

Check

$$\begin{aligned}
 q_o &= - h_o (t_{\infty} - t_1) \\
 &= - 336.5 (263 - 268.8) \text{ Wm}^{-2} \\
 &= \underline{1.943 \text{ kWm}^{-2}}
 \end{aligned}$$

mtp = mid thickness plane



(Fig.85(a))

from Case 2.1

$$x_{g1} = \underline{3.75 \times 10^{-3} \text{ m}}$$

$$\underline{U_{in} = 12.49 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_{\infty} - t_3) \\ &= 12.49 (253 - 296.3) \\ &= \underline{0.541 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (9) \quad q_h &= 1.943 + 0.541 \text{ kWm}^{-2} \\ &= \underline{2.484 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (10) \quad R_q &= \frac{q_o}{q_h} \\ &= \frac{1.943}{2.484} \\ &= \underline{0.78} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 296.3 - 0.541 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{292.6 \text{ K (19.6}^\circ\text{C)}} \quad (t_{n/p}) \end{aligned}$$

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 292.6 - 541 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ \underline{t_5} &= \underline{292.4 \text{ K (19.4}^\circ\text{C)}} \quad (t_{p/g}) \end{aligned}$$

$$\begin{aligned} t_{10} &= t_5 - q_{in} \frac{x_{g1}}{k_g} \\ &= 292.4 - 541 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{286.5 \text{ K (13.5}^\circ\text{C)}} \quad (t_{g/gf}) \end{aligned}$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 286.5 - 541 \times \frac{40.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{264.8 \text{ K } (-8.2^{\circ}\text{C})} \end{aligned} \quad (t_{gf/g})$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_{gl}}{k_g} \\ &= 264.8 - 541 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{258.9 \text{ K } (-14.1^{\circ}\text{C})} \end{aligned} \quad (t_{g/p})$$

$$\begin{aligned} t_{13} &= t_{12} - q_{in} \frac{x_p}{k_p} \\ &= 258.9 - 541 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{258.7 \text{ K } (-14.3^{\circ}\text{C})} \end{aligned} \quad (t_{p/a})$$

Check

$$\begin{aligned} t_{13} &= t_{\infty} + \frac{q_{in}}{h_{in}} \\ t_{13} &= 253 + \frac{0.541 \times 10^3}{94.9} \text{ K} \\ &= \underline{258.7 \text{ K } (-14.3^{\circ}\text{C})} \end{aligned} \quad (t_{p/a})$$

Case 2.4

A point 5.0 mm aft of the blade leading edge where the stagnation temperature rise is assumed to be 10.0 K, at the spanwise tip of the polyurethane foam cuff, under 10.0 mm of ice.

$$\begin{array}{ll}
 \text{OAT} = 263 \text{ K } (-20^{\circ}\text{C}) & x_i = 10.0 \text{ mm} \\
 t_2 = 273 \text{ K } (0^{\circ}\text{C}) & x_p = 0.381 \text{ mm} \\
 x_f = 0.0 \text{ mm} & x_g = 4.52 \text{ mm} \\
 x_c = 0.00 \text{ mm} & r = 749 \text{ mm} \quad \begin{array}{l} \text{(Section F')} \\ \text{(Fig.94(b))} \end{array}
 \end{array}$$

from Case 2.3

$$\begin{array}{lll}
 R_{\text{ex}} = 6.0156 \times 10^4 & (\text{at } x = 5.0 \text{ mm}) & (R_{\text{ex.in}}) \\
 h_{lx} = 336.5 \text{ Wm}^{-2}\text{K}^{-1} & & (h_o) \\
 h_{tx} = 94.9 \text{ Wm}^{-2}\text{K}^{-1} & & (h_{in})
 \end{array}$$

$$\begin{aligned}
 U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i} \\
 &= \frac{336.5 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.010 \times 336.5 \times 0.15 + 0.00180 \times 336.5 \times 2.30} \\
 &= 51.76 \text{ Wm}^{-2}\text{K}^{-1}
 \end{aligned}$$

from case 1.2

$$\begin{aligned}
 t_3 &= \frac{U_o t_{\infty n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \\
 &= \frac{51.76 \times 263 \times 1.8 \times 10^{-3} - 273 \times 0.15}{51.76 \times 1.8 \times 10^{-3} - 0.15} \text{ K} \\
 &= 289.4 \text{ K } (16.4^{\circ}\text{C}) \quad (t_h)
 \end{aligned}$$

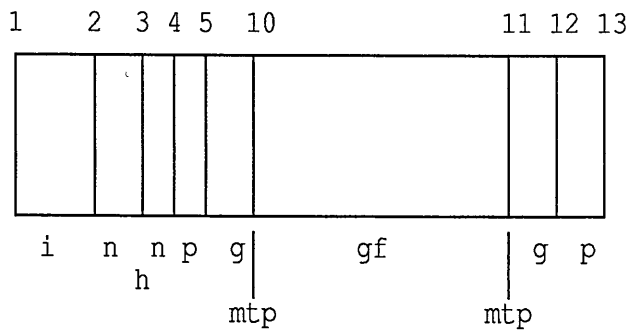
$$\begin{aligned} q_o &= - U_o (t_\infty - t_3) \\ &= - 51.76 (263 - 289.4) \text{ Wm}^{-2} \\ &= \underline{1.366 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (5) \quad t_1 &= t_2 - q_o \frac{x_i}{k_i} \\ &= 273 - 1.366 \times 10^3 \times \frac{10.0 \times 10^{-3}}{2.30} \text{ K} \\ &= \underline{267.1 \text{ K } (-5.9^\circ\text{C})} \quad (t_{i/a}) \end{aligned}$$

Check

$$\begin{aligned} q_o &= - h_o (t_\infty - t_1) \\ &= - 336.5 (263 - 267.1) \text{ Wm}^{-2} \\ &= \underline{1.366 \text{ kWm}^{-2}} \end{aligned}$$

mtp = mid thickness plane



(Fig.85(a))

from Case 2.1

$$\underline{x_{q1} = 3.75 \times 10^{-3} \text{ m}}$$

$$\underline{U_{in} = 12.49 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_\infty - t_3) \\ &= 12.49 (253 - 289.4) \\ &= \underline{0.455 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (9) \quad q_h &= 1.366 + 0.455 \text{ kWm}^{-2} \\ &= \underline{1.821 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (10) \quad R_q &= \frac{q_o}{q_h} \\ &= \frac{1.366}{1.821} \\ &= \underline{0.75} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 289.4 - 0.455 \times 10^3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{286.3 \text{ K (13.3}^\circ\text{C)}} \quad (n/p) \end{aligned}$$

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 286.3 - 455 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ t_5 &= \underline{286.2 \text{ K (13.2}^\circ\text{C)}} \quad (t_{p/g}) \end{aligned}$$

$$\begin{aligned} t_{10} &= t_5 - q_{in} \frac{x_{gl}}{k_g} \\ &= 286.2 - 455 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{281.1 \text{ K (8.1}^\circ\text{C)}} \quad (t_{g/gf}) \end{aligned}$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 281.1 - 455 \times \frac{40.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{262.9 \text{ K (-10.1}^\circ\text{C)}} \quad (t_{gf/g}) \end{aligned}$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_{g1}}{k_g} \\ &= 262.9 - 455 \times \frac{3.75 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{257.9 \text{ K } (-15.1^\circ\text{C})} \end{aligned} \quad (t_{g/p})$$

$$\begin{aligned} t_{13} &= t_{13} - q_{in} \frac{x_p}{k_p} \\ &= 257.9 - 455 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{257.8 \text{ K } (-15.2^\circ\text{C})} \end{aligned} \quad (t_{p/a})$$

Check

$$\begin{aligned} t_{13} &= t_\infty + \frac{q_{in}}{h_{in}} \\ t_{13} &= 253 + \frac{0.455 \times 10^3}{94.9} \text{ K} \\ &= \underline{257.8 \text{ K } (-15.2^\circ\text{C})} \end{aligned} \quad (t_{p/a})$$

Case 2.5

A point on the leading edge of the blade at section C (Fig.94(c)), under 5.0 mm of ice. Due to the section profile, the distance travelled in the glass fibres is estimated to be 60 mm instead of the 40 mm used in Case 2.3. The boundary layer Reynolds number is calculated at $x = 90$ mm, (measured over the surface). Although the carbon spar does not exist at the leading edge at this radial station it is over 8 mm thick beneath $x = 90$ mm. However, once heat energy flow in the glass fibres is established in the forward area where the carbon spar does not appear, it will continue thus until it finally deviates 'upwards' out of the blade. This is because the carbon spar has its forward edge a considerable distance aft from the blade leading edge such that by the time the heat energy flowing aft in the glass fibres is adjacent the carbon spar leading edge, the influence of the negative temperature gradient 'upward' and out of the blade will be greater than that of the better thermal conduction properties of the carbon fibres in the carbon/resin spar. Also, to change from conduction in the glass fibres to the carbon fibres requires crossing the intermediate resins which would necessitate an initial move to a thermally less conductive medium. Hence the heat energy will not be encouraged to travel into the carbon spar.

$$\begin{aligned} \text{OAT} &= 253 \text{ K } (-20^{\circ}\text{C}) & x_i &= 5.0 \text{ mm} \\ t_2 &= 273 \text{ K } (0^{\circ}\text{C}) & x_p &= 0.381 \text{ mm} \\ r &= 349 \text{ mm} & x_g &= 4.01 \text{ mm} \\ x_f &= 17.2 \text{ mm} & x_c &= 0.00 \text{ mm} \\ x_{gf} &= 60.0 \text{ mm} & x_j &= 10.0 \text{ mm} \end{aligned}$$

$$\begin{aligned} v &= \left[140^2 + \frac{(2\pi \times 0.349 \times 1331)^2}{3600} \right]^{0.5} \text{ ms}^{-1} \\ &= \underline{148 \text{ ms}^{-1}} \end{aligned}$$

From 1.1

$$a = \underline{318.8 \text{ ms}^{-1}}$$

$$(17) \quad M = \frac{v}{a} \quad (17)$$

$$M = \frac{148}{318.8}$$

$$M = 0.46$$

$$(18) \quad T = 253 \left[1 + \frac{(1.4 - 1)}{2} \times 0.46^2 \right] \text{ K}$$

$$t_{\infty \text{fwd}} = 263.7 \text{ K } (-9.0^\circ\text{C})$$

$$R_{\text{ex}} = \frac{1.2256 \times 148 \times 1.0 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 1.0 \text{ mm})$$

$$= \underline{1.017 \times 10^5} \quad (R_{\text{ex.o}})$$

$$h_{1x} = 0.332 \frac{k}{x} \times \text{Pr}^{1/3} \times R_{\text{ex}}^{0.5}$$

$$= 0.332 \times \frac{2.6 \times 10^{-2}}{90 \times 10^{-3}} \times 0.689^{1/3} \times (9.157 \times 10^5)^{0.5}$$

$$= \underline{769.0 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o)$$

$$R_{\text{ex}} = \frac{1.2256 \times 148 \times 90 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 90.0 \text{ mm})$$

$$= \underline{9.157 \times 10^5} \quad (R_{\text{ex.in}})$$

$$h_{\text{tx}} = 0.0073 R_{\text{ex}}^{-0.211} C_{pe}^v$$

$$= 0.0073 \times (9.157 \times 10^5)^{-0.211} \times 1005 \times 1.2256 \times 148$$

$$= \underline{73.48 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{\text{in}})$$

$$= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_n h_o k_i}$$

$$= \frac{769.0 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 769.0 \times 0.15 + 0.0018 \times 769.0 \times 2.30}$$

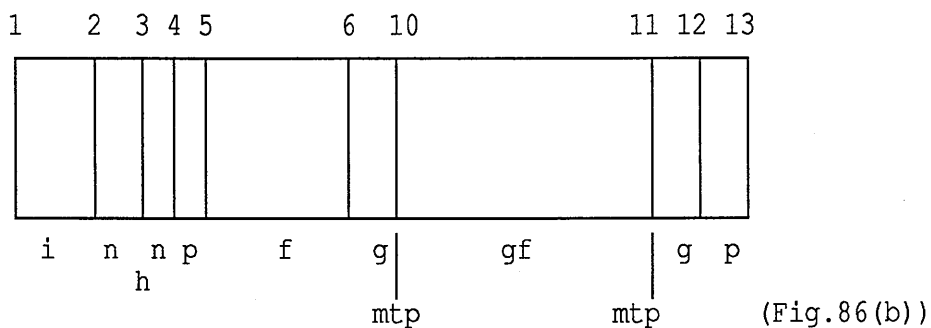
$$= \underline{64.62 \text{ Wm}^{-2}\text{K}^{-1}}$$

$$\begin{aligned} t_3 &= \frac{U_o t_{\infty n.o}^x - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \\ &= \frac{64.62 \times 263.7 \times 1.8 \times 10^{-3} - 273 \times 0.15}{64.62 \times 1.8 \times 10^{-3} - 0.15} \\ &= \underline{305.1 \text{ K (32.1}^\circ\text{C)}} \quad (t_h) \end{aligned}$$

$$\begin{aligned} q_o &= - U_o (t_\infty - t_3) \\ &= - 64.62 (263.7 - 305.1) \text{ Wm}^{-2} \\ &= \underline{2.677 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} t_1 &= t_2 - q_o \frac{x_i}{k_i} \\ &= 273 - 2.677 \times 10^3 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K} \\ &= \underline{267.2 \text{ K } (-5.8^\circ\text{C})} \quad (t_{i/a}) \end{aligned}$$

mtp = mid thickness plane



from Case 2.1

$$\begin{aligned} x_{g1} &= \frac{x_g}{2 \cos 52.9^\circ} \\ &= \frac{4.01 \times 10^{-3}}{2 \cos 52.9^\circ} \text{ m} \\ &= \underline{3.324 \times 10^{-3} \text{ m}} \end{aligned}$$

$$\begin{aligned} \frac{1}{U_{in}} &= \frac{x_{n.in}}{k_n} + 2 \frac{x_p}{k_p} + \frac{x_f}{k_f} + 2 \frac{x_{q1}}{k_g} + \frac{60.0 \times 10^{-3}}{k_{gf}} + \frac{1}{h_{tx}} \\ &= \frac{0.001016}{0.15} + 2 \times \frac{0.000381}{1.09} + \frac{0.01720}{0.03} + 2 \times \frac{0.00332}{0.34} + \frac{0.0600}{1.00} + \frac{1}{73.48} \end{aligned}$$

$$\frac{1}{U_{in}} = 0.674 \text{ W}^{-1} \text{ m}^2 \text{ K}$$

$$\underline{U_{in} = 1.484 \text{ Wm}^{-2} \text{ K}^{-1}}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_\infty - t_3) \\ &= - 1.484 (253 - 305.1) \text{ Wm}^{-2} \\ &= \underline{77.3 \text{ Wm}^{-2}} \end{aligned}$$

$$\begin{aligned} q_h &= q_o + q_{in} \\ &= 2.677 + 0.077 \text{ kWm}^{-2} \\ &= \underline{2.754 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} R_q &= \frac{q_o}{q_h} \\ &= \frac{2.677}{2.754} \\ &= \underline{0.97} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 305.1 - 77.7 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{304.6 \text{ K (31.6}^\circ\text{C)}} \quad (t_{n/p}) \end{aligned}$$

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 304.6 - 77.7 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \end{aligned}$$

$$t_5 = \underline{304.6 \text{ K (31.6}^\circ\text{C)}} \quad (t_{p/f})$$

$$\begin{aligned} t_6 &= t_5 - q_{in} \frac{x_f}{k_f} \\ &= 304.6 - 77.7 \times \frac{17.20 \times 10^{-3}}{0.03} \text{ K} \\ &= \underline{260.0 \text{ K (-13.0}^\circ\text{C)}} \quad (t_{f/g}) \end{aligned}$$

$$\begin{aligned} t_{10} &= t_6 - q_{in} \frac{x_{g1}}{k_g} \\ &= 260.0 - 77.7 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{259.3 \text{ K (-13.7}^\circ\text{C)}} \quad (t_{g/gf}) \end{aligned}$$

$$\begin{aligned} t_{11} &= t_{10} - q_{in} \frac{x_{gf}}{k_{gf}} \\ &= 259.3 - 77.7 \times \frac{60.0 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{254.6 \text{ K (-18.4}^\circ\text{C)}} \quad (t_{gf/g}) \end{aligned}$$

$$\begin{aligned} t_{12} &= t_{11} - q_{in} \frac{x_{g1}}{k_g} \\ &= 254.6 - 77.7 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{253.8 \text{ K (-19.2}^\circ\text{C)}} \quad (t_{g/p}) \end{aligned}$$

$$\begin{aligned} t_{13} &= t_{13} - q_{in} \frac{x_p}{k_p} \\ &= 253.8 - 77.7 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{253.8 \text{ K } (-19.2^\circ\text{C})} \end{aligned} \quad (t_{p/a})$$

Check

$$\begin{aligned} t_{13} &= t_\infty + \frac{q_{in}}{h_{in}} \\ t_{13} &= 253 + \frac{0.077 \times 10^3}{73.48} \text{ K} \\ &= \underline{253.9 \text{ K } (-19.1^\circ\text{C})} \end{aligned} \quad (t_{p/a})$$

Case 2.5.1

A point on the de-icer upper surface within the laminar flow boundary layer 15.0 mm aft of the leading edge, having an ice accretion thickness of 5.0 mm and at a radial station of 349 mm (section C). Assume the path through the blade is 60 mm, (to enable comparison with Case 1.2)

$$\begin{aligned} \text{OAT} &= 253 \text{ K } (-20^{\circ}\text{C}) & x_i &= 5.0 \text{ mm} \\ t_2 &= 273 \text{ K } (0^{\circ}\text{C}) & x_p &= 0.381 \text{ mm} \\ x_f &= 10.8 \text{ mm} & x_g &= 4.01 \text{ mm} \\ x_c &= 8.6 \text{ mm} & v &= 148 \text{ ms}^{-1} \quad (\text{Case 2.1.2}) \\ r &= 349 \text{ mm } (\text{Section C}) \quad (\text{Fig.94(c)}) \end{aligned}$$

@ $x = 15.0 \text{ mm}$

$$\begin{aligned} R_{\text{ex}} &= \frac{1.2256 \times 148 \times 15.0 \times 10^{-3}}{1.783 \times 10^{-5}} \\ &= \underline{1.526 \times 10^5} \quad (R_{\text{ex.o}}) \end{aligned}$$

from Case 2.1

$$\underline{\text{Pr} = 0.689}$$

$$\begin{aligned} h_{1x} &= 0.332 \frac{\text{k}}{\text{x}} \text{Pr}^{1/3} R_{\text{ex}}^{0.5} \\ &= 0.332 \times \frac{2.6 \times 10^{-2}}{15.0 \times 10^{-3}} \times 0.689^{1/3} \times (1.526 \times 10^5)^{0.5} \\ &= \underline{198.6 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_o) \end{aligned}$$

from Case 2.4

$$\begin{aligned} \underline{x_{g1} = 3.324 \text{ mm}} \\ \underline{h_{tx} = 73.48 \text{ Wm}^{-2}\text{K}^{-1}} \quad (h_{in}) \end{aligned}$$

$$U_o = \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_{n.o} h_o k_i}$$

$$= \frac{198.6 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.005 \times 198.6 \times 0.15 + 0.00180 \times 198.6 \times 2.30}$$

$$= \underline{52.06 \text{ Wm}^{-2}\text{K}^{-1}}$$

from Case 1.2

$$t_3 = \frac{U_o t_{\infty} x_{n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}}$$

$$= \frac{52.06 \times 253 \times 1.8 \times 10^{-3} - 273 \times 0.15}{52.06 \times 1.8 \times 10^{-3} - 0.15} \text{ K}$$

$$= \underline{306.3 \text{ K (33.1}^\circ\text{C)}} \quad (t_h)$$

$$q_o = - U_o (t_{\infty} - t_3)$$

$$= - 52.06 (253 - 306.3) \text{ Wm}^{-2}$$

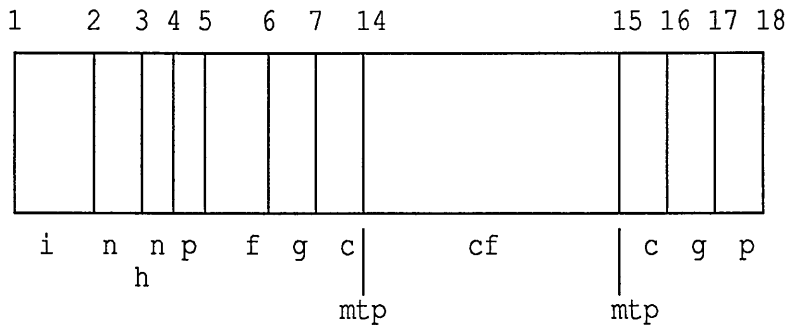
$$= \underline{2.774 \text{ kWm}^{-2}}$$

$$(5) \quad t_1 = t_2 - q_o \frac{x_i}{k_i}$$

$$= 273 - 2.774 \times 10^3 \times \frac{5.0 \times 10^{-3}}{2.30} \text{ K}$$

$$= \underline{267.0 \text{ K (-6.0}^\circ\text{C)}} \quad (t_{i/a})$$

mtp = mid thickness plane



(Fig.85 (b))

$$\begin{aligned}
 \text{Distance travelled in glass/resin layer (in each direction)} &= 2 x_{g1} \\
 &= 2 \times 3.324 \times 10^{-3} \text{ m} \\
 &= \underline{6.648 \text{ mm}}
 \end{aligned}$$

Distance travelled within carbon/resin layer to layer mid thickness plane at angle 58° to the normal:

$$\begin{aligned}
 x_{c1} &= \frac{x_c}{2 \cos 58^\circ} \\
 &= \frac{8.6}{2 \cos 58^\circ} \text{ mm} \\
 &= \underline{8.11 \text{ mm}}
 \end{aligned}$$

therefore, thermal path length in carbon fibres:

$$\begin{aligned}
 x_{cf} &= 60.0 - x_n - 2x_p - x_f - 4 x_{g1} - 2x_{c1} \text{ mm} \\
 &= 60.0 - 1.016 - 2 \times 0.381 - 10.8 - 4 \times 3.324 - 2 \times 8.11 \text{ mm} \\
 &= \underline{17.91 \text{ mm}}
 \end{aligned}$$

therefore

$$\begin{aligned}
 \frac{1}{U_{in}} &= \frac{x_{n.in}}{k_n} + 2 \frac{x_p}{k_p} + \frac{x_f}{k_f} + 4 \frac{x_{g1}}{k_g} + 2 \frac{x_{c1}}{k_c} + \frac{x_{cf}}{k_{cf}} + \frac{1}{h_{tx}} \\
 &= \frac{0.001016}{0.15} + 2 \times \frac{0.000381}{1.09} + \frac{0.0108}{0.03} + 4 \times \frac{0.00332}{0.34} \\
 &\quad + 2 \times \frac{0.00811}{1.00} + \frac{0.01791}{5.0} + \frac{1}{73.48} \\
 &= 0.440 \text{ W}^{-1} \text{ m}^2 \text{ K}
 \end{aligned}$$

$$\underline{U_{in} = 2.273 \text{ Wm}^{-2} \text{ K}^{-1}}$$

$$\begin{aligned}
 q_{in} &= - U_{in} (t_\infty - t_3) \\
 &= - 2.273 (253 - 306.3) \text{ Wm}^{-2} \\
 &= \underline{0.121 \text{ kWm}^{-2}}
 \end{aligned}$$

$$\begin{aligned}q_h &= q_o + q_{in} \\&= 2.775 + 0.121 \text{ kWm}^{-2} \\&= \underline{2.896 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}R_q &= \frac{q_o}{q_h} \\&= \frac{2.775}{2.896} \\&= \underline{0.96}\end{aligned}$$

$$\begin{aligned}(7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\&= 306.3 - 121 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\&= \underline{305.5 \text{ K (32.5}^\circ\text{C)}} \quad (t_{n/p})\end{aligned}$$

$$\begin{aligned}t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\&= 305.5 - 121 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\t_5 &= \underline{305.4 \text{ K (32.4}^\circ\text{C)}} \quad (t_{p/f})\end{aligned}$$

$$\begin{aligned}t_6 &= t_5 - q_{in} \frac{x_f}{k_f} \\&= 305.4 - 121 \times \frac{10.8 \times 10^{-3}}{0.03} \text{ K} \\&= \underline{261.5 \text{ K (-11.5}^\circ\text{C)}} \quad (t_{f/g})\end{aligned}$$

$$\begin{aligned}t_7 &= t_6 - q_{in} \times 2 \times \frac{x_{g1}}{k_g} \\t_7 &= 261.5 - 121 \times 2 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\&= \underline{259.2 \text{ K (-13.9}^\circ\text{C)}} \quad (t_{g/c})\end{aligned}$$

$$\begin{aligned}
 t_{14} &= t_6 - q_{in} \times \frac{x_{c1}}{k_c} \\
 &= 259.2 - 121 \times \frac{8.11 \times 10^{-3}}{1.0} \text{ K} \\
 &= \underline{258.2 \text{ K } (-14.8^\circ\text{C})} \quad (t_{c/cf})
 \end{aligned}$$

$$\begin{aligned}
 t_{15} &= t_{14} - q_{in} \frac{x_{cf}}{k_{cf}} \\
 &= 258.2 - 121 \times \frac{17.91 \times 10^{-3}}{5.0} \text{ K} \\
 &= \underline{257.8 \text{ K } (-15.2^\circ\text{C})} \quad (t_{cf/c})
 \end{aligned}$$

$$\begin{aligned}
 t_{16} &= t_{15} - q_{in} \times \frac{x_c}{k_c} \\
 &= 257.8 - 121 \times \frac{8.11 \times 10^{-3}}{1.0} \text{ K} \\
 &= \underline{256.8 \text{ K } (-16.2^\circ\text{C})} \quad (t_{c/g})
 \end{aligned}$$

$$\begin{aligned}
 t_{17} &= t_{16} - q_{in} \times 2 \times \frac{x_{g1}}{k_g} \\
 &= 256.8 - 121 \times 2 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\
 &= \underline{254.4 \text{ K } (-18.6^\circ\text{C})} \quad (t_{g/p})
 \end{aligned}$$

$$\begin{aligned}
 t_{18} &= t_{17} - q_{in} \frac{x_p}{k_p} \\
 &= 254.4 - 121 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\
 &= \underline{254.4 \text{ K } (-18.6^\circ\text{C})} \quad (t_{p/a})
 \end{aligned}$$

Check

$$\begin{aligned}
 t_{18} &= t_\infty + \frac{q_{in}}{h_{in}} \\
 t_{18} &= 253 + \frac{0.121 \times 10^3}{73.48} \text{ K} \\
 &= \underline{254.4 \text{ K } (-19.6^\circ\text{C})} \quad (t_{p/a})
 \end{aligned}$$

Case 2.5.2

A point on the de-icer upper surface within the laminar flow boundary layer 5.0 mm aft of the leading edge, having an ice accretion thickness of 5.0 mm and at a radial station of 349 mm (section C). Assume a stagnation temperature rise at $x = 5.0$ mm of 10.0 K.

$$\begin{aligned} \text{OAT} &= 263 \text{ K } (-20^\circ\text{C}) & x_i &= 5.0 \text{ mm} \\ t_2 &= 273 \text{ K } (0^\circ\text{C}) & x_p &= 0.381 \text{ mm} \\ x_f &= 15.1 \text{ mm} & x_g &= 4.01 \text{ mm} \\ x_c &= 8.6 \text{ mm} & v &= 148 \text{ ms}^{-1} \quad (\text{Case 2.5.1}) \\ r &= 349 \text{ mm } (\text{Section C}) \quad (\text{Fig.94(c)}) \end{aligned}$$

from Case 1.3

$$\begin{aligned} v &= 141.7 \text{ ms}^{-1} \\ R_{\text{ex}} &= \frac{1.2256 \times 141.7 \times 5.0 \times 10^{-3}}{1.783 \times 10^{-5}} \quad (\text{at } x = 5.0 \text{ mm}) \\ &= \frac{4.870 \times 10^4}{(R_{\text{ex.o}})} \end{aligned}$$

from Case 1.2

$$\begin{aligned} Pr &= 0.689 \\ h_{1x} &= 0.332 \times \frac{k}{x} Pr^{1/3} R_{\text{ex}}^{0.5} \\ &= 0.332 \times \frac{2.6 \times 10^{-2}}{5.0 \times 10^{-3}} \times 0.689^{1/3} \times (4.870 \times 10^4)^{0.5} \\ &= \frac{336.5 \text{ Wm}^{-2}\text{K}^{-1}}{(h_o)} \end{aligned}$$

from Case 2.5

$$\begin{aligned} R_{\text{ex}} &= 9.1576 \times 10^5 \quad (\text{at } x = 90.0 \text{ mm}) \quad (R_{\text{ex.in}}) \\ h_{tx} &= 73.48 \text{ Wm}^{-2}\text{K}^{-1} \quad (h_{in}) \end{aligned}$$

from Case 2.3

$$U_o = 58.32 \text{ Wm}^{-2}\text{K}^{-1}$$

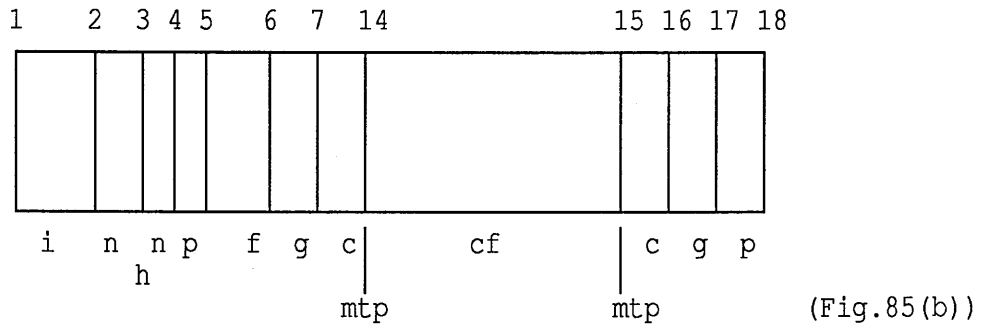
from case 2.3

$$\underline{t_3 = 296.3 \text{ K (23.3 } ^\circ\text{C)}} \quad (t_h)$$

$$\underline{q_o = 1.943 \text{ kWm}^{-2}}$$

$$\underline{t_1 = 268.8 \text{ K (- 4.8} ^\circ\text{C)}} \quad (t_{i/a})$$

mtp = mid thickness plane



from Case 2.5.1

$$\begin{aligned} \text{Distance travelled in glass/resin layer (in each direction)} &= 2 x_{g1} \\ &= \underline{6.648 \text{ mm}} \end{aligned}$$

Distance travelled within carbon/resin layer to layer mid thickness plane at angle 58° to the normal:

$$\underline{x_{c1} = 8.11 \text{ mm}}$$

thermal path length in carbon fibres:

$$\begin{aligned} x_{cf} &= 60.0 - x_n - 2x_p - x_f - 4 x_{g1} - 2x_{c1} \text{ mm} \\ &= 60.0 - 1.016 - 2 \times 0.381 - 15.1 - 4 \times 3.324 - 2 \times 8.11 \text{ mm} \\ &= \underline{13.61 \text{ mm}} \end{aligned}$$

therefore

$$\frac{1}{U_{in}} = \frac{x_{n.in}}{k_n} + 2 \frac{x_p}{k_p} + \frac{x_f}{k_f} + 4 \frac{x_{g1}}{k_g} + 2 \frac{x_{c1}}{k_c} + \frac{x_{cf}}{k_{cf}} + \frac{1}{h_{tx}}$$

$$\begin{aligned} \frac{1}{U_{in}} &= \frac{0.001016}{0.15} + 2 \times \frac{0.000381}{1.09} + \frac{0.0151}{0.03} + 4 \times \frac{0.00332}{0.34} \\ &\quad + 2 \times \frac{0.00811}{1.00} + \frac{0.01361}{5.0} + \frac{1}{73.48} \\ &= 0.582 \text{ W}^{-1} \text{ m}^2 \text{ K} \end{aligned}$$

$$\underline{U_{in} = 1.717 \text{ Wm}^{-2} \text{ K}^{-1}}$$

$$\begin{aligned} q_{in} &= - U_{in} (t_{\infty} - t_3) \\ &= - 1.717 (253 - 296.3) \text{ Wm}^{-2} \\ &= \underline{0.0743 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} q_h &= q_o + q_{in} \\ &= 1.943 + 0.0743 \text{ kWm}^{-2} \\ &= \underline{2.017 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} R_q &= \frac{q_o}{q_h} \\ &= \frac{1.943}{2.017} \\ &= \underline{0.96} \end{aligned}$$

$$\begin{aligned} (7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\ &= 296.3 - 74.3 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\ &= \underline{295.8 \text{ K (22.8}^\circ\text{C)}} \quad (t_{n/p}) \end{aligned}$$

$$\begin{aligned} t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\ &= 295.8 - 74.3 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ \underline{t_5} &= \underline{295.8 \text{ K (22.8}^\circ\text{C)}} \quad (t_{p/f}) \end{aligned}$$

$$\begin{aligned}t_6 &= t_5 - q_{in} \frac{x_f}{k_f} \\&= 295.8 - 74.3 \times \frac{15.1 \times 10^{-3}}{0.03} \text{ K} \\&= \underline{258.2 \text{ K } (-16.8^\circ\text{C})} \quad (t_{g/c})\end{aligned}$$

$$\begin{aligned}t_7 &= t_6 - q_{in} \times 2 \times \frac{x_{g1}}{k_g} \\&= 258.2 - 74.3 \times 2 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\&= \underline{256.7 \text{ K } (-16.3^\circ\text{C})} \quad (t_{g/c})\end{aligned}$$

$$\begin{aligned}t_{14} &= t_7 - q_{in} \times \frac{x_{c1}}{k_c} \\&= 256.7 - 74.3 \times \frac{8.11 \times 10^{-3}}{1.0} \text{ K} \\&= \underline{256.1 \text{ K } (-16.9^\circ\text{C})} \quad (t_{c/cf})\end{aligned}$$

$$\begin{aligned}t_{15} &= t_{14} - q_{in} \frac{x_{cf}}{k_{cf}} \\&= 256.1 - 74.3 \times \frac{13.61 \times 10^{-3}}{5.0} \text{ K} \\&= \underline{255.9 \text{ K } (-17.1^\circ\text{C})}\end{aligned}$$

$$\begin{aligned}t_{16} &= t_{15} - q_{in} \frac{x_{c1}}{k_c} \\&= 255.9 - 74.3 \times \frac{8.11 \times 10^{-3}}{1.0} \text{ K} \\&= \underline{255.3 \text{ K } (-17.7^\circ\text{C})} \quad (t_{c/g})\end{aligned}$$

$$\begin{aligned}t_{17} &= t_{16} - q_{in} \times 2 \times \frac{x_{g1}}{k_g} \\&= 255.3 - 74.3 \times 2 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\&= \underline{253.8 \text{ K } (-19.2^\circ\text{C})} \quad (t_{g/p})\end{aligned}$$

$$\begin{aligned}t_{18} &= t_{17} - q_{in} \frac{x_p}{k_p} \\&= 253.8 - 74.3 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\&= \underline{253.8 \text{ K } (-19.2^\circ\text{C})} \quad (t_{p/a})\end{aligned}$$

Check

$$\begin{aligned}t_{18} &= t_{\infty} + \frac{q_{in}}{h_{in}} \\t_{18} &= 253 + \frac{0.0743 \times 10^3}{73.48} \text{ K} \\&= \underline{253.8 \text{ K } (-19.2^\circ\text{C})} \quad (t_{p/a})\end{aligned}$$

Case 2.5.3

A point on the de-icer upper surface within the laminar flow boundary layer 5.0 mm aft of the leading edge, having an ice accretion thickness of 10.0 mm and at a radial station of 349 mm (section C). Assume a stagnation temperature rise at $x = 5.0$ mm of 10.0 K.

$$\begin{aligned} \text{OAT} &= 263 \text{ K } (-20^\circ\text{C}) & x_i &= 10.0 \text{ mm} \\ t_2 &= 273 \text{ K } (0^\circ\text{C}) & x_p &= 0.381 \text{ mm} \\ x_f &= 15.1 \text{ mm} & x_g &= 4.01 \text{ mm} \\ x_c &= 8.6 \text{ mm} & v &= 148 \text{ ms}^{-1} \quad (\text{Case 2.5.1}) \\ r &= 349 \text{ mm } (\text{Section C}) \quad (\text{Fig.94(c)}) \end{aligned}$$

from Case 2.5.2

$$\begin{aligned} \frac{h_{1x}}{h_{tx}} &= \frac{336.5 \text{ Wm}^{-2}\text{K}^{-1}}{73.48 \text{ Wm}^{-2}\text{K}^{-1}} & (h_o) \\ & & (h_{in}) \\ U_o &= \frac{h_o k_i k_n}{k_i k_n + x_i h_o k_n + x_n h_o k_i} \\ &= \frac{336.5 \times 2.30 \times 0.15}{2.30 \times 0.15 + 0.010 \times 336.5 \times 0.15 + 0.00180 \times 336.5 \times 2.30} \\ &= \underline{51.76 \text{ Wm}^{-2}\text{K}^{-1}} \end{aligned}$$

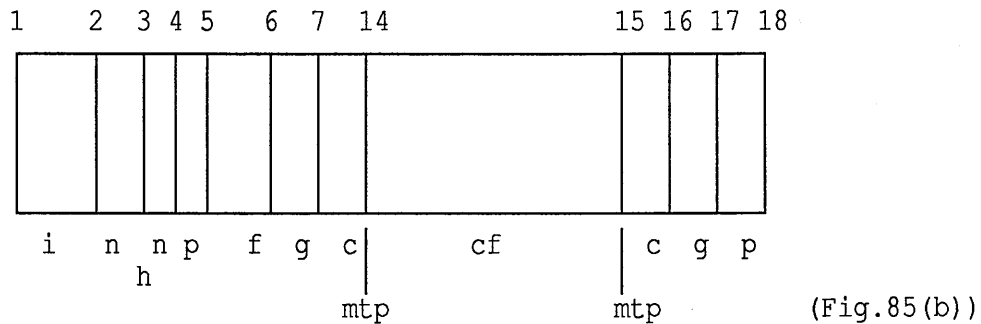
from Case 1.2

$$\begin{aligned} t_3 &= \frac{U_o t_{\infty n.o} - t_2 k_{n.o}}{U_o x_{n.o} - k_{n.o}} \\ &= \frac{51.76 \times 263 \times 1.8 \times 10^{-3} - 273 \times 0.15}{51.76 \times 1.8 \times 10^{-3} - 0.15} \text{ K} \\ &= \underline{289.4 \text{ K } (16.4^\circ\text{C})} & (t_h) \end{aligned}$$

$$\begin{aligned} q_o &= - U_o (t_\infty - t_3) \\ &= - 51.76 (263 - 289.4) \text{ Wm}^{-2} \\ &= \underline{1.366 \text{ kWm}^{-2}} \end{aligned}$$

$$\begin{aligned} (5) \quad t_1 &= t_2 - q_o \frac{x_i}{k_i} \\ &= 273 - 1.366 \times 10^3 \times \frac{10.0 \times 10^{-3}}{2.30} \text{ K} \\ &= \underline{267.1 \text{ K } (-6.1^\circ\text{C})} \quad (t_{i/a}) \end{aligned}$$

mtp = mid thickness plane



from Case 2.5.1

$$\begin{aligned} \text{Distance travelled in glass/resin layer (in each direction)} &= 2 x_{g1} \\ &= \underline{6.648 \text{ mm}} \end{aligned}$$

Distance travelled within carbon/resin layer to layer mid thickness plane at angle 58° to the normal:

$$\underline{x_{c1} = 8.11 \text{ mm}}$$

from Case 2.5.2

thermal path length in carbon fibres:

$$\underline{x_{cf} = 13.61 \text{ mm}}$$

$$\underline{U_{in} = 1.725 \text{ Wm}^{-2} \text{ K}^{-1}}$$

$$\begin{aligned}q_{in} &= - U_{in} (t_{\infty} - t_3) \\&= - 1.717 (253 - 289.4) \text{ Wm}^{-2} \\&= \underline{0.062 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}q_h &= q_o + q_{in} \\&= 1.366 + 0.062 \text{ kWm}^{-2} \\&= \underline{1.428 \text{ kWm}^{-2}}\end{aligned}$$

$$\begin{aligned}R_q &= \frac{q_o}{q_h} \\&= \frac{1.366}{1.428} \\&= \underline{0.96}\end{aligned}$$

$$\begin{aligned}(7) \quad t_4 &= t_3 - q_{in} \frac{x_{n.in}}{k_n} \\&= 289.4 - 62.5 \times \frac{1.016 \times 10^{-3}}{0.15} \text{ K} \\&= \underline{289.0 \text{ K (16.0}^\circ\text{C)}} \quad (t_{n/p})\end{aligned}$$

$$\begin{aligned}t_5 &= t_4 - q_{in} \frac{x_p}{k_p} \\&= 289.0 - 62.5 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\t_5 &= \underline{288.9 \text{ K (15.9}^\circ\text{C)}} \quad (t_{p/f})\end{aligned}$$

$$\begin{aligned}t_6 &= t_5 - q_{in} \frac{x_f}{k_f} \\&= 288.9 - 62.5 \times \frac{15.1 \times 10^{-3}}{0.03} \text{ K} \\&= \underline{257.3 \text{ K (-15.7}^\circ\text{C)}} \quad (t_{f/g})\end{aligned}$$

$$t_7 = t_6 - q_{in} \times 2 \times \frac{x_{g1}}{k_g}$$

$$\begin{aligned} t_7 &= 257.3 - 62.5 \times 2 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{256.1 \text{ K } (-16.9^\circ\text{C})} \end{aligned} \quad (t_{g/c})$$

$$\begin{aligned} t_{14} &= t_7 - q_{in} \times \frac{x_{c1}}{k_c} \\ &= 256.1 - 62.5 \times \frac{8.11 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{255.6 \text{ K } (-17.4^\circ\text{C})} \end{aligned} \quad (t_{c/cf})$$

$$\begin{aligned} t_{15} &= t_{14} - q_{in} \frac{x_{cf}}{k_{cf}} \\ &= 255.6 - 62.5 \times \frac{13.61 \times 10^{-3}}{5.0} \text{ K} \\ &= \underline{255.4 \text{ K } (-17.6^\circ\text{C})} \end{aligned} \quad (t_{cf/c})$$

$$\begin{aligned} t_{16} &= t_{15} - q_{in} \frac{x_{c1}}{k_c} \\ &= 255.4 - 62.5 \times \frac{8.11 \times 10^{-3}}{1.0} \text{ K} \\ &= \underline{254.9 \text{ K } (-18.1^\circ\text{C})} \end{aligned} \quad (t_{c/g})$$

$$\begin{aligned} t_{17} &= t_{16} - q_{in} \times 2 \times \frac{x_{g1}}{k_g} \\ &= 254.9 - 62.5 \times 2 \times \frac{3.32 \times 10^{-3}}{0.34} \text{ K} \\ &= \underline{253.6 \text{ K } (-19.4^\circ\text{C})} \end{aligned} \quad (t_{g/p})$$

$$\begin{aligned} t_{18} &= t_{17} - q_{in} \frac{x_p}{k_p} \\ &= 253.6 - 62.5 \times \frac{0.381 \times 10^{-3}}{1.09} \text{ K} \\ &= \underline{253.6 \text{ K } (-19.4^\circ\text{C})} \end{aligned} \quad (t_{p/a})$$

Check

$$t_{18} = t_{\infty} + \frac{q_{in}}{h_{in}}$$

$$t_{18} = 253 + \frac{0.062 \times 10^3}{73.48} \text{ K}$$

$$= \underline{253.6 \text{ K } (-19.4^{\circ}\text{C})}$$

($t_{p/a}$)

APPENDIX B

18 APPENDIX B

18.1 Existing Spraymat Design Method

18.1.1 Sample Calculations

Calculation Sheet - Limit of Catch Cases 7 and 16 - Upper Surface

Actual Section and Chord	L90 Intake Lip (90°)	
Simulated Aerofoil Section	Joukowski 15% t/c cambered, upper surface	
Simulated Chord (C) ins.	60	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 7	Case 16
Speed Case	138	207
Droplet Reynolds Number	159.7	239.5
$R_u = 35.3 \times 10^{-3} U.d.\sigma$		
Scale Factor $\psi = 562 \frac{C\sigma}{d}$	560.7	560.7
Droplet Diameter, Microns (d)	44.4	44.4
Upper Surface Limit of Catch	9.3	10.5
Upper Surface Limit of Catch at Design Incidence % L	9.3	10.5
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	5.6 (142.2 mm)	6.3 (160.0 mm)
Lower Surface Limit of Catch		
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		

Calculation Sheet - Limit of Catch

Cases 7 and 16 - Lower Surface

Actual Section and Chord	L90 Intake Lip (90°)	
Simulated Aerofoil Section	Joukowski 15% t/c cambered, upper surface	
Simulated Chord (C) ins.	30	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 7	Case 16
Speed Case	138	207
Droplet Reynolds Number	159.7	239.5
$R_u = 35.3 \times 10^{-3} U.d.\sigma$		
Scale Factor $\psi = 562 \frac{C\sigma}{d}$	280.4	280.4
Droplet Diameter, Microns (d)	44.4	44.4
Upper Surface 0		
Limit 2		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L		
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Lower Surface 0	13.5	14.4
Limit 2		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L	13.5	14.4
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	4.1 (104.1 mm)	4.3 (109.2 mm)

Calculation Sheet - Limit of Catch

Cases 8 and 17 - Upper Surface

Actual Section and Chord	L90 Intake Lip (135°)	
Simulated Aerofoil Section	Joukowski 15% t/c cambered, upper surface	
Simulated Chord (C) ins.	56	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 8	Case 17
Speed Case	138	207
Droplet Reynolds Number	159.7	239.5
$R_u = 35.3 \times 10^{-3} \text{ U.d.}\sigma$		
Scale Factor $\psi = 562 \frac{C\sigma}{d}$	523.3	523.3
Droplet Diameter, Microns (d)	44.4	44.4
Upper Surface 0	9.4	10.6
Limit 2		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L	9.4	10.6
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	5.3 (134.6 mm)	5.9 (149.9 mm)
Lower Surface 0		
Limit 2		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		

Calculation Sheet - Limit of Catch

Cases 8 and 17 - Lower Surface

Actual Section and Chord	L90 Intake Lip (135°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	35	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 8	Case 17
Speed Case	138	207
Droplet Reynolds Number	237.4	158.2
$R_u = 35.3 \times 10^{-3} U.d.\sigma$		
Scale Factor $\psi = 562 \frac{C\sigma}{d}$	327.1	327.1
Droplet Diameter, Microns (d)	44.4	44.4
Upper Surface	0	
Limit	2	
of Catch	4	
Upper Surface Limit of Catch at Design Incidence % L		
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Lower Surface	0	
Limit	2	
of Catch	4	
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	4.3	4.7
	(109.2 mm)	(119.4 mm)

Calculation Sheet - Limit of Catch

Cases 9 and 18 - Upper Surface

Actual Section and Chord	L90 Intake Lip (180°)	
Simulated Aerofoil Section	Joukowski 15% t/c cambered, upper surface	
Simulated Chord (C) ins.	40	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 9	Case 18
Speed Case	138	207
Droplet Reynolds Number	237.4	158.2
$R_u = 35.3 \times 10^{-3} U.d.\sigma$		
Scale Factor $\psi = 562 \frac{C\sigma}{d}$	373.8	373.8
Droplet Diameter, Microns (d)	44.4	44.4
Upper Surface 0	11.9	12.6
Limit 2		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L	11.9	12.6
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	4.8 (121.9 mm)	5.0 (127.0 mm)
Lower Surface 0		
Limit 2		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		

Calculation Sheet - Limit of Catch

Cases 9 and 18 - Lower Surface

Actual Section and Chord	L90 Intake Lip (180°)	
Simulated Aerofoil Section	Joukowski 15% t/c cambered, upper surface	
Simulated Chord (C) ins.	36	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 9	Case 18
Speed Case	138	207
Droplet Reynolds Number	159.7	239.5
$R_u = 35.3 \times 10^{-3} U.d.\sigma$		
Scale Factor $\psi = 562 \frac{C\sigma}{d}$	336.4	336.4
Droplet Diameter, Microns (d)	44.4	44.4
Upper Surface 0		
Limit 2		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L		
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Lower Surface 0	12.0	13.3
Limit 2		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L	12.0	13.3
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	4.3 (109.2 mm)	4.8 (121.9 mm)

18.1.2 Calculation Sheet - Ice Accretion Rate

Cases 7 and 16 - Upper Surface

Actual Section and Chord	L90 Intake Lip (90°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	60	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 7	Case 16
Speed Case	138	207
Reynolds No. $R_{u0} = R_u \times \frac{20}{44.4}$	71.9	107.9
Scale Factor $\psi_0 = \psi \frac{44.4}{20}$	1244.8	1244.8
Upper Surface 0	2.7	3.2
Limit 2 (1)		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L	2.7	3.2
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	1.6 (40.6 mm)	1.9 (48.3 mm)
Lower Surface 0		
Limit 2 (1)		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Overall Efficiency of Catch E_m % (5)	12.4	16.0
Max Thickness of Aerofoil (T) ins	7.5	7.5
Water Concentration (W) Grm.m ⁻³	0.6	0.3
Rate of Ice Buildup at Stagnation		
$h_u = \frac{3.92 \times 10^{-7} W.E.m.U.T}{2L_u} \text{ ins.s}^{-1}$	9.43×10^{-4}	7.69×10^{-4}

Calculation Sheet - Ice Accretion Rate

Cases 7 and 16 - Lower Surface

Actual Section and Chord	L90 Intake Lip (90°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	30	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 7	Case 16
Speed Case	138	207
Reynolds No. $R_{u0} = R_u \times \frac{20}{44.4}$	71.9	107.9
Scale Factor $\psi_0 = \psi \frac{44.4}{20}$	622.5	622.5
Upper Surface 0		
Limit 2 (1)		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L		
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Lower Surface 0	6.8	7.8
Limit 2 (1)		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L	6.8	7.8
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	2.0 (50.8 mm)	2.3 (58.4 mm)
Overall Efficiency of Catch E_m % (5)	22.4	27.4
Max Thickness of Aerofoil (T) ins	3.75	3.75
Water Concentration (W) Grm.m ⁻³	0.6	0.3
Rate of Ice Buildup at Stagnation		
$h_1 = \frac{3.92 \times 10^{-7} W.E.m.U.T}{2L_u} \text{ ins.s}^{-1}$	6.82×10^{-4}	5.44×10^{-4}

Calculation Sheet - Ice Accretion Rate

Cases 8 and 17 - Upper Surface

Actual Section and Chord	L90 Intake Lip (135°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	56	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 8	Case 17
Speed Case	138	207
Reynolds No. $R_{u0} = R_u \times \frac{20}{44.4}$	71.9	107.9
Scale Factor $\psi_0 = \psi \frac{44.4}{20}$	1161.7	1161.7
Upper Surface 0	2.1	2.6
Limit 2 (1)		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L	2.1	2.6
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	1.2 (30.5 mm)	1.5 (38.1 mm)
Lower Surface 0		
Limit 2 (1)		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Overall Efficiency of Catch E %	13.4	17.2
Max Thickness of Aerofoil (T) ins	7.0	7.0
Water Concentration (W) Grm.m ⁻³	0.6	0.3
Rate of Ice Buildup at Stagnation		
$h_u = \frac{3.92 \times 10^{-7} W.E.m.U.T}{2L_u} \text{ ins.s}^{-1}$	1.27×10^{-3}	9.77×10^{-4}

Calculation Sheet - Ice Accretion Rate

Cases 8 and 17 - Lower Surface

Actual Section and Chord	L90 Intake Lip (135°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	35	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 8	Case 17
Speed Case	138	207
Reynolds No. $R_{u0} = R_u \times \frac{20}{44.4}$	71.9	107.9
Scale Factor $\psi_0 = \psi \frac{44.4}{20}$	726.2	726.2
Upper Surface	0	
Limit	2	
of Catch	4	
	(1)	
Upper Surface Limit of Catch at Design Incidence % L		
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Lower Surface	0	
Limit	2	
of Catch	4	
	(1)	
Lower Surface Limit of Catch at Design Incidence % L	6.2	7.2
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	2.2	2.5
	(55.9 mm)	(63.5 mm)
Overall Efficiency of Catch E_m %	19.9	24.5
	(5)	
Max Thickness of Aerofoil (T) ins	4.4	4.4
Water Concentration (W) Grm.m ⁻³	0.6	0.3
Rate of Ice Buildup at Stagnation		
$h_1 = \frac{3.92 \times 10^{-7} W.E.m.U.T}{2L_1} \text{ ins.s}^{-1}$	6.46×10^{-4}	5.25×10^{-4}

Calculation Sheet - Ice Accretion Rate

Cases 9 and 18 - Upper Surface

Actual Section and Chord	L90 Intake Lip (180°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	40	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 9	Case 18
Speed Case	138	207
Reynolds No. $R_{u0} = R_u \times \frac{20}{44.4}$	71.9	107.9
Scale Factor $\psi_0 = \psi \frac{44.4}{20}$	829.8	829.8
Upper Surface 0	5.7	6.5
Limit 2 (1)		
of Catch 4		
Upper Surface Limit of Catch at Design Incidence % L	5.7	6.5
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	2.3 (58.4 mm)	2.6 (66.0 mm)
Lower Surface 0		
Limit 2 (1)		
of Catch 4		
Lower Surface Limit of Catch at Design Incidence % L		
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Overall Efficiency of Catch $E_m \%$ (5)	17.5	18.7
Max Thickness of Aerofoil (T) ins	5.0	5.0
Water Concentration (W) Grm.m ⁻³	0.6	0.3
Rate of Ice Buildup at Stagnation		
$h_u = \frac{3.92 \times 10^{-7} W \cdot E_m \cdot U \cdot T}{2L_u} \text{ ins.s}^{-1}$	6.17×10^{-4}	5.15×10^{-4}

Calculation Sheet - Ice Accretion Rate

Cases 9 and 18 - Lower Surface

Actual Section and Chord	L90 Intake Lip (180°)	
Simulated Aerofoil Section	Joukowski 15% t/c	
	cambered, upper surface	
Simulated Chord (C) ins.	36	
Incidence Relative to Fuselage	0°	
Flight Conditions	-20.0/-19.8°C	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6ms ⁻¹)	
Altitude Feet	8153 (74.808 kPa)	
Effective Incidence	0°	
Relative Density (σ)	0.7383	
	Case 9	Case 18
Speed Case	138	207
Reynolds No. $R_{u0} = R_u \times \frac{20}{44.4}$	71.9	107.9
Scale Factor $\psi_0 = \psi \frac{44.4}{20}$	746.8	746.8
Upper Surface	0	
Limit	2	
of Catch	4	
Upper Surface Limit of Catch at Design Incidence % L		
Upper Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$		
Lower Surface	0	
Limit	2	
of Catch	4	
Lower Surface Limit of Catch at Design Incidence % L	6.1	6.9
Lower Surface Limit of Catch at Design Incidence (ins) = $\frac{LC}{100}$	2.2 (55.9 mm)	2.5 (63.5 mm)
Overall Efficiency of Catch E %	19.2	23.7
Max Thickness of Aerofoil (T) ins	4.5	4.5
Water Concentration (W) Grm.m ⁻³	0.6	0.3
Rate of Ice Buildup at Stagnation		
$h_1 = \frac{3.92 \times 10^{-7} W.E.M.U.T}{2L_1} \text{ ins.s}^{-1}$	6.37×10^{-4}	5.19×10^{-4}

Combined Rate of Ice Accretion

using:

$$h = \frac{h_l + h_u}{2}$$

Case	Rate of Ice Accretion (h)			
	ins.s ⁻¹	ins.min ⁻¹	mm.s ⁻¹	mm.min ⁻¹
7	8.13 x 10 ⁻⁴	1.36 x 10 ⁻⁵	2.07 x 10 ⁻²	3.45 x 10 ⁻⁴
8	9.58 x 10 ⁻⁴	1.60 x 10 ⁻⁵	2.43 x 10 ⁻²	4.05 x 10 ⁻⁴
9	6.27 x 10 ⁻⁴	1.05 x 10 ⁻⁵	1.59 x 10 ⁻²	2.65 x 10 ⁻⁴
16	6.57 x 10 ⁻⁴	1.10 x 10 ⁻⁵	1.67 x 10 ⁻²	2.78 x 10 ⁻⁴
17	7.51 x 10 ⁻⁴	1.25 x 10 ⁻⁵	1.91 x 10 ⁻²	3.18 x 10 ⁻⁴
18	5.17 x 10 ⁻⁴	8.62 x 10 ⁻⁶	1.31 x 10 ⁻²	2.18 x 10 ⁻⁴

Calculation Sheet References

- (1) Report, S/DES/1, Part 2, Section 2.2, Fig.1 - Fig.12
Lucas Aerospace, Luton
- (2) Report, DEV/R/110/771B Iss.2, Fig.2, Lucas Aerospace, Luton
- (3) Report, DEV/R/283/773 Fig.4, Lucas Aerospace, Luton
- (4) Report, DEV/R/283/773 Fig.8, Lucas Aerospace, Luton
- (5) Report, S/DES/1, Part 2, Section 2.3, Fig.1 - Fig.9
Lucas Aerospace, Luton

18.1.3 Calculation Sheet - Heat Requirements

Cases 7 and 16 - Leading Edge

Leading Edge Radius (R) ins.	2.63	
Flight Condition	-20.0/-19.8°C	0.6/0.3 gm ⁻³
Speed M.P.H. T.A.S. (U)	138/207	(61.73/92.6 ms ⁻¹)
Altitude Ft.	8153	
Relative Density (σ)	0.7383	
	Case 7	Case 16
Speed Case	138	207
Droplet Diameter Microns (d)	20	20
Droplet Inertia Function		
$K = \frac{0.638 \times 10^{-4} d^2 U}{R}$	1.34	2.01
Velocity and Scale Function	3846	5769
$\Phi = 19.44 \sigma^2 R U.$		
Efficiency of Catch at Stagnation Point β %	41.0	27.6
Heat to Water at 100% (CHU/Ft.Hr)	615	900
Catch Efficiency = H_{100}		
Heat to Water $H_1 = \beta_0 \frac{H_{100}}{100} 100$	252	248
Convection and Evaporation Loss Factor $\frac{\sqrt{R} (H_2 + H_3)}{\sqrt{6}}$	570	685
Convection and Evaporation Loss = $H_2 + H_3$	861	1035
Leading Edge Power Intensity		
$\text{Watts.in}^{-2} = \frac{H_1 + H_2 + H_3}{273 \times 0.8}$	5.10	5.87

Calculation Sheet - Heat Requirements

Cases 8 and 17 - Leading Edge

Leading Edge Radius (R) ins.	2.02	
Flight Condition	-20.0/-19.8°C 0.6/0.3 gm ⁻³	
Speed M.P.H. T.A.S. (U)	138/207 (61.73/92.6 ms ⁻¹)	
Altitude Ft.	8153	
Relative Density (σ)	0.7383	
	Case 8	Case 17
Speed Case	138	207
Droplet Diameter Microns (d)	20	20
Droplet Inertia Function		
$K = \frac{0.638 \times 10^{-4} d^2 U}{R}$	1.74	2.62
Velocity and Scale Function $\Phi = 19.44 \sigma^2 R.U.$	2954	4431
Efficiency of Catch at Stagnation Point R_0 %	53.2	49.1
Heat to Water at 100% (CHU/Ft.Hr) Catch Efficiency = H_{100}	615	900
Heat to Water $H_1 = R_0 \frac{H_{100}}{100}$	327	442
Convection and Evaporation Loss Factor $\frac{\sqrt{R} (H_2 + H_3)}{\sqrt{6}}$	570	685
Convection and Evaporation Loss = $H_2 + H_3$	982	1181
Leading Edge Power Intensity		
$\text{Watts.in}^{-2} = \frac{H_1 + H_2 + H_3}{273 \times 0.8}$	5.99	7.43

Calculation Sheet - Heat Requirements

Cases 9 and 18 - Leading Edge

Leading Edge Radius (R) ins.	1.97	
Flight Condition	-20.0/-19.8°C	0.6/0.3 gm ⁻³
Speed M.P.H. T.A.S. (U)	138/207	(61.73/92.6 ms ⁻¹)
Altitude Ft.	8153	
Relative Density (σ)	0.7383	
	Case 9	Case 18
Speed Case	138	207
Droplet Diameter Microns (d)	20	20
Droplet Inertia Function		
$K = \frac{0.638 \times 10^{-4} d^2 U}{R}$	1.79	2.68
Velocity and Scale Function $\Phi = 19.44 \sigma^2 R.U.$	2881	4321
Efficiency of Catch at Stagnation Point β_0 %	54.3	51.3
Heat to Water at 100% (CHU/Ft.Hr) Catch Efficiency = H_{100}	615	900
Heat to Water $H_1 = \beta_0 \frac{H_{100}}{100}$	334	462
Convection and Evaporation Loss Factor $\frac{\sqrt{R} \cdot (H_2 + H_3)}{\sqrt{6}}$	570	685
Convection and Evaporation Loss = $H_2 + H_3$	995	1195
Leading Edge Power Intensity		
$\text{Watts.in}^{-2} = \frac{H_1 + H_2 + H_3}{273 \times 0.8}$	6.08	7.59

19 Tables

19.1 Table 10(a) : LIP.DAT

L90 INTAKE (90)

0 7 29 0.0 0.009 0.115

0.0000000	0.0000000
0.0010000	0.0120
0.0020000	0.0170
0.0030000	0.0215
0.0050000	0.0290
0.0070000	0.0340
0.0090000	0.0385

0.0000000	0.0000000
0.0010000	-0.0100
0.0020000	-0.0145
0.0030000	-0.0185
0.0050000	-0.0230
0.0070000	-0.0260
0.0090000	-0.0285
0.0100000	-0.0295
0.0110000	-0.0305
0.0130000	-0.0320
0.0150000	-0.0335
0.0170000	-0.0350
0.0200000	-0.0370
0.0250000	-0.0400
0.0300000	-0.0425
0.0350000	-0.0445
0.0400000	-0.0465
0.0450000	-0.0480
0.0500000	-0.0500
0.0550000	-0.0515
0.0600000	-0.0530
0.0650000	-0.0545
0.0700000	-0.0555
0.0750000	-0.0570
0.0800000	-0.0580
0.0850000	-0.0590
0.0900000	-0.0600
0.1000000	-0.0615
0.1150000	-0.0635

Corresponding to:

ITITLE

ISYM,NU,NL,XLE,,XTEU,XTEL

X,Y

etc.

where:

ITITLE = Lip/aerofoil defining title to appear on plots.
ISYM = Switch to indicate symmetry (see "LIP.DAT").
NU = Number of co-ordinates on upper surface of lip.
NL = Number of co-ordinates on lower surface of lip.
XLE = Abscissa of lip leading edge, (ordinate = 0.0).
XTEU = Abscissa of upper surface lip trailing edge.
XTEL = Abscissa of lower surface lip trailing edge.
X,Y = Surface node co-ordinates.

(see "LIP.DAT" for units and further detail)

19.2 Table 10(b) : LTRAJ2.DAT

DEMO RUN L90 INTAKE LIP-90: -20 C, V=180kt, 0.3 g.m-3, 10000ft
1,0,92.6,0.0000,1.0,20.0,74.808
-20.0,0.30,-1.0,1.0,40,0.005
0.30,0.09,0.2,7,1.0
0.00035,0,1.0,0.045,1.00,1.5,0

Corresponding to:

KTITLE

ITYPE,ILONG,VINF,XSTAG,CLE,DD,PINF

TINF,LWC,TIME,FACR2,M,DELS

XMAX,YMAX,DSTEPI,NTRJ,FACR1

RUFF,IBL,COE,DEQI,ASYMF,TUF,IDEN

where:

KTITLE = Case defining title to appear on output files.

ITYPE = Switch to indicate type of program execution required (see TRAJ2.FOR coding).

ILONG = Determines extent of program output (1: full output ie. including TRAJ2.RES (digital data in addition to plots), other: short output (plotted data)).

VINF = V_{∞} , freestream ambient velocity.

XSTAG = Abscissa of required forward stagnation point, (-ve on lower surface, and vice versa).

CLE = Factor to vary ratio of lip chord to aerofoil chord.

DD = Droplet diameter.

PINF = P_{∞} , ambient static pressure.

TINF = T_{∞} , ambient static temperature.

LWC = Flow liquid water content.

TIME = Time in icing, ie. time over which the ice growth rate is integrated to develop the ice accretion shape.

FACR2 = Plotting scale factor.

M = Number of equi-spaced nodes on each aerofoil surface at which the ice growth rate is calculated.

DELS = Non-dimensional surface spacing between nodes.

XMAX = Trajectory evaluation limit, (non-dimensional with respect to aerofoil chord).

YMAX = As XMAX in the Y direction.

DSTEPI = Dimensionless initial integral step length.

NTRJ = Number of droplet trajectories required, (including the two catch limit trajectories).

FACR1 = Plotting scale factor.

RUFF = Equivalent sand grain roughness for HTC calculation.

IBL = Switch for HTC calculation (1: integral
boundary layer, other: empirical HTC.
COE = HTC correction factor for integral boundary
layer case.
DEQI = Aerofoil leading edge equivalent cylinder
diameter.
ASYMF = Asymmetry factor to vary leading edge
equivalent cylinder diameters for upper and
lower surfaces.
TUF = HTC multiplication factor, empirical case.
IDEN = Switch for ice density, (1: variable,
other: two fixed values :- glaze = 917 kg.m^{-3}
rime = 880 kg.m^{-3}).

(Ref.14)

(see "Notation" for units)

19.3 Table 10(c) : LTRAJ3.DAT

DEMO RUN L90 INTAKE LIP-90: -20 C, V=180kt, 0.3 g.m-3, 10000ft
1,0,92.6,0.0000,1.0,20.0,74.808
-20.0,0.30,-1.0,1.0,40,0.005
0.30,0.09,0.2,7,1.0
0,1.0,0.045,1.00,1.5,0
0.0035,1.0,1.0

Corresponding to:

KTITLE
ITYPE, ILONG, VINI, ALFA, CHD, DD, PINI
TINI, LWC, TIME, FACR2, M, DELS
XMAX, YMAX, DSTEPI, NTRJ, FACR1
RUFF, IBL, COE, DEQI, ASYMF, TUF, IDEN
XSTAG, CLE, BLF

where:

KTITLE = Case defining title to appear on output files.
ITYPE = Switch to indicate type of program execution required (see TRAJ2.FOR coding).
ILONG = Determines extent of program output (1: full output ie. including TRAJ2.RES (digital data in addition to plots), other: short output (plotted data)).
VINI = V_{∞} , freestream ambient velocity.
ALFA = α , incidence (lip and aerofoil).
CHD = Chord of total (100% chord) aerofoil.
DD = Droplet diameter.
PINI = P_{∞} , ambient static pressure.
TINI = T_{∞} , ambient static temperature.
LWC = Flow liquid water content.
TIME = Time in icing, ie. time over which the ice growth rate is integrated to develop the ice accretion shape.
FACR2 = Plotting scale factor.
M = Number of equi-spaced nodes on each aerofoil surface at which the ice growth rate is calculated.
DELS = Non-dimensional surface spacing between nodes.
XMAX = Trajectory evaluation limit, (non-dimensional with respect to aerofoil chord).
YMAX = As XMAX in the Y direction.
DSTEPI = Dimensionless initial integral step length.
NTRJ = Number of droplet trajectories required, (including the two catch limit trajectories).
FACR1 = Plotting scale factor.
RUFF = Equivalent sand grain roughness for HTC calculation.

IBL = Switch for HTC calculation (1: integral boundary layer, other: empirical HTC).
COE = HTC correction factor for integral boundary layer case.
DEQI = Aerofoil leading edge equivalent cylinder diameter.
ASYMF = Asymmetry factor to vary leading edge equivalent cylinder diameters for upper and lower surfaces.
TUF = HTC multiplication factor, empirical case.
IDEN = Switch for ice density, (1: variable, other: two fixed values :- glaze = 917 kg.m^{-3} rime = 880 kg.m^{-3}).
XSTAG = Desired forward stagnation point abscissa, (-ve = lower surface, and vice versa).
CLE = Factor to vary ratio of lip chord to aerofoil chord (see "LTRAJ3.DAT").
BLF = Factor to vary degree of aerofoil trailing edge 'blunting' (see "LTRAJ3.DAT").

(Ref.14)

(see "Notation" for units)

(see "LTRAJ3.DAT" for further detail)

19.4 Table 11 :CRD.DAT

L90 INTAKE (90)

0 76 76 0.0 0.402361

0.000000	0.000000
0.000176	0.003179
0.000706	0.009639
0.001586	0.015155
0.002817	0.020691
0.004396	0.027048
0.006320	0.032426
0.008586	0.037605
0.011190	0.042794
0.014128	0.047629
0.017393	0.052115
0.020981	0.056262
0.024885	0.060077
0.029098	0.063570
0.033613	0.066749
0.038422	0.069622
0.043517	0.072197
0.048888	0.074483
0.054526	0.076488
0.060422	0.078221
0.066564	0.079690
0.072943	0.080903
0.079547	0.081870
0.086364	0.082597
0.093383	0.083095
0.100590	0.083370
0.107974	0.083432
0.115522	0.083289
0.123220	0.082950
0.131055	0.082422
0.139012	0.081714
0.147079	0.080835
0.155241	0.079792
0.163483	0.078595
0.171791	0.077252
0.180151	0.075771
0.188548	0.074161
0.196967	0.072429
0.205394	0.070585
0.213813	0.068637
0.222210	0.066593
0.230570	0.064461
0.238878	0.062251
0.247120	0.059969
0.255282	0.057626
0.263349	0.055229
0.271306	0.052787
0.279141	0.050307

0.286839	0.047799
0.294387	0.045271
0.301771	0.042731
0.308979	0.040188
0.315997	0.037650
0.322814	0.035125
0.329418	0.032622
0.335797	0.030150
0.341939	0.027716
0.347835	0.025329
0.353473	0.022998
0.358845	0.020730
0.363939	0.018535
0.368748	0.016421
0.373263	0.014395
0.377477	0.012468
0.381381	0.010646
0.384968	0.008938
0.388234	0.007353
0.391171	0.005900
0.393775	0.004586
0.396041	0.003419
0.397965	0.002410
0.399544	0.001565
0.400775	0.000893
0.401656	0.000402
0.402185	0.000102
0.402361	0.000000
0.000000	0.000000
0.000176	0.002613
0.000706	-0.007992
0.001586	-0.012786
0.002817	-0.017855
0.004396	-0.021943
0.006320	-0.025036
0.008586	-0.028044
0.011190	-0.030669
0.014128	-0.032832
0.017393	-0.035278
0.020981	-0.037617
0.024885	-0.039935
0.029098	-0.042099
0.033613	-0.043944
0.038422	-0.045926
0.043517	-0.047523
0.048888	-0.049571
0.054526	-0.051369
0.060422	-0.053137
0.066564	-0.054816
0.072943	-0.056386
0.079547	-0.057918
0.086364	-0.059284

0.093383	-0.060563
0.100590	-0.061582
0.107974	-0.062611
0.115522	-0.063559
0.123220	-0.064294
0.131055	-0.064802
0.139012	-0.065092
0.147079	-0.065173
0.155241	-0.065053
0.163483	-0.064743
0.171791	-0.064251
0.180151	-0.063586
0.188548	-0.062757
0.196967	-0.061774
0.205394	-0.060645
0.213813	-0.059380
0.222210	-0.057989
0.230570	-0.056479
0.238878	-0.054860
0.247120	-0.053141
0.255282	-0.051332
0.263349	-0.049441
0.271306	-0.047477
0.279141	-0.045451
0.286839	-0.043370
0.294387	-0.041244
0.301771	-0.039082
0.308979	-0.036893
0.315997	-0.034686
0.322814	-0.032471
0.329418	-0.030256
0.335797	-0.028051
0.341939	-0.025864
0.347835	-0.023706
0.353473	-0.021584
0.358845	-0.019508
0.363939	-0.017488
0.368748	-0.015532
0.373263	-0.013649
0.377477	-0.011849
0.381381	-0.010140
0.384968	-0.008532
0.388234	-0.007034
0.391171	-0.005655
0.393775	-0.004404
0.396041	-0.003290
0.397965	-0.002323
0.399544	-0.001511
0.400775	-0.000864
0.401656	-0.000390
0.402185	-0.000099
0.402361	0.000000

Corresponding to:

ITITLE
ISYM,NU,NL,XLE,XTE

where:

ITITLE = Lip/aerofoil defining title to appear on plots.
ISYM = Switch to indicate symmetry (see "LIP.DAT")
NU = Number of co-ordinates on aerofoil upper surface.
NL = Number of co-ordinates on aerofoil lower surface.
XLE = Abscissa of aerofoil leading edge.
XTE = Abscissa of aerofoil trailing edge.

(see "CRD.DAT" for units and further detail)

19.5 Table 12(a) : TEMP1.DAT (generated by PTRAJ2)

L90 INTAKE (90)

151	76	19.873258	-0.917291		
1.000000	1.000004	-2.096629	0.058521	-3.825992	
0.999561	-0.000246	-1.096379	6.986824	0.529207	
0.998246	-0.000969	-1.094878	5.622461	-0.007242	
0.996057	-0.002146	-1.092392	5.522310	0.008629	
0.992998	-0.003755	-1.088936	5.300790	-0.060616	
0.989074	-0.005773	-1.084523	5.136430	-0.107547	
0.984292	-0.008177	-1.079171	4.982537	-0.152075	
0.978660	-0.010945	-1.072895	4.836212	-0.192244	
0.972188	-0.014054	-1.065716	4.699820	-0.233550	
0.964888	-0.017482	-1.057651	4.564829	-0.271255	
0.956773	-0.021205	-1.048722	4.434900	-0.308469	
0.947856	-0.025201	-1.038951	4.308859	-0.346034	
0.938154	-0.029448	-1.028360	4.186456	-0.381373	
0.927682	-0.033922	-1.016973	4.068475	-0.417037	
0.916461	-0.038601	-1.004815	3.956557	-0.452044	
0.904509	-0.043463	-0.991911	3.852092	-0.488020	
0.891847	-0.048485	-0.978290	3.754819	-0.522679	
0.878498	-0.053644	-0.963979	3.665064	-0.557707	
0.864484	-0.058917	-0.949006	3.587496	-0.593291	
0.849832	-0.064282	-0.933402	3.519952	-0.628592	
0.834565	-0.069716	-0.917198	3.462349	-0.664984	
0.818712	-0.075197	-0.900424	3.417453	-0.700574	
0.802299	-0.080701	-0.883113	3.380421	-0.738167	
0.785357	-0.086207	-0.865298	3.354452	-0.776758	
0.767913	-0.091691	-0.847013	3.333812	-0.815358	
0.750000	-0.097131	-0.828291	3.321896	-0.856046	
0.731648	-0.102504	-0.809169	3.315236	-0.898101	
0.712889	-0.107788	-0.789680	3.314542	-0.940542	
0.693757	-0.112960	-0.769862	3.316565	-0.986424	
0.674286	-0.117997	-0.749749	3.324269	-1.032226	
0.654508	-0.122877	-0.729378	3.335695	-1.081604	
0.634460	-0.127576	-0.708786	3.346843	-1.132661	
0.614175	-0.132073	-0.688009	3.365583	-1.184919	
0.593690	-0.136344	-0.667084	3.386049	-1.241054	
0.573041	-0.140368	-0.646047	3.410266	-1.299114	
0.552264	-0.144121	-0.624933	3.437109	-1.361011	
0.531395	-0.147580	-0.603780	3.465223	-1.423500	
0.510471	-0.150723	-0.582621	3.497719	-1.490860	
0.489529	-0.153528	-0.561491	3.531581	-1.560986	
0.468604	-0.155971	-0.540425	3.569698	-1.634807	
0.447736	-0.158031	-0.519455	3.610238	-1.711500	
0.426958	-0.159684	-0.498612	3.652479	-1.792675	
0.406309	-0.160907	-0.477927	3.694169	-1.877022	
0.385824	-0.161679	-0.457427	3.743402	-1.964976	
0.365540	-0.161976	-0.437141	3.786833	-2.056050	
0.345491	-0.161776	-0.417091	3.832601	-2.150529	
0.325714	-0.161055	-0.397300	3.879064	-2.245141	
0.306242	-0.159793	-0.377788	3.913395	-2.340384	
0.287110	-0.157965	-0.358569	3.934945	-2.426421	

0.268352	-0.155608	-0.339663	3.901857	-2.483263
0.250000	-0.153051	-0.321134	3.894747	-2.550364
0.232087	-0.150520	-0.303043	4.072965	-2.748126
0.214643	-0.147341	-0.285312	4.040914	-2.806887
0.197700	-0.143947	-0.268032	4.138029	-2.958910
0.181288	-0.140137	-0.251184	4.124701	-3.033234
0.165435	-0.136235	-0.234857	4.228762	-3.196189
0.150168	-0.132064	-0.219031	4.293090	-3.336437
0.135516	-0.127668	-0.203734	4.326325	-3.452696
0.121502	-0.123200	-0.189025	4.565098	-3.744059
0.108153	-0.118111	-0.174739	4.192849	-3.528872
0.095491	-0.114140	-0.161469	4.935840	-4.257655
0.083539	-0.109216	-0.148542	4.713350	-4.173460
0.072318	-0.104630	-0.136420	5.281196	-4.797047
0.061847	-0.099253	-0.124649	5.309181	-4.959925
0.052144	-0.093490	-0.113364	5.371635	-5.140522
0.043227	-0.087678	-0.102720	5.625905	-5.535138
0.035112	-0.081598	-0.092580	5.457270	-5.488897
0.027812	-0.076223	-0.083514	6.449186	-6.662086
0.021340	-0.069700	-0.074326	6.503176	-6.897312
0.015708	-0.062224	-0.064966	6.266058	-6.834278
0.010926	-0.054535	-0.055911	6.643785	-7.454907
0.007002	-0.044375	-0.045020	5.983775	-6.948222
0.003943	-0.031778	-0.032057	5.299744	-6.378889
0.001754	-0.019862	-0.019941	5.167853	-6.434675
0.000439	-0.006493	-0.006508	4.775634	-6.154782
0.000000	0.000000	0.000000	5.071601	-6.669787
0.000439	0.007902	0.007914	4.442078	-5.942596
0.001754	0.023955	0.024021	4.253280	-5.942605
0.003943	0.037666	0.037906	3.992568	-5.761749
0.007002	0.051425	0.052000	3.643422	-5.463338
0.010926	0.067223	0.068279	3.722894	-5.779443
0.015708	0.080590	0.082476	3.445510	-5.569486
0.021340	0.093460	0.096524	3.253085	-5.429388
0.027812	0.106358	0.110955	3.170188	-5.485318
0.035112	0.118373	0.125013	3.008602	-5.408915
0.043227	0.129523	0.138804	2.846202	-5.307743
0.052144	0.139829	0.152432	2.695955	-5.179622
0.061847	0.149312	0.166000	2.492749	-4.996109
0.072318	0.157993	0.179601	2.325097	-4.805724
0.083539	0.165893	0.193325	2.146799	-4.587235
0.095491	0.173032	0.207247	1.949108	-4.347705
0.108153	0.179432	0.221434	1.775534	-4.104746
0.121502	0.185114	0.235942	1.640150	-3.879843
0.135516	0.190097	0.250815	1.456730	-3.625647
0.150168	0.194404	0.266087	1.316679	-3.398822
0.165435	0.198055	0.281784	1.197620	-3.182066
0.181288	0.201071	0.297922	1.045147	-2.956725
0.197700	0.203473	0.314509	0.958905	-2.769936
0.214643	0.205281	0.331548	0.819140	-2.562909
0.232087	0.206518	0.349035	0.754988	-2.400288
0.250000	0.207202	0.366961	0.649929	-2.223319
0.268352	0.207357	0.385314	0.573443	-2.069629

0.287110	0.207001	0.404076	0.486331	-1.914729
0.306242	0.206157	0.423226	0.417238	-1.773867
0.325714	0.204845	0.442742	0.363123	-1.648199
0.345491	0.203086	0.462598	0.276374	-1.510581
0.365540	0.200900	0.482765	0.226519	-1.397121
0.385824	0.198310	0.503214	0.166970	-1.282976
0.406309	0.195335	0.523914	0.104409	-1.172277
0.426958	0.191997	0.544831	0.053431	-1.071555
0.447736	0.188316	0.565932	-0.003081	-0.972194
0.468604	0.184313	0.587181	-0.061667	-0.874760
0.489529	0.180010	0.608543	-0.113832	-0.785973
0.510471	0.175427	0.629981	-0.171894	-0.696162
0.531395	0.170585	0.651458	-0.229941	-0.614410
0.552264	0.165504	0.672936	-0.286326	-0.533746
0.573041	0.160207	0.694378	-0.351498	-0.453444
0.593690	0.154713	0.715746	-0.408847	-0.379724
0.614175	0.149044	0.737000	-0.468274	-0.308683
0.634460	0.143220	0.758104	-0.538846	-0.239858
0.654508	0.137263	0.779019	-0.602886	-0.173595
0.674286	0.131192	0.799707	-0.679628	-0.108592
0.693757	0.125030	0.820131	-0.740163	-0.051696
0.712889	0.118797	0.840253	-0.817766	0.007012
0.731648	0.112514	0.860036	-0.879896	0.060825
0.750000	0.106201	0.879443	-0.941663	0.111889
0.767913	0.099881	0.898439	-0.972842	0.158478
0.785357	0.093572	0.916988	-0.993036	0.206021
0.802299	0.087298	0.935055	-0.559953	0.260942
0.818712	0.081077	0.952607	-0.467816	0.309624
0.834565	0.074932	0.969609	-2.085531	0.299247
0.849832	0.068883	0.986031	-2.582798	0.308371
0.864484	0.062951	1.001838	-3.026105	0.312164
0.878498	0.057157	1.017002	-3.371483	0.312517
0.891847	0.051522	1.031492	-3.659945	0.309698
0.904509	0.046066	1.045279	-3.907008	0.304739
0.916461	0.040811	1.058336	-4.124729	0.295783
0.927682	0.035777	1.070634	-4.318594	0.283874
0.938154	0.030986	1.082150	-4.497725	0.268881
0.947856	0.026458	1.092857	-4.664493	0.250304
0.956773	0.022215	1.102732	-4.825812	0.228035
0.964888	0.018276	1.111753	-4.984068	0.201571
0.972188	0.014663	1.119898	-5.145916	0.170626
0.978660	0.011397	1.127147	-5.315195	0.134929
0.984292	0.008499	1.133481	-5.498751	0.092264
0.989074	0.005989	1.138881	-5.708155	0.042781
0.992998	0.003888	1.143332	-5.961624	-0.021092
0.996057	0.002219	1.146818	-6.301330	-0.078063
0.998246	0.001000	1.149323	-6.947468	-0.324779
0.999561	0.000253	1.150835	-8.605546	0.302816
1.000000	0.000000	1.151342	0.000000	0.000000

Corresponding to:

ITITLE
NPTS, ILE, CLMAG, THETA
X, Y, SC, GAM1, GAM2
etc.

Where:

ITITLE = Title defining aerofoil to appear on plots.
NPTS = Total number of points defining aerofoil.
ILE = Node number of leading edge.
CLMAG = Lift coefficient.
THETA = Inclination of lift coefficient.
X, Y = Non-dimensional co-ordinates defining aerofoil.
SC = Node distances over curved surface incremental
from leading edge.
GAM1 = Panel strength for $\alpha = 0^\circ$.
GAM2 = Panel strength for $\alpha = 90^\circ$.

19.6 Table 12(b) : TEMP3.DAT (generated by PTRAJ3)

L90 INTAKE (90)

151 76

0.022368	0.095685	0.040644	0.087562		
0.285813	0.157818	0.288456	-0.137994		
1.00000	0.00000	0.00000	0.01135	8.81813	-7.33446
0.99979	-0.00350	0.00351	0.16192	8.85386	-7.36838
0.99915	-0.00694	0.00701	0.30756	8.74575	-7.28739
0.99808	-0.01032	0.01055	0.44230	8.51809	-7.10859
0.99659	-0.01363	0.01418	0.56251	8.18991	-6.84853
0.99468	-0.01687	0.01794	0.66456	7.78875	-6.52924
0.99234	-0.02005	0.02189	0.74948	7.34852	-6.17816
0.98957	-0.02317	0.02606	0.81761	6.89368	-5.81512
0.98638	-0.02622	0.03047	0.87163	6.44409	-5.45659
0.98276	-0.02920	0.03516	0.91289	6.01167	-5.11182
0.97872	-0.03212	0.04015	0.94440	5.60286	-4.78605
0.97425	-0.03498	0.04546	0.96706	5.22101	-4.48267
0.96935	-0.03777	0.05109	0.98288	4.86595	-4.20074
0.96403	-0.04049	0.05707	0.99143	4.53248	-3.93596
0.95829	-0.04315	0.06340	0.99477	4.22397	-3.69118
0.95211	-0.04575	0.07010	0.98004	3.88069	-3.41393
0.93879	-0.05104	0.08443	0.97211	3.40477	-3.03776
0.92473	-0.05647	0.09950	0.98506	3.10622	-2.81297
0.90998	-0.06202	0.11526	0.99997	2.86714	-2.63830
0.89456	-0.06766	0.13169	1.01664	2.67119	-2.50071
0.87849	-0.07339	0.14874	1.03368	2.50410	-2.38786
0.86180	-0.07915	0.16640	1.05085	2.35844	-2.29376
0.84453	-0.08495	0.18462	1.06816	2.22945	-2.21453
0.82669	-0.09074	0.20337	1.08512	2.11329	-2.14702
0.80833	-0.09652	0.22262	1.10202	2.00773	-2.08922
0.78947	-0.10224	0.24233	1.11880	1.91099	-2.03998
0.77016	-0.10790	0.26246	1.13525	1.82116	-1.99759
0.75041	-0.11346	0.28297	1.15166	1.73775	-1.96183
0.73027	-0.11891	0.30383	1.16785	1.65928	-1.93146
0.70977	-0.12421	0.32500	1.18391	1.58521	-1.90620
0.68896	-0.12934	0.34645	1.19980	1.51501	-1.88566
0.66785	-0.13429	0.36812	1.21558	1.44802	-1.86926
0.64650	-0.13902	0.38999	1.23121	1.38375	-1.85700
0.62494	-0.14352	0.41202	1.24677	1.32191	-1.84847
0.60320	-0.14776	0.43416	1.26208	1.26200	-1.84342
0.58133	-0.15171	0.45639	1.27727	1.20379	-1.84197
0.55936	-0.15535	0.47866	1.29231	1.14706	-1.84379
0.53734	-0.15866	0.50093	1.30704	1.09126	-1.84875
0.51529	-0.16161	0.52317	1.32148	1.03650	-1.85699
0.49327	-0.16418	0.54535	1.33559	0.98235	-1.86825
0.47130	-0.16635	0.56742	1.34915	0.92839	-1.88235
0.44943	-0.16809	0.58936	1.36204	0.87482	-1.89944
0.42769	-0.16938	0.61113	1.37416	0.82114	-1.91921
0.40613	-0.17019	0.63271	1.38505	0.76703	-1.94139
0.38478	-0.17050	0.65407	1.39453	0.71262	-1.96573
0.36368	-0.17029	0.67517	1.40187	0.65718	-1.99140
0.34286	-0.16953	0.69600	1.40643	0.60119	-2.01791

0.32236	-0.16820	0.71654	1.40677	0.54347	-2.04273
0.30222	-0.16628	0.73677	1.39905	0.48398	-2.06080
0.28248	-0.16380	0.75667	1.37183	0.41980	-2.05387
0.26316	-0.16111	0.77618	1.35137	0.36129	-2.05985
0.24430	-0.15844	0.79522	1.39337	0.31782	-2.16803
0.22594	-0.15510	0.81389	1.36013	0.25598	-2.16554
0.20811	-0.15152	0.83207	1.36850	0.20279	-2.23453
0.19083	-0.14751	0.84981	1.33812	0.14458	-2.24598
0.17414	-0.14341	0.86700	1.34313	0.09051	-2.32293
0.15807	-0.13901	0.88366	1.33286	0.03398	-2.38216
0.14265	-0.13439	0.89976	1.31064	-0.02223	-2.42535
0.12790	-0.12968	0.91524	1.34442	-0.08370	-2.58741
0.11385	-0.12433	0.93028	1.20126	-0.12760	-2.40537
0.10052	-0.12015	0.94425	1.36928	-0.20917	-2.86236
0.08794	-0.11496	0.95785	1.26244	-0.25790	-2.77107
0.07612	-0.11014	0.97061	1.36086	-0.35124	-3.14553
0.06510	-0.10448	0.98301	1.31087	-0.41972	-3.21890
0.05489	-0.09841	0.99488	1.25986	-0.48547	-3.29572
0.04550	-0.09229	1.00609	1.25470	-0.57516	-3.52090
0.03696	-0.08589	1.01676	1.14495	-0.61317	-3.45517
0.02928	-0.08023	1.02630	1.27593	-0.79494	-4.17071
0.02246	-0.07337	1.03598	1.18030	-0.87415	-4.27806
0.01654	-0.06550	1.04583	1.03529	-0.91313	-4.21278
0.01150	-0.05741	1.05536	0.97929	-1.04169	-4.56823
0.00737	-0.04671	1.06683	0.74224	-1.01494	-4.23250
0.00415	-0.03345	1.08047	0.51659	-0.96619	-3.86738
0.00185	-0.02091	1.09322	0.37143	-0.99955	-3.89314
0.00046	-0.00684	1.10736	0.19869	-0.97405	-3.71632
0.00000	0.00000	1.11421	0.13138	-1.06294	-4.03262
0.00046	0.00832	1.12254	0.02635	-0.95036	-3.58570
0.00185	0.02522	1.13950	-0.14492	-0.95445	-3.59975
0.00415	0.03965	1.15412	-0.28519	-0.91854	-3.49866
0.00737	0.05413	1.16895	-0.40298	-0.86280	-3.34219
0.01150	0.07076	1.18609	-0.59142	-0.88892	-3.55479
0.01654	0.08483	1.20103	-0.71741	-0.83248	-3.46345
0.02246	0.09838	1.21582	-0.83520	-0.78039	-3.40670
0.02928	0.11196	1.23101	-0.98926	-0.74970	-3.48431
0.03696	0.12460	1.24581	-1.12110	-0.69484	-3.48691
0.04550	0.13634	1.26032	-1.24176	-0.63154	-3.47550
0.05489	0.14719	1.27467	-1.34784	-0.55994	-3.44238
0.06510	0.15717	1.28895	-1.43777	-0.48202	-3.39036
0.07612	0.16631	1.30327	-1.51136	-0.39947	-3.32093
0.08794	0.17462	1.31771	-1.56858	-0.31481	-3.23755
0.10052	0.18214	1.33237	-1.61064	-0.22953	-3.14386
0.11385	0.18888	1.34730	-1.63921	-0.14556	-3.04357
0.12790	0.19486	1.36257	-1.65636	-0.06328	-2.94054
0.14265	0.20010	1.37823	-1.66389	0.01548	-2.83693
0.15807	0.20464	1.39431	-1.66356	0.09146	-2.73592
0.17414	0.20848	1.41083	-1.65745	0.16400	-2.63886
0.19083	0.21165	1.42782	-1.64655	0.23283	-2.54616
0.20811	0.21418	1.44528	-1.63217	0.29847	-2.45947
0.22594	0.21609	1.46321	-1.61545	0.36125	-2.37864
0.24430	0.21739	1.48162	-1.59685	0.42128	-2.30405

0.26316	0.21811	1.50049	-1.57684	0.47865	-2.23517
0.28248	0.21827	1.51981	-1.55643	0.53440	-2.17277
0.30222	0.21790	1.53956	-1.53532	0.58775	-2.11536
0.32236	0.21701	1.55972	-1.51425	0.63999	-2.06389
0.34286	0.21563	1.58026	-1.49303	0.69106	-2.01747
0.36368	0.21377	1.60116	-1.47209	0.74097	-1.97589
0.38478	0.21147	1.62239	-1.45122	0.79017	-1.93900
0.40613	0.20875	1.64391	-1.43084	0.83924	-1.90671
0.42769	0.20562	1.66570	-1.41051	0.88747	-1.87820
0.44943	0.20210	1.68772	-1.39086	0.93627	-1.85423
0.47130	0.19823	1.70993	-1.37132	0.98478	-1.83373
0.49327	0.19401	1.73230	-1.35222	1.03425	-1.81741
0.51529	0.18948	1.75479	-1.33346	1.08376	-1.80427
0.53734	0.18466	1.77735	-1.31493	1.13450	-1.79500
0.55936	0.17956	1.79996	-1.29684	1.18617	-1.78920
0.58133	0.17422	1.82257	-1.27890	1.23918	-1.78692
0.60320	0.16864	1.84514	-1.26123	1.29378	-1.78813
0.62494	0.16286	1.86763	-1.24385	1.35029	-1.79326
0.64650	0.15689	1.89000	-1.22647	1.40876	-1.80160
0.66785	0.15076	1.91222	-1.20944	1.46998	-1.81424
0.68896	0.14449	1.93424	-1.19239	1.53392	-1.83071
0.70977	0.13810	1.95601	-1.17549	1.60127	-1.85152
0.73027	0.13161	1.97751	-1.15860	1.67247	-1.87709
0.75041	0.12505	1.99869	-1.14173	1.74819	-1.90751
0.77016	0.11844	2.01952	-1.12485	1.82898	-1.94360
0.78947	0.11179	2.03994	-1.10806	1.91618	-1.98603
0.80833	0.10514	2.05994	-1.09097	2.01033	-2.03563
0.82669	0.09850	2.07946	-1.07396	2.11333	-2.09307
0.84453	0.09189	2.09848	-1.05695	2.22692	-2.16092
0.86180	0.08534	2.11696	-1.03972	2.35325	-2.23976
0.87849	0.07888	2.13486	-1.02273	2.49624	-2.33358
0.89456	0.07251	2.15214	-1.00584	2.66053	-2.44598
0.90998	0.06626	2.16878	-0.98950	2.85353	-2.58267
0.92473	0.06017	2.18474	-0.97498	3.08934	-2.75641
0.93879	0.05423	2.20000	-0.96245	3.38428	-2.97954
0.95211	0.04849	2.21451	-0.97146	3.85782	-3.35432
0.95829	0.04568	2.22129	-0.98682	4.20011	-3.63047
0.96403	0.04281	2.22771	-0.98297	4.50429	-3.87205
0.96935	0.03988	2.23379	-0.97370	4.83103	-4.13185
0.97425	0.03689	2.23952	-0.95709	5.17698	-4.40720
0.97872	0.03384	2.24493	-0.93287	5.54750	-4.70188
0.98276	0.03073	2.25004	-0.89989	5.94157	-5.01676
0.98638	0.02756	2.25485	-0.85692	6.35634	-5.34804
0.98957	0.02433	2.25939	-0.80094	6.78534	-5.69244
0.99234	0.02103	2.26369	-0.73131	7.21763	-6.03914
0.99468	0.01768	2.26778	-0.64521	7.63669	-6.37588
0.99659	0.01426	2.27170	-0.54209	8.02070	-6.68578
0.99808	0.01079	2.27548	-0.42235	8.34338	-6.94514
0.99915	0.00725	2.27917	-0.28779	8.58459	-7.14068
0.99979	0.00366	2.28282	-0.14133	8.72841	-7.25827
1.00000	0.00000	2.28649	0.01135	8.81813	-7.33446

Corresponding to:

ITITLE
NPTS, ILE
XU (NUO) , YU (NUO) , XMARKU, YMARKU
XL (NUO) , YL (NUO) , XMARKL, YMARKL
X, Y, SC, GAM1, GAM2, GAM3
etc.

Where:

ITITLE = Title defining aerofoil to appear on plots.
NPTS = Total number of points defining aerofoil.
ILE = Node number of leading edge.
XU (NUO) = Abscissa inner end lip upper surface tick mark.
YU (NUO) = Ordinate inner end lip upper surface tick mark.
XMARKU = Abscissa outer end lip upper surface tick mark.
YMARKU = Ordinate outer end lip upper surface tick mark.
XL (NUO) = Abscissa inner end lip lower surface tick mark.
YL (NUO) = Ordinate inner end lip lower surface tick mark.
XMARKL = Abscissa outer end lip lower surface tick mark.
YMARKL = Ordinate outer end lip lower surface tick mark.
X, Y = Non-dimensional co-ordinates defining aerofoil.
SC = Node distances over curved surface incremental
from leading edge.
GAM1 = Panel strength for $\alpha = 0^\circ$.
GAM2 = Panel strength for $\alpha = 90^\circ$.
GAM3 = Panel strength added to achieve desired forward
stagnation point position.

19.7 Table 12(c) : TEMP1.DAT (generated by TRAJ2)

L90 INTAKE (90)

151	76	19.873258	-0.917291		
1.000000	1.000004	-2.096629	0.058521	-3.825992	
0.999561	-0.000246	-1.096379	6.986824	0.529207	
0.998246	-0.000969	-1.094878	5.622461	-0.007242	
0.996057	-0.002146	-1.092392	5.522310	0.008629	
0.992998	-0.003755	-1.088936	5.300790	-0.060616	
0.989074	-0.005773	-1.084523	5.136430	-0.107547	
0.984292	-0.008177	-1.079171	4.982537	-0.152075	
0.978660	-0.010945	-1.072895	4.836212	-0.192244	
0.972188	-0.014054	-1.065716	4.699820	-0.233550	
0.964888	-0.017482	-1.057651	4.564829	-0.271255	
0.956773	-0.021205	-1.048722	4.434900	-0.308469	
0.947856	-0.025201	-1.038951	4.308859	-0.346034	
0.938154	-0.029448	-1.028360	4.186456	-0.381373	
0.927682	-0.033922	-1.016973	4.068475	-0.417037	
0.916461	-0.038601	-1.004815	3.956557	-0.452044	
0.904509	-0.043463	-0.991911	3.852092	-0.488020	
0.891847	-0.048485	-0.978290	3.754819	-0.522679	
0.878498	-0.053644	-0.963979	3.665064	-0.557707	
0.864484	-0.058917	-0.949006	3.587496	-0.593291	
0.849832	-0.064282	-0.933402	3.519952	-0.628592	
0.834565	-0.069716	-0.917198	3.462349	-0.664984	
0.818712	-0.075197	-0.900424	3.417453	-0.700574	
0.802299	-0.080701	-0.883113	3.380421	-0.738167	
0.785357	-0.086207	-0.865298	3.354452	-0.776758	
0.767913	-0.091691	-0.847013	3.333812	-0.815358	
0.750000	-0.097131	-0.828291	3.321896	-0.856046	
0.731648	-0.102504	-0.809169	3.315236	-0.898101	
0.712889	-0.107788	-0.789680	3.314542	-0.940542	
0.693757	-0.112960	-0.769862	3.316565	-0.986424	
0.674286	-0.117997	-0.749749	3.324269	-1.032226	
0.654508	-0.122877	-0.729378	3.335695	-1.081604	
0.634460	-0.127576	-0.708786	3.346843	-1.132661	
0.614175	-0.132073	-0.688009	3.365583	-1.184919	
0.593690	-0.136344	-0.667084	3.386049	-1.241054	
0.573041	-0.140368	-0.646047	3.410266	-1.299114	
0.552264	-0.144121	-0.624933	3.437109	-1.361011	
0.531395	-0.147580	-0.603780	3.465223	-1.423500	
0.510471	-0.150723	-0.582621	3.497719	-1.490860	
0.489529	-0.153528	-0.561491	3.531581	-1.560986	
0.468604	-0.155971	-0.540425	3.569698	-1.634807	
0.447736	-0.158031	-0.519455	3.610238	-1.711500	
0.426958	-0.159684	-0.498612	3.652479	-1.792675	
0.406309	-0.160907	-0.477927	3.694169	-1.877022	
0.385824	-0.161679	-0.457427	3.743402	-1.964976	
0.365540	-0.161976	-0.437141	3.786833	-2.056050	
0.345491	-0.161776	-0.417091	3.832601	-2.150529	
0.325714	-0.161055	-0.397300	3.879064	-2.245141	
0.306242	-0.159793	-0.377788	3.913395	-2.340384	
0.287110	-0.157965	-0.358569	3.934945	-2.426421	

0.268352	-0.155608	-0.339663	3.901857	-2.483263
0.250000	-0.153051	-0.321134	3.894747	-2.550364
0.232087	-0.150520	-0.303043	4.072965	-2.748126
0.214643	-0.147341	-0.285312	4.040914	-2.806887
0.197700	-0.143947	-0.268032	4.138029	-2.958910
0.181288	-0.140137	-0.251184	4.124701	-3.033234
0.165435	-0.136235	-0.234857	4.228762	-3.196189
0.150168	-0.132064	-0.219031	4.293090	-3.336437
0.135516	-0.127668	-0.203734	4.326325	-3.452696
0.121502	-0.123200	-0.189025	4.565098	-3.744059
0.108153	-0.118111	-0.174739	4.192849	-3.528872
0.095491	-0.114140	-0.161469	4.935840	-4.257655
0.083539	-0.109216	-0.148542	4.713350	-4.173460
0.072318	-0.104630	-0.136420	5.281196	-4.797047
0.061847	-0.099253	-0.124649	5.309181	-4.959925
0.052144	-0.093490	-0.113364	5.371635	-5.140522
0.043227	-0.087678	-0.102720	5.625905	-5.535138
0.035112	-0.081598	-0.092580	5.457270	-5.488897
0.027812	-0.076223	-0.083514	6.449186	-6.662086
0.021340	-0.069700	-0.074326	6.503176	-6.897312
0.015708	-0.062224	-0.064966	6.266058	-6.834278
0.010926	-0.054535	-0.055911	6.643785	-7.454907
0.007002	-0.044375	-0.045020	5.983775	-6.948222
0.003943	-0.031778	-0.032057	5.299744	-6.378889
0.001754	-0.019862	-0.019941	5.167853	-6.434675
0.000439	-0.006493	-0.006508	4.775634	-6.154782
0.000000	0.000000	0.000000	5.071601	-6.669787
0.000439	0.007902	0.007914	4.442078	-5.942596
0.001754	0.023955	0.024021	4.253280	-5.942605
0.003943	0.037666	0.037906	3.992568	-5.761749
0.007002	0.051425	0.052000	3.643422	-5.463338
0.010926	0.067223	0.068279	3.722894	-5.779443
0.015708	0.080590	0.082476	3.445510	-5.569486
0.021340	0.093460	0.096524	3.253085	-5.429388
0.027812	0.106358	0.110955	3.170188	-5.485318
0.035112	0.118373	0.125013	3.008602	-5.408915
0.043227	0.129523	0.138804	2.846202	-5.307743
0.052144	0.139829	0.152432	2.695955	-5.179622
0.061847	0.149312	0.166000	2.492749	-4.996109
0.072318	0.157993	0.179601	2.325097	-4.805724
0.083539	0.165893	0.193325	2.146799	-4.587235
0.095491	0.173032	0.207247	1.949108	-4.347705
0.108153	0.179432	0.221434	1.775534	-4.104746
0.121502	0.185114	0.235942	1.640150	-3.879843
0.135516	0.190097	0.250815	1.456730	-3.625647
0.150168	0.194404	0.266087	1.316679	-3.398822
0.165435	0.198055	0.281784	1.197620	-3.182066
0.181288	0.201071	0.297922	1.045147	-2.956725
0.197700	0.203473	0.314509	0.958905	-2.769936
0.214643	0.205281	0.331548	0.819140	-2.562909
0.232087	0.206518	0.349035	0.754988	-2.400288
0.250000	0.207202	0.366961	0.649929	-2.223319
0.268352	0.207357	0.385314	0.573443	-2.069629

0.287110	0.207001	0.404076	0.486331	-1.914729
0.306242	0.206157	0.423226	0.417238	-1.773867
0.325714	0.204845	0.442742	0.363123	-1.648199
0.345491	0.203086	0.462598	0.276374	-1.510581
0.365540	0.200900	0.482765	0.226519	-1.397121
0.385824	0.198310	0.503214	0.166970	-1.282976
0.406309	0.195335	0.523914	0.104409	-1.172277
0.426958	0.191997	0.544831	0.053431	-1.071555
0.447736	0.188316	0.565932	-0.003081	-0.972194
0.468604	0.184313	0.587181	-0.061667	-0.874760
0.489529	0.180010	0.608543	-0.113832	-0.785973
0.510471	0.175427	0.629981	-0.171894	-0.696162
0.531395	0.170585	0.651458	-0.229941	-0.614410
0.552264	0.165504	0.672936	-0.286326	-0.533746
0.573041	0.160207	0.694378	-0.351498	-0.453444
0.593690	0.154713	0.715746	-0.408847	-0.379724
0.614175	0.149044	0.737000	-0.468274	-0.308683
0.634460	0.143220	0.758104	-0.538846	-0.239858
0.654508	0.137263	0.779019	-0.602886	-0.173595
0.674286	0.131192	0.799707	-0.679628	-0.108592
0.693757	0.125030	0.820131	-0.740163	-0.051696
0.712889	0.118797	0.840253	-0.817766	0.007012
0.731648	0.112514	0.860036	-0.879896	0.060825
0.750000	0.106201	0.879443	-0.941663	0.111889
0.767913	0.099881	0.898439	-0.972842	0.158478
0.785357	0.093572	0.916988	-0.993036	0.206021
0.802299	0.087298	0.935055	-0.559953	0.260942
0.818712	0.081077	0.952607	-0.467816	0.309624
0.834565	0.074932	0.969609	-2.085531	0.299247
0.849832	0.068883	0.986031	-2.582798	0.308371
0.864484	0.062951	1.001838	-3.026105	0.312164
0.878498	0.057157	1.017002	-3.371483	0.312517
0.891847	0.051522	1.031492	-3.659945	0.309698
0.904509	0.046066	1.045279	-3.907008	0.304739
0.916461	0.040811	1.058336	-4.124729	0.295783
0.927682	0.035777	1.070634	-4.318594	0.283874
0.938154	0.030986	1.082150	-4.497725	0.268881
0.947856	0.026458	1.092857	-4.664493	0.250304
0.956773	0.022215	1.102732	-4.825812	0.228035
0.964888	0.018276	1.111753	-4.984068	0.201571
0.972188	0.014663	1.119898	-5.145916	0.170626
0.978660	0.011397	1.127147	-5.315195	0.134929
0.984292	0.008499	1.133481	-5.498751	0.092264
0.989074	0.005989	1.138881	-5.708155	0.042781
0.992998	0.003888	1.143332	-5.961624	-0.021092
0.996057	0.002219	1.146818	-6.301330	-0.078063
0.998246	0.001000	1.149323	-6.947468	-0.324779
0.999561	0.000253	1.150835	-8.605546	0.302816
1.000000	0.000000	1.151342	0.000000	0.000000

Corresponding to:

ITITLE
NPTS, ILE, CLMAG, THETA
X, Y, SC, GAM1, GAM2
etc.

Where:

ITITLE = Title defining aerofoil to appear on plots.
NPTS = Total number of points defining aerofoil.
ILE = Node number of leading edge.
CLMAG = Lift coefficient.
THETA = Inclination of lift coefficient.
X, Y = Non-dimensional co-ordinates defining aerofoil.
SC = Node distances over curved surface incremental
from leading edge.
GAM1 = Panel strength for $\alpha = 0^\circ$.
GAM2 = Panel strength for $\alpha = 90^\circ$.

19.8 Table 13 : PLOT.DAT

LABEL		
SYMB0		
TITLE Chord	0.468313	m
FRAME		
RATIO		
AXIS X		
AXIS Y		
LABEL		
SYMB0		
0.064060	0.102495	
0.077439	0.087630	
LABEL		
SYMB0		
0.181502	-0.165487	
0.183492	-0.145587	
LABEL		
SYMB0		
0.000000	0.000000	
0.000462	0.003551	
0.001846	0.012287	
0.004150	0.023048	
0.007371	0.032314	
0.011501	0.041097	
0.016535	0.049246	
0.022463	0.056036	
0.029276	0.066461	
0.036960	0.075344	
0.045502	0.084238	
0.054889	0.094394	
0.065102	0.103331	
0.076124	0.111435	
0.087936	0.118865	
0.100517	0.125637	
0.113846	0.131770	
0.127897	0.137282	
0.142648	0.142189	
0.158072	0.146510	
0.174142	0.150263	
0.190829	0.153465	
0.208106	0.156134	
0.225940	0.158288	
0.244302	0.159944	
0.263158	0.161121	
0.282476	0.161835	
0.302221	0.162105	
0.322360	0.161949	
0.342857	0.161383	
0.363675	0.160426	
0.384779	0.159096	
0.406131	0.157410	
0.427694	0.155387	

0.449430	0.153043
0.471301	0.150396
0.493268	0.147465
0.515293	0.144266
0.537338	0.140818
0.559363	0.137139
0.581330	0.133246
0.603201	0.129156
0.624937	0.124889
0.646500	0.120460
0.667852	0.115889
0.688956	0.111192
0.709774	0.106388
0.730271	0.101494
0.750410	0.096528
0.770156	0.091508
0.789473	0.086451
0.808330	0.081375
0.826691	0.076298
0.844526	0.071238
0.861802	0.066212
0.878490	0.061238
0.894560	0.056334
0.909984	0.051518
0.924734	0.046807
0.938786	0.042218
0.952114	0.037771
0.958286	0.035593
0.964033	0.033368
0.969353	0.031093
0.974248	0.028770
0.978717	0.026398
0.982761	0.023977
0.986379	0.021508
0.989572	0.018989
0.992338	0.016423
0.994679	0.013807
0.996595	0.011143
0.998085	0.008430
0.999149	0.005669
0.999787	0.002859
1.000000	0.000000

LABEL
SYMB0

0.000000	0.000000
0.000462	-0.002684
0.001846	-0.011030
0.004150	-0.024021
0.007371	-0.034857
0.011501	-0.044152
0.016535	-0.051418
0.022463	-0.064348
0.029276	-0.073622

0.036960	-0.085133
0.045502	-0.093884
0.054889	-0.105238
0.065102	-0.115230
0.076124	-0.124903
0.087936	-0.133151
0.100517	-0.141170
0.113846	-0.147713
0.127897	-0.153668
0.142648	-0.158047
0.158072	-0.162878
0.174142	-0.164707
0.190829	-0.166406
0.208106	-0.167712
0.225940	-0.168577
0.244302	-0.169018
0.263158	-0.169050
0.282476	-0.168691
0.302221	-0.167955
0.322360	-0.166858
0.342857	-0.165416
0.363675	-0.163644
0.384779	-0.161560
0.406131	-0.159178
0.427694	-0.156515
0.449430	-0.153586
0.471301	-0.150406
0.493268	-0.146993
0.515293	-0.143361
0.537338	-0.139527
0.559363	-0.135507
0.581330	-0.131315
0.603201	-0.126968
0.624937	-0.122483
0.646500	-0.117874
0.667852	-0.113157
0.688956	-0.108349
0.709774	-0.103465
0.730271	-0.098521
0.750410	-0.093533
0.770156	-0.088516
0.789473	-0.083487
0.808330	-0.078462
0.826691	-0.073455
0.844526	-0.068484
0.861802	-0.063563
0.878490	-0.058709
0.894560	-0.053937
0.909984	-0.049264
0.924734	-0.044704
0.938786	-0.040275
0.952114	-0.035992
0.958286	-0.033899

0.964033	-0.031762
0.969353	-0.029581
0.974248	-0.027357
0.978717	-0.025088
0.982761	-0.022776
0.986379	-0.020421
0.989572	-0.018021
0.992338	-0.015578
0.994679	-0.013091
0.996595	-0.010560
0.998085	-0.007986
0.999149	-0.005368
0.999787	-0.002706
1.000000	0.000000

19.9 Table 14 : Stagnation Point Locations

Lip Profile	Speed		Stagnation Point Location m aft of leading edge
	kt	m.s ⁻¹	
90	180	92.6	0.0000
135	180	92.6	-0.0035
180	180	92.6	-0.0010
90	120	61.73	-0.0030
135	120	61.73	0.0000
180	120	61.73	-0.0010

negative indicates lower surface

19.10 Table 15 : TRAJ2 Arrays

Array Size (Number of Elements)	Number of Arrays
40 000	1
1 000	6
200	24
151-153	22
57-59	10
44	5
29-32	16
14-16	3
4	5

19.11 Table 16 : Case Comparison Chart

Case	Lucas Photo. Ref.	Fig.	Fig.
15 - 18	MX211/1 MX206/1 MX206/19 MX208/4	60 - 63	P23 - P26 P117 - P120 P43 - P46 P137 - P140 P63 - P66 P157 - P160 P83 - P86 P177 - P180

19.12 Table17(a) : Theoretical Cases

Case	Lip Angle °	Flow Vel. ms ⁻¹	LWC gm ⁻³	drop dia. µm	Temp. °C	Ice Time min.	xstag m	Ambient Press. kPa
1	90	92.6	0.3	20	-20.0	2 %	0.0000	74.808
2	180	92.6	0.3	20	-20.0	2 %	0.0000	74.808
3	90	61.73	0.3	20	-20.0	2 %	-0.0030	74.808
4	135	61.73	0.3	20	-20.0	2 %	0.0000	74.808
5	90	92.6	0.6	20	-20.0	2 %	0.0000	74.808
6	180	92.6	0.6	20	-20.0	2 %	0.0000	74.808
7	90	61.73	0.6	20	-20.0	2 %	-0.0030	74.808
8	135	61.73	0.6	20	-20.0	2 %	0.0000	74.808
9	180	61.73	0.6	20	-20.0	2 %	-0.0010	74.808
10	180	92.6	0.3	20	-20.0	2 %	0.0000	74.808
11	180	92.6	0.3	20	-20.0	2 %	0.0000	74.808
12	180	92.6	0.3	20	-20.0	2 %	0.0000	74.808
13	180	92.6	0.3	20	-20.0	2 %	0.0000	74.808
14	180	92.6	0.3	20	-20.0	2 %	0.0000	74.808
15	180	92.6	0.3	20	-20.8	1.5	0.0000	74.808
16	90	92.6	0.3	20	-19.8	1.75	0.0000	74.808
17	135	92.6	0.3	20	-19.8	1.75	-0.0035	74.808
18	180	92.6	0.3	20	-19.8	1.75	0.0000	74.808
19	135	92.6	0.3	20	-20.0	1.75	0.0000	74.808
20	135	92.6	0.3	20	-20.0	1.75	0.0000	74.808
21	180	92.6	0.3	20	-20.0	1.75	0.0000	74.808
22	180	92.6	0.3	20	-20.0	1.75	0.0000	74.808
23	180	92.6	0.3	20	-20.0	1.75	0.0000	74.808
24	180	92.6	0.3	20	-20.0	1.75	0.0000	74.808
25	180	92.6	0.3	20	-20.0	1.75	0.0000	74.808

2% = time to accrete leading edge ice thickness of 2% chord

19.13 Table17(b) : Theoretical case Plot index

Case	CLE	Figure numbers PTRAJ2/TRAJ2	CLE	BLF	Figure Numbers PTRAJ3/TRAJ3
1	1.0	P9, P29, P49, P69	1.5	1.0	P103,P123,P143,P163
2	1.0	P10, P30, P50, P70	1.5	1.0	P104,P124,P144,P164
3	1.0	P11, P31, P51, P71	1.5	1.0	P105,P125,P145,P165
4	1.0	P12, P32, P52, P72	1.5	1.0	P106,P126,P146,P166
5	1.0	P13, P33, P53, P73	1.5	1.0	P107,P127,P147,P167
6	1.0	P14, P34, P54, P74	1.5	1.0	P108,P128,P148,P168
7	1.0	P15, P35, P55, P75	1.5	1.0	P109,P129,P149,P169
8	1.0	P16, P36, P56, P76	1.5	1.0	P110,P130,P150,P170
9	1.0	P17, P37, P57, P77	1.5	1.0	P111,P131,P151,P171
10	1.1	P18, P38, P58, P78	1.1	1.0	P112,P132,P152,P172
11	1.2	P19, P39, P59, P79	1.2	1.0	P113,P133,P153,P173
12	1.3	P20, P40, P60, P80	1.3	1.0	P114,P134,P154,P174
13	1.4	P21, P41, P61, P81	1.4	1.0	P115,P135,P155,P175
14	1.5	P22, P42, P62, P82	1.5	1.0	P116,P136,P156,P176
15	1.0	P23, P43, P63, P83	1.5	1.0	P117,P137,P157,P177
16	1.0	P24, P44, P64, P84	1.5	1.0	P118,P138,P158,P178
17	1.0	P25, P45, P65, P85	1.5	1.0	P119,P139,P159,P179
18	1.0	P26, P46, P66, P86	1.5	1.0	P120,P140,P160,P180
19	1.0	P27, P47, P67, P87	1.5	1.0	P121,P141,P161,P181
20	1.0	P28, P48, P68, P88	1.5	1.0	P122,P142,P162,P182
21			1.5	0.8	P183,P188,P193,P198
22			1.5	0.6	P184,P189,P194,P199
23			1.5	0.4	P185,P190,P195,P200
24			1.5	0.2	P186,P191,P196,P201
25			1.5	0.0	P187,P192,P197,P202

19.14 Table17(c) : Theoretical Ice Catch

PTRAJ2/TRAJ2

(ie. 'sharp' trailing edge)

Case	Foil chord mm	Catch							
		Upper surface				Lower surface			
		% chord	% lip chord	% s/c	mm aft of l.e	% chord	% lip chord	% s/c	mm aft of l.e
1	402	2.0	9.3	9.3	37	7.0	24.1	13.5	38
2	285	3.2	9.3	9.8	28	12.1	40.6	22.8	65
3	402	2.0	9.3	9.1	36	17.8	61.2	24.7	99
4	339	2.0	39.9	9.5	32	7.0	21.6	13.5	46
5	402	2.0	9.3	9.3	37	7.0	24.1	13.5	54
6	285	2.0	19.0	7.5	21	14.9	50.0	26.0	74
7	402	1.4	6.5	5.5	22	13.2	45.4	22.7	91
8	339	1.2	23.9	5.5	19	13.4	41.3	22.7	77
9	285	0.7	6.7	4.0	11	15.0	50.3	26.0	74
10	318	2.8	29.7	8.3	26	13.4	50.1	23.3	74
11	354	4.1	48.4	10.2	36	9.5	39.6	23.0	81
12	396	4.8	63.4	10.5	42	9.5	44.3	17.4	69
13	442	5.2	76.6	10.8	48	8.1	42.1	15.2	67
14	493	5.8	95.3	11.0	54	5.1	29.6	10.9	54
15	285	2.0	19.0	7.5	21	14.9	50.0	26.0	74
16	402	2.0	9.3	9.3	37	7.1	24.4	13.6	55
17	339	2.0	39.9	9.3	32	7.2	22.2	13.7	46
18	318	1.9	20.1	7.5	24	14.9	55.7	26.0	83
19	339	2.0	39.9	9.3	32	5.0	15.4	11.1	38
20	339	2.0	39.9	9.3	32	5.0	15.4	11.2	38

19.15 Table17(d) : Theoretical Ice Catch

PTRAJ3/TRAJ3

(ie. 'blunt' trailing edge)

Case	Foil chord mm	Catch							
		Upper surface				Lower surface			
		% chord	% lip chord	% s/c	mm aft of l.e	% chord	% lip chord	mm aft of l.e	% s/c
1	662	2.9	22.3	9.0	60	2.2	12.4	5.8	38
2	468	5.2	81.1	10.7	50	6.5	35.8	13.5	63
3	662	0.7	5.4	4.4	29	4.6	26.0	8.5	56
4	558	3.7	121.4	9.7	54	3.7	18.8	7.5	42
5	662	2.9	22.3	9.0	60	2.2	12.4	5.8	38
6	468	5.2	81.1	10.7	50	6.5	35.8	13.5	63
7	662	0.7	5.4	4.4	29	4.6	26.0	8.5	56
8	558	3.7	121.4	9.7	54	3.7	18.8	7.5	42
9	468	3.7	57.7	8.6	40	6.5	35.8	13.5	63
10	302	3.7	37.2	10.0	30	10.0	35.5	21.0	63
11	337	4.0	44.9	10.1	34	10.0	39.6	20.1	68
12	337	4.0	44.9	10.1	34	10.0	39.6	20.1	68
13	420	4.7	65.8	10.4	44	7.5	37.1	15.5	65
14	468	5.2	81.1	10.7	50	6.5	35.8	13.5	63
15	468	5.2	81.1	10.7	50	6.5	35.8	13.5	63
16	662	2.9	22.3	9.0	60	2.2	12.4	5.7	38
17	558	2.2	72.2	7.2	40	10.0	50.7	14.9	83
18	468	5.2	81.1	10.7	50	6.5	35.8	13.5	63
19	558	4.0	131.3	10.0	56	6.5	33.0	10.9	61
20	558	4.0	131.3	10.1	56	6.5	33.0	10.9	61
21	439	4.9	71.7	10.5	46	6.9	35.6	14.4	63
22	409	4.6	21.9	10.4	43	7.4	25.9	15.5	63
23	380	4.4	98.4	10.3	39	8.0	27.6	16.7	63
24	350	4.0	16.3	10.1	35	8.7	26.0	18.1	63
25	320	3.8	40.5	10.0	32	9.5	35.8	19.8	63

20 Computer System

Spraymat Design

For Spraymat design purposes, the new computer system must be capable of running TRAJ2, PTRAJ3 and TRAJ3. As mentioned earlier, TRAJ2 and TRAJ3 are more demanding programs on the computer system than PTRAJ3, and thus a system capable of satisfying the requirements of TRAJ2 and TRAJ3 is automatically capable of running PTRAJ3. Thus, TRAJ2 only was the program used for assessment of the specification necessary for the new system. At RAE, TRAJICE2 is run on a VAX 11/750 mainframe computer with VMS (virtual memory system) and occasionally on a MICROVAX 2000 micro computer (also with VMS). Virtual memory means that effectively the store memory is opened up as extra RAM, working memory. The system carries out the organisation itself by temporarily sending data not in immediate use to store. It then retrieves it as and when required, rather than attempt to place all of the data used in a complete run of the program in RAM memory throughout the run, as is the case in non-virtual memory systems. At Cranfield, during the interim, before establishment of the new computer system at Lucas Aerospace, TRAJ2 was developed on another VAX 11/750. The Fortran coding file of TRAJ2 ("TRAJ2.FOR") occupies approximately 300 blocks of storage space on the VAX, a block being equivalent to 0.5 kb, making TRAJ2 150 kb in size. Within the program are many arrays (Table 15) requiring a total of 56000 data elements. Additionally there are over 400 variables in the program. Thus, allowing four bytes per data element, the data alone required during a run of TRAJ2 requires some 230 kb of RAM. Once linked to the graphical routines required, it would therefore be safe to assume that the program requires of the order of 1 Mb of RAM when also taking the extensive I/O (input/output) data into account. It is the executable version (machine code) of the program ("TRAJ2.EXE") which is actually linked to the 'called' routines, and is run through the processor. TRAJ2.EXE occupies a memory space of similar size to TRAJ2.FOR and thus the previous minimum requirement of 1 Mb of RAM still applies.

TRAJ2 and PTRAJ3, as explained earlier, contain CFD panel methods to evaluate the aerofoil panel strengths and develop droplet trajectories. They are therefore highly iterative in nature, requiring a relatively vast amount of 'number crunching'. Taking for example, in TRAJ2, the tracking of a streamline and subsequent formation of a droplet trajectory. Subroutine TRACAL is 'called' once for each droplet trajectory, there being typically eight trajectories in a case run. Within TRACAL, subroutine RHS is called four times. Subroutine RHS calls subroutine VCAL in which the main 'DO LOOP' is cycled "NPTS-1" times, NPTS being the number of co-ordinates defining the simulated aerofoil, typically 151. Thus for a typical case, the large DO LOOP of VCAL is employed 2400 times. However, in subroutine FOIL, there exists a DO LOOP within a DO LOOP, which is itself within a DO LOOP, such that the inner most LOOP is cycled 3.5 million times per run of the program. There are some 88 DO LOOPS in all within the program, six occurrences of a DO LOOP within a DO LOOP, and one occurrence of a DO LOOP within a DO LOOP within a DO LOOP. Thus it can be seen that there is a great deal of mathematical manipulation within each run of the program and hence, should it be run on a micro

computer, rather than mainframe or mini, then a math co-processor is a definite requirement. This assessment was further justified by eventually running the program on a PC (Compaq Deskpro 386) at Bristol University with and without use of the '80387' maths co-processor. Without the co-processor, the run time was approximately 4.5 hours. This was reduced to 44 minutes using the co-processor.

All of the icing software is written in Fortran, therefore it is necessary for the new computer system to contain a suitable Fortran software package. As the three RAE programs (TRAJICE2, HRB1D and TMOD2DPC) were originally written on a VAX computer, advantage was taken of the VAX Fortran extensions to standard Fortran (Fortran 77). Therefore, to reduce this dependence on VAX, the software has been developed to contain only standard Fortran 77 (as mentioned earlier). The most favourable alternative for the new system when considering only the running of the four icing programs would be a microvax 2000 as all VAX systems use the same operating system and thus require no alterations to software between systems. However, to facilitate the rest of the department, the new system would have to employ the MSDOS operating system and thus would not be directly 'VAX compatible'.

For online observation (viewing) of the graphical results produced, most of the more usable part of the results of all of the icing programs being in graphical form, and also in order to assess their applicability with respect to the requirement for subsequent program executions, it is necessary to facilitate colour graphics of reasonable dimensions and resolution. Thus it was established that what was required was an Intel 386 micro processor based personal computer operating at a 'clockspeed' (working speed) of 16 MHz or greater, preferably with a 16 inch colour screen of 'VGA' (Video Graphics Array) graphics resolution. It should also have the facility for future upgrade to ultra VGA "UVGA" to incorporate CAD "computer aided design" compatibility). Hence, it was additionally necessary to acquire a suitable graphics software package of routines capable of emulating the requirements of the icing programs. At RAE, the package used was a CIL package suitable for VAX use, but rather dated and not really suitable for MSDOS on PC's. At Cranfield was a 'BENSON' package, again not really suited to the new application in mind. There are now many options available of standard graphics software packages, which prompted a survey of the market. The final decision was to employ the well established and supported "Lotus Freelance" package. This choice was found acceptable to all other applications within the department for which a graphics capability was required.

Regarding peripheral equipment, in order to safeguard against accidental damage due to operator error, power failure, foreign object damage, etc., it is essential to provide some form of backup memory recording to support the new computer system. The preferential solution is a standard tape 'streamer' as the number of floppy disks required to provide a back-up on 'floppies' would be excessive (84 1.44 Mb 3.5 inch disks for a 120 Mb store).

As the main part of the output from the icing programs is graphical, there is a requirement for a plotter. Although all of the

plotted output from these four programs is arranged to fit A4 paper, it is clearly foreseeable that A3 will be required at some future time and thus a plotter capable of handling both A3 and A4 is necessary. The one and two-dimensional thermal transient programs (HRB1D and TMOD2DPC) output graphs displaying several curves of a similar nature on one set of axes (temperature histories at several levels within a composite laminate) and thus demonstrate a definite need for a six pen plotter (six colours). In addition to the graphical output, there is from all four programs, a great deal of printed data (to support the graphs), and thus a standard printer is also required. As for the graphical software package, surveys of available Fortran compilers, A4/A3 6-pen plotters and printers were executed. Thus it was established that the new computer system would contain an 80386 based PC with 80387 math co-processor, "PROSPERO" Fortran compiler, 16 inch colour VGA screen, tape streamer, Hewlett Packard HP7475A six pen plotter, and 'Epson FX1050' line printer.

In order to process the large arrays in a reasonably fast manner, without slowing down the system excessively much for other users, and to cope with possible future additions and expansions to the programs, it was foreseen that the new system should be capable of accepting either some form of virtual memory system (e.g. "XENIX") or contain at least 8 Mb of RAM. To avoid continual adding of memory store at increased cost, the system should possess a good sized store from the onset to cope with all of the needs of the department. This was assessed at around 500 Mb, or a minimum of 300 Mb. As explained earlier, it would be extremely useful and time saving in the future to be able to input the intake lip (or other body) profiles direct from drawings using a standard digitising 'mouse'.

Hence the actual PC system should include a plotter, printer, mouse, streamer, 16 inch UVGA screen, and be capable of comfortably running at at least 16 Mhz with a minimum 8 Mb of RAM and minimum 300 Mb of store. A considerable number of such machines are offered on the market, which created an extensive assessment programme. However, the timing of this research programme conveniently coincided with two important, large breakthroughs in PC and PC operating system design and development which eventually established a clear 'winner' in the assessment with a performance/cost level beyond all competition. This system is in the new IBM PS/2 range of PC's with the, also new, OS/2 operating system. PS/2 employs a completely new architecture ("Microchannel") offering fewer parts, improved reliability and enhanced scope for growth and development without restructuring at each stage. Thus the chosen option for spraymat design (and to suit the rest of the department), the PS/2 model 80 runs at 20 MHz, was configured with 16 Mb of RAM and 628 Mb of store. It has been designed to be capable of running at 80 MHz with 64 Mb of RAM and several Gb of store when these facilities become available in the future. It was recognised during the assessment, that for "value-for-money" and a realistic depreciation life in excess of ten years where no parts are made redundant during upgrades, and with the support of a well established manufacturer, the IBM PS/2 range offered clear advantages above all other options. No other option offered any comparable

consideration of the purchaser's continual upgrade, financial depreciation and growing demand requirements.

Considering the operating system, although MSDOS is extremely well established and easy to use, with widely accepted compatibility between systems and a great deal of software package support, it has a severe 640 kb memory limitation which has previously never been successfully broken. It is also 'single tasking' ie. only one operation may be effected at a time. Thus it is not possible for instance to edit a program or input data whilst a large program is running and the system may therefore stand effectively unusable for 44 Minutes whilst TRAJ2 or TRAJ3 are running. Using the new OS/2 operating system from IBM for which the PS/2 was designed, which is capable of running existing MSDOS applications, the old 640 kb limit is currently opened up to 16 Mb. OS/2 is also 'multi-tasking' being capable of running many applications simultaneously, e.g. TRAJ3 may be running in the background, also PTRAJ3, graphical output may be being transferred to the plotter, new input data may be entered via the mouse, and an edit on another program may be carried out, all at the same time. Hence the system utilisation factor is high, and the implications for the rest of the department in their computing requirements as well as those for spraymat design are extensive. An advantage of employing both the PC and the operating system from the same manufacturer is in 'single sourcing' such that the two are completely compatible (designed with that in mind), and that any problems, difficulties or queries are dealt with by a single organisation who consider implications to both entities. Therefore it was decided to opt for an IBM tape streamer (which is incorporated in the 'system box' for the PS/2). For cost, availability and acceptability within the company, the HP7475A and Epson FX1050 were not displaced by IBM equivalents, due to their excellence in their particular fields, but were purchased from the same distributor as the rest of the IBM equipment.

Engineering Department

During the assessments mentioned above, all other areas of application within the engineering department (also incorporating the 'Quality Control' department) were catered for, resulting in the eventual decision to construct a PC network (detailed later). These other areas requiring computing facilities over and above those presently available (and about to be replaced), within the department, are briefly described below.

CAD/CAM

Computer aided manufacture (CAM) is still some way from full consideration within the engineering department, relatively plentifully available in a number of options within the market and awaiting an assessment of the effectiveness of the implementation of computer aided design (CAD) before CAM will be more seriously considered. In this manner it is intended to arrange the CAD and CAM systems to be fully compatible in a computer integrated management (CIM) system. Thus as the computing power requirements of a CAD system

are much greater than those of a CAM system (for the order of extensivity of both required at Lucas Aerospace) such that, apart from a relatively small amount of additional specific software, a system capable of satisfying the CAD requirements of the department, would easily be capable of satisfying its CAM requirements. Thus only the CAD system requirements are considered for the computer system designation exercise.

The immediate applicability of a CAD system is only for 'art' work in designing electroluiminescent lighting (EL) panels and their associated legends, but it is realised that it would subsequently be applied to the production of engineering drawings and, on a longer term, implementation of a full three-dimensional CAD system. Such a CAD system using a single work station (part time) would require an 80386 based processor with maths co-processor working at a minimum speed of 16 MHz with at least 1 Mb RAM and 70 Mb store. It would require a high resolution screen of at least 16 inches diagonal dimension and eventually an A0 plotter with immediate requirement for an A4/A3 plotter. Thus the option taken (previous section) for the computer system is fully compatible with the minimum requirements for CAD/CAM. The main CAD software will initially be in the form of a standard proprietary package such as "AUTOCAD" or "ANVIL" which are easily accommodated under the specified hardware and operating system. Further hardware to better facilitate CAD as the network develops will include the above mentioned A0 plotter, a graphics digitising 'Tablet', a 20-30 inch screen, and eventually a 'super-micro' processor such as the IBM RS6000 to operate a comprehensive 3-D software package such as CATIA (IBM).

General Engineering Office

This area of usage of the system is the most variable and unpredictable as it covers a wide range of activities not already covered in the specific subject areas. To assess the needs of the various sections within the office required communication with each future potential 'user' to not only assess his current computing requirements, but also predict how they would grow once adequate facilities were available. In this manner it was intended to provide a system to satisfy all possible users well into the future. This study initiated the requirements for several peripherals, such as a 'modem' (telephone communication with other computers) of international coverage, and an optical disk data storage system for the technical library. Also required are a postscript quality laser printer and scanner for the technical authors to produce maintenance manuals (a considerably large activity in an aerospace company producing relatively small order items), and a 5.25 inch external disk drive to accommodate reading of all incoming data, etc.. Regarding software, there was a demand for several commercially available standard packages such as, a desktop publishing (DTP) package for the technical authors, a modern multi-tasking word processor for the secretaries (and engineers), a programme managers package for the section leaders, various calculation packages such as Lotus spreadsheets, "data-ease", etc. for the engineers and eventually an FEA (Finite element analysis) package. Considering the latter requirement for engineering stressing

purposes, it will also be advantageous to investigate several new finite element 'mesh' generation packages now available claiming to be compatible with both the standard CAD packages and standard FEA packages, allowing a single model geometry to automatically generate the CAD and FEA grids, thus offering significant potential effort, time and cost savings. Useful programming languages to include would be Basic, BasicA, Fortran, Pascal and C. One of the lesser activities encompassed within the engineering department is PCB (printed circuit board) design for integration in some of the equipment produced. There are now several standard PCB design commercial software packages available.

When assessing the actual computing power requirements of this sector, it is the FEA software which requires the greatest computing power. It would be safe to assume that a 3000 element model will suffice the requirements of Lucas Aerospace at Luton for the foreseeable future, with all the usual rotational, translational, vibrational and display modes currently available and introduced to the market during the interim between procurement of the system hardware and eventual acquisition of the FEA software. Hence it would be reasonable to assume a minimum requirement for 2 Mb of RAM and 70 Mb of store, thus fitting comfortably within the previously determined system specification.

20.1 Proposed Computer Network

As stated earlier, all of the material gained in the various investigative and assessment activities was correlated to arrive at the proposed network of (Fig.64). For economic and potential utilisation reasons, the network will be acquired in a progressive manner, constructed from the integration of seven blocks of equipment purchase (Fig.64(a-g)). The timescale applicable is somewhat flexible dependent on growing demand, but estimated dates of procurement are indicated within the diagram. The over-riding main economical objectives to this approach to acquisition were that all equipment purchased should be immediately useable, no equipment should be disregarded as the network is constructed, all of the block purchases were of the same order of financial cost, and the level of facilities provided should approximately match their order of requirement within the organisation. The network must also be capable of being extended to cover the whole manufacturing site and must be able to effectively and efficiently communicate with other Lucas sites and all major customers and suppliers. It must also have the potential to link to modern mainframe and mini computers without the requirement for complex interface systems (excluding the current Lucas Aerospace (Luton) mini computer). The network shown in (Fig.64) satisfies all of these requirements with the potential to exceed them comfortably beyond the level to which these general requirements themselves will progress into the future.

APPENDIX C

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BIBLIOGRAPHY

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BIBLIOGRAPHY

A Bibliography of Work Associated with Aircraft De-Icing

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Report 8817, January 5, 1989

1 SUMMARY

This report contains a bibliography of material associated with the icing and de-icing of aircraft and parts thereof. It was compiled as a part of the Total Technology PhD research programme "The Application of Computational Techniques to the Design of Thermal Ice Protection Systems", by C. W. Leah at the College of Aeronautics, Cranfield Institute of Technology, 1989.

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2 INTRODUCTION

This bibliography of experimental and theoretical work on subjects associated with aircraft icing is compiled as a part of the Lucas Aerospace/Cranfield PhD research programme and is merely a list of references. Some of the material referenced is given a more detailed analysis within the research programme. No bibliography can be considered to contain 100% of a universal literature survey, but this bibliography may be considered to contain most of the work more specifically oriented to aircraft de-icing available in Europe, USA and Canada, most of the work carried out on aerofoil ice accretion, a large amount of experimental work on the physical properties of ice, and a selection of reports and articles on associated meteorology.

The bracketed reference numbers refer to the original index situated with the author, and remain for convenience in cross-referencing throughout the PhD research programme at the College of Aeronautics, Cranfield Institute of Technology for Lucas Aerospace Limited, Luton, during which the bibliography has been continually updated. Articles are referenced title first. An author index giving the reference number (bracketed) and section of articles by the various listed authors is presented in the Appendix. It should be noted that the spelling of the author's names is taken either from their articles or from a reference to an article, thus all reasonably conceivable spellings should be consulted. Although many articles may be applicable to several areas headed, each article is referenced (in full) only once under the heading of major interest to that article, and cross-referenced by number (bracketed) only, in other sections of interest to the article. In cases where a report is located by bracketed number only, in the "Also References" block at the end of a section or subsection, the section containing the complete description of the reference may be located using the cross reference index (Table 1) in the Appendix, from whence the full description of the reference may be located and observed. "Unseen" articles are cross-referenced only from the implications of their title. For a list of analysed articles see Table 2 in the Appendix.

The material in each subsection is arranged in chronological order with undated material situated at the end of that subsection. The subsections with titles containing the word "General", contain references specific to the main section in which it is situated but not specific to a particular subsection in that section. Also featured in the "General", subsections are reports, unseen, which appear from their titles to be of a general nature, but may be of a more specific nature classifiable in one or more of the subsections presented. Thus, when looking for material on a particular subject, it is important to study the associated "General" section.

Some articles dated pre 1965 reference further material by author, omitting the title. Some of this material (referenced in "Miscellaneous" subsections), remains unlocated in this bibliography but may contain useful background reading.

3 BIBLIOGRAPHY

3.1 Physical Properties Of Ice

3.1.1 Density

1. (542) "The Density of Hailstones Collected from a Summer Storm". W. C. Macklin, E. Strauch and F. H. Ludlam, Quarterly Journal of the Royal Meteorological Society, Vol.3, pp.12, 1960
2. (217) "The Density and Structure of Ice Formed by Accretion". W. C. Macklin, Imperial College, London (Now at Department of Physics, Nedlands, University of Western Australia). Royal Meteorological Society Quarterly Journal, Vol.88, No.375, pp.30-50, January 1962
3. (400) "Measurement and Correlation of Water Frost Thermal Conductivity and Density". Biguria and Wenzel, I and EC Fundamentals, Vol.9, No.1, pp.129, February 1970
4. (393) "The Density of Ice Collecting on Rotating Cylinders". D. L. Loughborough, B. F. Goodrich Company

Also references : 125 311 395 399 404

3.1.2 Strength

5. (298) "Experiments on Strength of Ice". E. Brown, In Report of Joint Board of Engineers, St. Lawrence Waterway Project, pp.423-453, Ottawa, 1926
6. (529) "Strength Studies on Snow". M. Mellor and James H. Smith, Symposium on the Scientific Aspects of Snow and Ice Avalanches, Davos. CRREL Research, Report 168, pp.1-21, 1965

Also references : 125 173 239 279 300 333 505 552
598

3.1.2.1 Tension

7. (306) "The Effect of the Speed of Deformation on the Ultimate Strength of River Ice Subject to Uniaxial Tension". K. N. Korzhavin Trudy Novosibirskogo Instituta Inzhenerov Zheleznodorozhnogo Transporta, Vol.11, pp.205-216, 1955
8. (309) "The Differences in the Properties of Ice Under Compression and Under Tension". V. V. Lavrov, The Arctic and Antarctic Scientific Research Institute (Presented by B. P. Konstantinov, November 21, 1964), Translated from Doklady Akademii Nauk SSSR, Vol.162, No.1, pp.54-56, May 1965. Soviet Physics-Doklady, Vol.10, No.5, pp.429-431, 1965

Also references : 125 173 205 239 285 298 299 300
315 335 507 555 557

3.1.2.2 Compression

9. (307) "The Ultimate Compressive Strength of Permafrost and Ice in their Natural States". I. S. Khomichevskaya Trudy Komiteta po Vechnoy Merzlote, Vol.10, pp.37-83, 1940
10. (299) "Ultimate Strength of Ice". T. R. Butkovich U.S. Snow, Ice and Permafrost Research Establishment Research Paper 11, 1954
11. (525) "Crushing Strength of Lake Ice". T. R. Butkovich, Snow, Ice and Permafrost Research Establishment, Corps of Engineering, U.S. Army Research Paper 15, pp.5, 1955
12. (308) "Evaluation of the Compressive Strength of Ice Under Short-Term Rapidly Increasing Load". K. N. Korzhavin, Materialy VIII Vsesoyuznogo Mezhdunarodnogo Soveshchaniya po Geokriologii (Merzlotovedeniye), Tom 5, pp.61-72, 1966

Also references : 125 205 300 302 303 309 311 312
313

3.1.2.3 Shear

13. (506) "Tests on the Shearing Strength of Ice". John N. Finlayson, Canadian Engineering, Vol.53, No.1, pp.101-103, 1927

14. (556) "Effect of Hydrostatic Pressure on Shear Deformation of Single Ice Crystals". G. P. Rigsby, Journal of Glaciology, Vol.3, pp.273-278, 1958
15. (290) "Shear Characteristics of Ice in Bulk at Ice/Solid Interfaces, and at Ice/Lubricants Solid Interfaces in a Laboratory Device". T. F. Ford and O. D. Nichols, Naval Research Laboratory Report, pp.5662, NRL Problem C02-14, Project SF 013-99-02, Task 059, June 13, 1961
16. (605) "The Shear Strength of Ice". I. E. Kozitsokii, Meteorologiya i Gidrologiya, No.3, pp.103-105, 1978
17. (597) "Structural Properties of Impact Ices". R. J. Scavuzzo and M. L. Chu, Mechanical Engineering Department, The University of Akron, Akron, Ohio. William V. Olsen, NASA Lewis Research Center, Cleveland, Ohio. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986

Also references : 125 239 279 288 299 300 315 319
335 412 604

3.1.2.4 Bending

18. (305) "Flexural Strength of Clear Lake Ice". Robert D. Hitch, U.S. Snow, Ice and Permafrost Research Establishment. Corps of Engineers, Wilmette, Illinois. Technical Report 65, July 1959
19. (315) "Bending and Shear Tests on Lake Ice". James T. Wilson and J. M. Horeth, Transactions of the American Geophysical Union, Vol.29, No.6, pp.909-912, 1961

Also references : 300 504

3.1.2.5 Deformation

20. (505) "Mechanical Properties of Single Crystals of Ice. Part 1. Geometry of Deformation". U. Nakaya, SIPRE Research Report 28, pp.1-44, 1958
21. (531) "The Eshelby-Schoeck Viscous Dislocation Damping Mechanism Applied to the Steady-State Creep of Ice". J. Weertman, "Ice and Snow". (W. D. Kingery, ed.), M.I.T. Press, pp.28-33, Cambridge, Massachusetts, 1962

22. (554) "Deformation Mechanisms in Ice". L. W. Gold, "Ice and Snow", (W. D. Kingery, ed.), M.I.T. Press, pp.8-27, Cambridge, Massachusetts, 1963
23. (530) "Non-Basal Slip as a Major Deformation Process in the Creep of Polycrystalline Ice". W. J. McG. Tegart, Journal of Glaciology, Vol.5, pp.251-254, 1964
24. (461) "The Deformation of Ice Single Crystals at Low Temperatures". J. W. Glen and S. J. Jones, Physics of Snow and Ice: International Conference on Low Temperature Science, Vol.1, Pt.1, pp.267-275, Hokkaido University, Japan, 1966
25. (302) "Deformation Rates of Polycrystalline Ice". Howard B. Dillon and O. B. Andersland, Department of Civil Engineering, Michigan State University, East Lansing, Michigan, U.S.A., Physics of Snow and Ice: International Conference on Low Temperature Science Vol.1, Part 1, pp.313-327, Institute of Low Temperature Science, Hokkaido University, 1966
26. (316) "Variations of the Deformation Modulus of Ice in Relation to Temperature and the Duration of Loading". A. E. Yakunin, Ministerstvo Vysshogo i Srednogo Spetsial'nogo Obrazovaniya. Izvestiya, Vysshikh Uchebnikh Zavdenii. Stroitel'stvo i Arkhitektura, Vol.11, No.5, pp.42-43, 1968
27. (205) "Deformation and Fracture of Ice Under Uniaxial Stress". Ivor Hawkes and Malcolm Mellor, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755, U.S.A.. Journal of Glaciology, Vol.11, No.61, pp.103-131, 1972

Also references : 125 306 309 556

3.1.2.5.1 Elastic -

28. (303) "Some Observations on the Dependence of Strain on Stress for Ice". L. W. Gold. Canadian Journal of Physics, Vol.36, No.10, pp.1265-1275, 1958

Also references : 125 205 305 309 311

3.1.2.5.2 Plastic -

29. (613) "Results of Preliminary Experiments on the Plasticity of Ice Crystals". J. Steinemann, Journal of Glaciology, Vol.2, pp.404, 1952

30. (528) "Viscoelastic Properties of Ice". H. H. G. Jellinek, Journal of Applied Physics Vol.27, pp.1198-1209, 1956
31. (552) "The Mechanical Properties of Ice. I. The Plastic Properties of Ice". J. W. Glen, Advances in Physics, Vol.7, pp.254-265, 1958
32. (280) "On the Effect of Pressure in Lowering the Freezing Point of Water and on the Plasticity of Ice". J. Thomson, Belfast Natural History and Philosophical Society, pp.1-4, 1858
33. (527) "Plastic Deformation of Hollow Ice Cylinders Under Hydrostatic Pressure". A. Higashi, SIPRE Research Report 51, pp.1-10, 1959
34. (463) "Plastic Yielding in Ice Single Crystals". A. Higashi, S. Koinuma and S. Mae, Japanese Journal of Applied Physics, Vol.3, No.10, pp. 610-616, 1964
35. (304) "Mechanisms of Plastic Deformation in Ice Single Crystals". A. Higashi, Department of Applied Physics, Faculty of Engineering, Hokkaido University, Sapporo, Japan, Physics of Snow and Ice: International Conference Low on Temperature Science, Vol.1, Part 1, pp.277-289, Institute of Low Temperature Science. Hokkaido University, 1966
36. (277) "The Effect of Hydrogen Disorder on Dislocation Movement and Plastic Deformation of Ice". J. W. Glen, Department of Physics, University of Birmingham, July 7, 1967. Physik der kondensierten Materie Bd.7, Ht.1, pp.43-51, 1968
37. (460) "Plastic Flow and Pressure Melting in the Deformation of Ice I". P. Barnes and D. Tabor, Nature. Vol.210, No.5039, pp.878-882
38. (58) "Plastic Deformation of Thick-Walled Snow-Ice Cylinders Under Hydrostatic Pressure". H. H. G. Jellinek, SIPRE Research Report 63, pp.1-7

Also references : 125 305 309

3.1.2.6 Creep

39. (551) "The Creep of Polycrystalline Ice". J. W. Glen, Proceedings of the Royal Society, A. Vol.228, pp.519-538, 1955

40. (526) "Creep of Ice at Low Stresses". T. R. Butkovich and J. K. Landauer, SIPRE Research Report 72, pp.1-6, 1960
41. (504) "Bending Creep of Ice Single Crystals". A. Higashi, S. Koinuma and S. Mae, Journal of Applied Physics, Vol.4, pp.575-582, 1965
42. (465) "Creep Behaviour of Pure Ice and Ice Dispersed with Ultrafine Amorphous Silica (SiO₂)". H. J. Nayar, Unpublished. PhD Thesis, Department of Materials Engineering, Rensselaer Polytechnic Institute, Troy, New York, 1966
43. (311) "Creep of Snow and Ice". Malcolm Mellor and James H. Smith, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A.. Physics of Snow and Ice: International Conference on Low Temperature Science Vol.1, Part2, pp.843-855, Institute of Low Temperature Science. Hokkaido University, 1966
44. (313) "Effect of Temperature on the Creep of Ice". Malcolm Mellor and Richard Testa, U.S. Army Terrestrial Sciences Center, Hanover, New Hampshire 03755, U.S.A.. Journal of Glaciology, Vol.8, No.52, pp.131-145, 1969
45. (312) "Creep of Ice Under Low Stress". Malcolm Mellor and Richard Testa, U.S. Army Terrestrial Sciences Center, Hanover, New Hampshire 03755, U.S.A.. Journal of Glaciology, Vol.8, No.52, pp.147-152, 1969

Also references : 125 172 239 277 278 279 302 530
531

3.1.2.7 Strength Testing

46. (300) "Recommended Standards for Small-Scale Ice Strength Tests". T. R. Butkovich, U.S. Snow, Ice and Permafrost Research Establishment, Corps of Engineers, Wilmette, Illinois. Technical Report 57, 1958

Also references : 10 19 91 125 146 161 172 205 239
288 290 299 302 303 309 311 312
313 315 319 333 412 597

3.1.3 Cohesion

47. (284) "On the Cohesion of Ice". D. C. Jensen, Pennsylvania State University. MS Thesis, 1956
48. (172) "The Cohesive and Adhesive Strength of Ice". E. H. Andrews and N. A. Lockington, Department of Materials, Queen Mary College, Mile End Road, London E1 4NS. U.K. Journal of Materials Science Vol.18, pp.1455, 1983

Also references : 125 173 239 288 290

3.1.4 Adhesion

49. (412) "Adhesion of Ice in its Relation to the De-Icing of Airplanes". A. M. Rothrock and R. F. Selden, NACA TN 723, August 1939
50. (239) "The Adhesion and Strength Properties of Ice". L. E. Raraty and D. Tabor Research Laboratory for the Physics and Chemistry of Surfaces Department of Physical Chemistry, University of Cambridge, March 5, 1957
51. (286) "Adhesive Properties of Ice". H. H. G. Jellinek, U.S. Army Snow, Ice and Permafrost Research Establishment. Research Report 38, 1957
52. (333) "Strength Characteristics of Ice - in Contact with Various Kinds of Surfaces". S. G. Eskin, The Dole Valve Company, Chicago, W. E. Fontaine, Purdue Center for Research in Refrigeration and Climate Control, and O. W. Witzell, Department of Mechanical Engineering, Purdue University. 44th Semiannual Meeting of ASRE, Chicago, November 14-16, 1957. Refrigerating Engineering, Vol.65, No.12, pp.33-38, 52, December 1957
53. (288) "Adhesive Properties of Ice". H. H. G. Jellinek, U.S. Army Snow, Ice and Permafrost Research Establishment, Corps of Engineers, Wilmette, Illinois. Journal of Colloid Science Vol.14, pp.268-280, January 9, 1959
54. (287) "Adhesive Properties of Ice, Part II". H. H. G. Jellinek U.S. Army Snow, Ice and Permafrost Research Establishment. Research Report 62, 1959
55. (146) "Ice Adhesion". H. H. G. Jellinek, Department of Chemistry, Assumption University, Windsor, Ontario. Canadian Journal of Physics, Vol.40, pp.1294-1309, May 16, 1962

56. (91) "On the Adhesion of Ice to Various Materials". J. R. Stallabrass and R. D. Price, Low Temperature Laboratory, Division of Mechanical Engineering, National Research Laboratories, Ottawa, Canada, NRC LR-350, July 1962
57. (289) "Adhesive Properties of Ice, Part II". H. H. G. Jellinek. Canadian Journal of Physics Vol.40, pp.1294, 1962
58. (319) "Ice Adhesion to Hydrophylic and Hydrophobic Surfaces". W. D. Bascom, R. L. Cottingham and C. R. Singletary, Chemistry Division, Naval Research Laboratory, Washington D.C. 20390. Journal of Adhesion, Vol.1, pp.246-263, June 5, 1969
59. (601) "Adhesion of Rime and Glaze on Conductors Protected by Various Materials". C. L. Phan, P. McComber and A. Mansianx, Transactions of CSME. Vol.4, No.4, pp.204-208, 1976-77
60. (163) "Mechanical Measurement of Interatomic Bonding Energies at Interfaces". E. H. Andrews, Materials Department, Queen Mary College, Mile End Road, London E1 4NS. U.K. Journal of Materials Science, Edited by K. L. Mittal, Plenum Publishing Corporation, 1984

Also references : 125 172 240 290 336 597

3.1.4.1 Metallic Substrate

61. (335) "Ice Formation on Metal Surfaces", W. L. Sibbitt, W. E. Fontaine and J. P. Dotson, Purdue University, Lafayette, Indiana. 50th Annual Meeting of the American Society of Refrigeration Engineers, Philadelphia, November 29 - December 1, 1954. Refrigerating Engineering, Vol.62, No.12, pp.49-51, 92 and 94, December 1954
62. (285) "Tensile Properties of Ice Adhering to Stainless Steel". H. H. G. Jellinek, U.S. Army Snow, Ice and Permafrost Research Establishment. Research Report 23, 1957
63. (600) "The Adhesion of Glaze and Rime on Aluminium Electrical Conductors". J. Druez, C. L. Phan, J. L. Laforte and D. D. Nguyen, Transactions of CSME. Vol.5, No.4, pp.215-220, October 1979
64. (602) "Adhesion of Ice on Aluminium Conductor and Crystal Size in the Surface Layer". J. L. Laforte, C. L. Phan, B. Felin and R. Martin, CRREL Special Report 83-17, 1983

Also references : 91 125 146 172 173 206 239 288
290 319 333

3.1.4.2 Flexible Substrate Or Ice Phobic

65. (161) "Adhesion of Ice to a Flexible Substrate". E. H. Andrews, H. A. Majid and N. A. Lockington, Department of Materials, Queen Mary College, Mile End Road, London E1 4NS. U.K. Journal of Materials Science, Vol.19, pp.73-81. Chapman and Hall, 1984
66. (240) "Adhesion of Ice to Polymers and Other Surfaces". K. Itagaki, U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755, USA

Also references : 10 91 125 239 288 319 333 335 601

3.1.4.3 De-Icer

67. (10) "Reduction of the Adhesion of Ice to De-Icer Surfaces". D. L. Loughborough and E. G. Haas, The B. F. Goodrich Company. Journal of Aerospace Science Vol.13, pp.126-134, March 1946

Also references : 125 161 319

3.1.5 General Mechanical Properties

68. (310) "Review of the Properties of Snow and Ice". H. T. Mantis, U.S. Snow, Ice and Permafrost Research Establishment Report 4, 1951
69. (524) "The Mechanics of Drops". R. R. Hughes and E. R. Gilliland, Proceedings of the Heat Transfer and Fluid Mechanics Institute, pp.53-72, 1951
70. (281) "On Some Properties of Ice Near Its Melting Point". J. D. Forbes, Proceedings of the Royal Society Vol.4, pp.103, Edingburgh, 1858

71. (301) "Some Physical Properties of Ice from the TUTO Tunnel and Ramp, Thule, Greenland". T. R. Butkovich, 1959
72. (604) "The Mechanical Properties of Ice". K. F. Voitovskii, Translation. The American Meteorological Society, 45 Beacon Street, Boston, Massachusetts, 1960
73. (297) "Properties of Ice". Rudolf Brill and Paul R. Camp, U.S. Army Snow, Ice and Permafrost Research Establishment Research Report 68, May 1961
74. (186) "Physics of Snow and Ice". N. Maeno, edited by H. Oura, Hokkaido University, Sapporo, Japan. Proceedings of the International Conference. Vol.1, Part 1, pp.207, Sapporo, Japan, 1967
75. (399) "Cryogenic Frost Properties". P. L. T. Brian and R. C. Reid, Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts. Cryogenic Technology, September/October 1969
76. (125) "Ice Physics". Peter V. Hobbs, University of Washington, Clarendon Press, Oxford, 1974
77. (606) "The Mechanics of Ice". J. W. Glen, CRREL, Monograph 11-C2b, December 1975
78. (1305) "Physics and Mechanics of Ice". International Union of Applied Mechanics". Symposium, Copenhagen, August 6-10, 1979. Editor Per Tryde Professor, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark
79. (184) "Physics and Mechanics of Ice". D. J. Goodman, Springer Verlag pp.129, Berlin, 1980
80. (507) "Mechanical Properties of Ice". Boris Weinberg, International Union of Geodesy and Geophysics. Bulletin 23, Riga
81. (555) "Mechanical Properties of Ice". T. R. Halbrook, Unpublished Ms Thesis, Michigan State University, East Lansing, Michigan
82. (557) "Mechanical Properties of Ice". K. F. Voytkovskiy, Academic Science U.S.S.R

Also references : 205 279

3.1.5.1 Surface Structure

83. (358) "Surface Structure of Water and Some of Its Physical and Chemical Manifestations". W. A. Weyl, Department of Mineral Technology, The Pennsylvania State College, Pennsylvania. Journal of Colloid Science, Vol.6, PP.389-405, April 16, 1951
84. (282) "Evidence of the Existence of a Liquid-Like Film on Ice Surfaces". U. Nakaya and A. Matsumoto, U.S. Army Snow, Ice and Permafrost Research Establishment. Research Paper 4, 1953
85. (294) "Surface Structure of Water and Ice". N. H. Fletcher, Department of Physics, The University of New England, Armidale, N.S.W., Australia. Philosophical Magazine Vol.17, pp.255, July 17, 1961
86. (292) "Liquid-Like Layers on Ice". H. H. G. Jellinek. Journal of Applied Physics Vol.32, pp.1793, 1961
87. (295) "Surface Structure of Water and Ice". R. J. Watts-Tobin, Medical Research Council Laboratory for Molecular Biology, Hills Road, Cambridge, England, October 23, 1962, Revised November 10, 1962. Philosophical Magazine Vol.8, pp.333, 1963
88. (296) "The Growth Habits and Surface Structure of Ice Crystals". B. J. Mason, G. W. Bryant and A. P. Van den Heuvel, Physics Department, Imperial College, London, England. Philosophical Magazine Vol.8, pp.505, January 9, 1963
89. (206) "Liquid-Like (transition) Layer on Ice". H. H. G. Jellinek, Department of Chemistry, Clarkson College of Technology, Potsdam, New York, August 1, 1966
90. (1100) "Some Frictional Properties of Thin Water Films". US Army Snow, Ice and Permafrost Research Establishment, Corps of Engineers, Special Report 37, AD658132, SIPRE, USA

Also references : 125 146 438 602

3.1.6 Supercooling

91. (267) "Mixtures of Air and Vapour at Temperatures Below Freezing". C. D. Shields, Refrigeration Engineering, Vol.38, No.5, pp.293-297, November 1939

92. (537) "The Supercooling of Water". E. K. Bigg, Proceedings of the Physics Society, Series B, Vol.66, pp.688, 1953
93. (610) "The Supercooling and Neucleation of Water". Advances in Physics, Vol.7, No.26, pp.221-234, 1958
94. (541) "The Heterogeneous and Homogeneous Nucleation of Supercooled Water". E. J. Langham and B. J. Mason, Proceedings of the Royal Physics Society, Series A, Vol.247, pp.493, 1958

Also references : 125 398 445 451 596 1024 1025

3.1.7 Effect Of Impurities

95. (388) "The Trapping of Air in the Formation of Rime". J. H. Coste. Quarterly Journal of the Royal Meteorological Society, Vol.66, pp. 365, 1940
96. (336) "Effect of Impurities in Water on Ice Adhesion, Part II". R. Smith-Johannsen, General Electric Research Laboratory, U.S. Army Air Force, Air Material Command, TR 5539, pp.169 et seq, Edited by R. D. Bower, January 1947
97. (314) "Studies of Salt Ice". W. F. Weeks, U.S. Cold Regions Research and Engineering Laboratory. Research Report 80, 1961
98. (598) "Growth, Structure and Strength of Sea Ice". A. Assur and W. F. Weeks, U.S. Cold Regions Research and Engineering Laboratory. Research Report 135, 1964
99. (278) "Softening of Ice Crystals by Dissolved Flouride Ions". S. J. Jones, Physics Letters Vol.25A, No.5, pp.366-367, 1967
100. (279) "The Effect of Dissolved Impurities on the Mechanical Properties of Ice Crystals". S. J. Jones, Philosophical Magazine, Eighth Series, Vol.19, No.157, pp.13-24, 1969
101. (1079) "Ice-Formation by Use of Synthetic Zeolite Nuclei". L. Krastanov and L. Levkov, Institute of Geophysics, Bulgarian Academy of Sciences, Bulgaria

Also references : 125 172 205 239 398 465 596 1045 1069

3.1.8 Spontaneous Freezing

102. (558) "Photomicrographic Investigation of Spontaneous Freezing Temperatures of Supercooled Water Droplets". Robert G. Dorsch and Paul T. Hacker, NACA TN 2142, 1950
103. (559) "Statistical Explanation of Spontaneous Freezing of Water Droplets". Joseph Levine, NACA TN 2234, 1950
104. (1045) "Artificial Ice-Forming Nuclei". B. J. Mason and J. Hallet, Imperial College of Science and Technology, London, Nature Journal, pp.681, April 14, 1956
105. (1078) "A Wind Tunnel Investigation of the Growth Rate and Growth Mode of Ice Particles by Riming". J. C. Pflaum and H. R. Pruppacher, University of California, Los Angeles, California

Also references : 125 398 1069 1079 1082 1097

3.1.9 Micro-Structure

106. (612) "On the Crystalline Form of Ice". J. Smithson, Annals of Philosophy (London), Vol.21, pp.340, 1823
107. (561) "The Crystal Structure of Ice". D. M. Dennison, Physics Review, 2nd Series, Vol.XVII, No.1 pp.20-22, January 1921
108. (562) "The Crystal Structure of Ice Between 0 Degrees Celcius and -183 Degrees Celcius". William Howard Barnes, Proceedings of the Royal Society, London, Series A, Vol.125, No.799, pp.670-693, November 1, 1929
109. (563) "The Crystal Structure of Ice". W. H. Bragg, Proceedings of the Physics Society (London), Vol.XXXIV, pp.98-103, January 7, 1922
110. (564) "The Structure and Entropy of Ice and of Other Crystals with Some Randomness of Atomic Arrangement". Linus Pauling, Journal of the American Chemical Society, Vol.57, No.12, pp.2680-2684, December 27, 1935
111. (565) "Neutron Diffraction Study of the Structure of Ice". E. O. Wollan, W. L. Davidson and C. G. Schull, Physics Review, Vol.75, No.9, pp.1348-1352, May 1, 1949

112. (615) "Solid Solutions of Ice and NH F and Their Dielectric Properties". S. Zaromb and R. Brill, Journal of Chemistry and Physics, Vol.24, pp.895-902, 1956
113. (397) "On the Melting of Hail Stones". B. J. Mason. Quarterly Journal of the Royal Meteorological Society, Vol.82, pp.209, 1956
114. (392) "Rate of Growth of Ice Crystals in Supercooled Water". C. S. Lindenmeyer, G. T. Orrok, K. A. Jackson and B. Chalmers, Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts. Journal of Chemistry, Vol.27, pp.822, 1957
115. (611) "A Single Crystal Neutron Diffraction Study of Heavy Ice". S. W. Peterson and H. H. Levy, Acta Crystallographica, Vol.10, pp.70-76, 1957
116. (283) "On the Aggregation of Ice Crystals to Form Snow". C. L. Hosler, D. C. Jensen and L. Goldshlak. Journal of Meteorology Vol.14, pp.415, 1957
117. (608) "The Growing of Large Single Crystals of Ice". J. K. Landauer, USA SIPRE Research Report 48, pp.7, 1958
118. (609) "The Growth of Ice Crystals from the Vapour and Melt". B. J. Mason, Advances in Physics, Vol.7, No.26, pp.235-253, 1958
119. (614) "Thermal Motion in Ice and Heavy Ice". A. Zajac, Journal of Chemistry and Physics, Vol.29, pp.1324, 1958
120. (173) "The Influence of Imperfections on the Strength of Ice". H. H. G. Jellinek, Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army, Wilmette, Illinois. Proceedings of the Physics Society (London), Vol.71, No.5, pp.797, 1958
121. (390) "The Influence of Temperature and Supersaturation on the Habit of Ice Crystals Grown from the Vapour". J. Hallett and B. J. Mason, Proceedings of the Royal Society, A247, PP.440, 1958
122. (396) "The Composition of Coagulation-Elements in Cumulonimbus". F. H. Ludlam, Imperial College of Science and Technology and Meteorological Office, London. Quarterly Journal of the Royal meteorological Society, Vol.76, pp.52-58, 1958
123. (343) "Optical Characteristics of Water and Ice in the Infrared and Radiowave Regions of the Spectrum". L. D. Kislovskii, Optics and Spectroscopy, Vol.7, No.3, pp.201-206, September 1959
124. (540) "Crystal Growth and the Formation of Spikes on the Surface of Supercooled Water". J. Hallett, Journal of Glaciology, Vol.3, No.28, pp.698, 1960

125. (394) "The Production of Ice Splinters During Riming". W. C. Macklin. Quarterly Journal of the Royal Meteorological Society, Vol.3, pp.30, 1960
126. (398) "The Fragmentation and Electrification of Freezing Water Drops". B. J. Mason and J. Maybank, Imperial College, London. Quarterly Journal of the Royal Meteorological Society, Vol.86, pp.176-185, 1960
127. (395) "Accretion in Mixed Clouds". W. C. Macklin, Imperial College, London. Quarterly Journal of the Royal Meteorological Society, Vol.87, pp.413-424, 1961
128. (467) "Two-Dimensional Grain Growth in Ice". D. v. d. S. Roos, Journal of Glaciology, Vol.6, No.45, pp.411-420, 1966
129. (342) "Radiant Energy Transport within Cryogenic Condensates". D. McConnell, NASA TMX 52192, 1966
130. (341) "Infrared Optical Properties of Water and Ice Spheres". W. M. Irvine and J. C. Pollock, Icams, Vol.8, pp.324-360, 1967
131. (596) "Effect of Growth Parameters on Substructure Spacing in NaCl Ice Crystals". Gary Lofgren and W. F. Weeks, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755, U.S.A., Journal of Glaciology, Vol.8, No.52, 1969
132. (401) "Heat and Mass Transfer in Thick Frost Layers". J. White, Ph.D. Dissertation, University of Kentucky, Mechanical Engineering Department, 1973
133. (451) "X-Ray Diffraction Study of the Internal Structure of Supercooled Water". Robert G. Dorsch and Bemrose Boyd. NACA TN 2532
134. (1077) "New Technology for Studying the Deposition of Droplets on the Ice Crystal Surface". P. Yue and J. Podzimek, Graduate Center for Cloud Physics Research, University of Missouri-Rolla, Rolla, Mo.65401
135. (1082) "Ice Nucleation by Aerosol Particles". N. Fukuta and R. C. Schaller, Denver Research Institute, University of Denver, Denver, Colorado 80210
136. (1307) "Microgravity Thaw Experiment (MITEX)". Andrew C. Klein, Kean G. Stump, Gene Wallis, William J. Krotiuk and Brent J. Webb (Battelle Pacific Northwest Laboratories, Richland Washington), New Mexico University, Transactions of the 5th Symposium on Nuclear Power Systems, 1988, pp.321-324, 1988

Also references : 125 217 240 277 294 295 296 299
313 315 319 348 358 396 399 400
445 524 530 533 541 598 602 613
1078 1079 1097

3.1.10 Self Diffusion In Single Crystals

137. (464) "Self Diffusion in Single Crystals of Ice". K. Itagaki, Journal of the Physical Society of Japan, Vol.19, no.6, pp.1081, 1964
138. (466) "Self-Diffusion in Monocrystals". R. O. Ramseier, U.S. Cold Regions Research and Engineering Laboratory. Research Report 232, 1967

Also reference : 125

3.1.11 Regelation, Surface Diffusion, Sintering And Ablation

139. (291) "Regelation, Surface Diffusion and Ice Sintering". W. D. Kingery. Journal of Applied Physics, Vol.31, pp.883, 1960
140. (293) "A Study of Ice Sintering". D. Kuroiwa, U.S. Army Cold Regions Research Engineering Laboratory Research Report 86, 1962
141. (438) "Errors in Short-Term Ablation Measurements on Melting Ice Surfaces". Fritz Muller and Charles M. Keeler, Faculty of Graduate Studies and Research, McGill University, Montreal, Quebec, Canada. Journal of Glaciology, Vol.8, No.52, 1969

Also reference : 125

3.1.12 Miscellaneous

142. (389) L. Dufour, Arch. Science Physics et Nat., Vol.10, pp.346, 1861
143. (356) S. H. Bastow and I. P. Bowden, Proceedings of the Royal Society (London), A, 151, 220, 1935

144. (361) H. H. G. Jellinek and R. Brill. Journal of Applied Physics, Vol.27, pp.1198, 1956
145. (357) H. H. G. Jellinek, U.S. Army Snow, Ice and Permafrost Research Establishment, Corps of Engineers, Special Report 37, 1960
146. (185) A. E. Carte, Proceedings of the Physics Society (London), Vol.77, pp.757, 1961
147. (176) L. W. Gold. Canadian Journal of Physics, Vol.41, pp.1712, 1963
148. (553) "The Rheology of Ice". J. W. Glen, "Ice and Snow". (W. D. Kingery, ed.), M.I.T. Press, pp.3-7, Cambridge, Massachusetts, 1963
149. (177) H. H. G. Jellinek. Journal of Colloid Interface Science, Vol.25, pp.192, 1967
150. (181) E. H. Andrews and A. J. Kinloch, Proceedings of the Royal Society (London), Vol.A332, pp.385, 1973
151. (175) H. C. Wu, K. J. Chang and J. Schwartz, Engineering Fracture Mechanics, Vol.8. pp.365, 1976
152. (182) E. H. Andrews and A. Stevenson. Journal of Adhesion Vol.1, pp.17, 1980
153. (178) C. Vlachos, Ph.D. Thesis, University of London, 1982
154. (183) E. H. Andrews, H. E. Pingsheng and C. Vlachos, Proceedings of the Royal Society (London), Vol.A381, pp.345, 1982

3.2 Ice Accretion

Also references : 125 340 388 390 392 395 540 1073
1075 1076 1078 1079

3.2.1 Sphere

155. (221) "The Impact of Aerosol Particles on Cylindrical and Spherical Collectors". W. E. Ranz, Technical Report 3 Engineering Experimentation Station, Contract AT(30-3)-28, U.S. Atomic Energy Commission. University of Illinois, March 31, 1951
156. (42) "Impingement of Water Droplets on a Sphere". R. G. Dorsch, P. G. Saper and C. F. Kadow, NACA TN3587, November 1955
157. (591) "Experimental Droplet Impingement on Four Bodies of Revolution". J. P. Lewis and R. S. Ruggeri, NACA TN 4092, December 1957

Also references : 571 275

3.2.2 Cylinder

158. (331) "The Heat Economy of a Rimed Cylinder". F. H. Ludlam, Imperial College, London. Quarterly Journal of the Meteorological Society, Vol.77, pp.663-666, 1951
159. (60) "Impingement of Cloud Droplets on Aerodynamic Bodies as Affected by Compressibility of Air Flow Around the Body". Rinaldo J. Brun, John S. Serafini and Helen M. Gallagher, NACA TN 2903, March 1953
160. (61) "Impingement of Water Droplets on a Cylinder in an Incompressible Flow Field and Evaluation of Rotating Multicylinder Method for Measurement of Droplet-Size Distribution, Volume-Median Droplet Size, and Liquid-Water Content in Clouds". Rinaldo J. Brun and Harry W. Mergler, NACA TN 2904, 1953
161. (500) "Impingement of Particles on a Transverse Cylinder". C. N. Davies and C. V. Peetz, Proceedings of the Royal Society (London), Series A, Vol.234, No.1197, pp.269-295, February 7, 1956

162. (411) "Formation of a Layer of Frost on a Cylinder in Crossflow of Air". S. M. Andrichak, The Ohio State University, 1962
163. (571) "The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Disks". K. R. May and T. L. Schricker, Annual Occup. Hyg., Vol.10, pp.83-95, 1967
164. (328) "Ice Shapes on Cylinders and Rotor Blades". J. R. Stallabrass and E. P. Lozowski, NRC Low Temperature Laboratory, NATO Panel X Symposium on Helicopter Icing, 1978
165. (212) "The Icing of an Unheated Non-Rotating Cylinder in Liquid Water Droplet-Ice Crystal Clouds". E. P. Lozowski, J. R. Stallabrass and P. F. Hearty, Division of Mechanical Engineering, Report LTR LT 96, National Research Council of Canada, February 1979
166. (1074) "On the Variation of the Collection Efficiencies of Icing Cylinders". Roland List, P. I. Joe, G. Lesins, P. R. Kry, J. D. McTaggart-Cowan, P. W. Stagg, E. Freire, R. E. Stewart, C. G. List, M. C. Steiner, Department of Physics, University of Toronto, Toronto, Canada, M. R. deQuervain, Swiss Federal Institute for Snow and Avalanche Research, Davos, E. P. Lozowski, University of Alberta, Edmonton, Alberta, Canada

Also references : 152 154 221 324 374 381 393 395
591

3.2.2.1 Ellipsoid

167. (496) "Impingement of Water Droplets on an Ellipsoid with Fineness Ratio 5 in Axisymmetric Flow". Rinaldo J. Brun and Robert G. Dorsch, NACA TN 3099, 1954
168. (495) "Impingement of Water Droplets on an Ellipsoid with Fineness Ratio 10 in Axisymmetric Flow". Rinaldo J. Brun and Robert G. Dorsch, NACA TN 3147, 1954

Also reference : 591

3.2.3 Aerofoil (General)

169. (1125) "Scale-Model test of Airfoils in Simulated Heavy Rain". E. C. Hastings Jr. and G. S. Manuel, NASA Langley Research Center, Hampton, Virginia, Journal of Aircraft, Vol.22, No.6, pp.536

3.2.3.1 1930 - 1960

170. (246) "Ice Formation on Aircraft and Its Prevention". Merit Scott, Department of Physics, Cornell University. Journal of the Franklin Institute, Vol.210, No.5, pp.537-586, First Publication as NACA TN 345, November 1930
171. (632) "Ice Accretion and De-Icing Part 2". (45 references), H. Lewis, R.T.P. Bibliography No.28, September 1941
172. (522) "Investigation of Runback". Tracey B. Gardner, Air Material Command Ice Research Base Report IRB 46-36-1F, July 1946
173. (1111) "Comparison of Heat Transfer from Airfoil in Natural and Simulated Icing Conditions". T. F. Gelder and J. P. Lewis, NACA TN 2480, September 1951
174. (223) "Impingement of Water Droplets on an NACA 651-212 Airfoil at an Angle of Attack of 4 Degrees". Rinaldo J. Brun, John S. Serafini and George J. Moshos, NACA RM E52B12, 1952
175. (977) "Occurrence of High Rates of Ice Accretion on Aircraft". A. C. Best, Meteorological Office Professional Notes No.106, Vol.7, No.6, 1952
176. (48) "Impingement of Water Droplets on NACA 651-208 and 651-212 Airfoils at 4 Degrees Angle of Attack". Rinaldo J. Brun, Helen M. Gallagher and Dorothea E. Vogt, NACA TN 2952, 1953
177. (137) "Impingement of Water Droplets on NACA 65A004 Airfoil and Effect of Change in Airfoil Thickness from 12 to 4 Percent at 4 Degrees Angle of Attack". Rinaldo J. Brun, Helen M. Gallagher and Dorothea E. Vogt, NACA TN 3047, November 1953
178. (1295) "Impingement of Water Droplets on Bodies". Brun and Dorsch, NACA TN 3153, 1953
179. (1323) "Impingement of Water Droplets on NACA651-208 and 651-212 Airfoils at 4 deg. Angle of Attack". R. Brun, H. Gallagher and D. Voyt, NACA TN 2952, 1953

180. (138) "Impingement of Water Droplets on NACA 65A004 Airfoil at 8 Degrees Angle of Attack". Rinaldo J. Brun, Helen M. Gallagher and Dorothea E. Vogt, NACA TN 3155, July 1954
181. (523) "Impingement of Water Droplets on Wedges and Double-Wedge Airfoils at Supersonic Speeds". John S. Serafini, NACA Report 1159, (supersedes NACA TN 2971), 1954
182. (823) "Icing Limit and Wet Surface Temperature Variation for Two Airfoil Shapes Under Simulated High-Speed Flight Conditions". W. D. Coles, NACA TN 3, February 1955
183. (139) "Impingement of Water Droplets on NACA 65A004 Airfoil at 0 Degrees Angle of Attack". Rinaldo J. Brun and Dorothea E. Vogt, NACA TN 3586, November 1955
184. (1296) "Impingement of Water Droplets on Bodies". Brun and Dorsch, NACA TN 3410, 1955
185. (72) "Experimental Droplet Impingement on Several Two-Dimensional Airfoils with Thickness Ratios of 6 to 16 Percent". Thomas F. Gelder, William H. Smyers Jr. and Uwe H. von Glahn, NACA TN 3839, 1956
186. (136) "Impingement of Cloud Droplets on 36.5-Percent-Thick Joukowski Airfoil at Zero Angle of Attack and Discussion of Use of Cloud Measuring Instrument in Dye-Tracer Technique". Rinaldo J. Brun and Dorothea E. Vogt, NACA TN 4035, September 1957
187. (1041) "Icing Flight Development". B. T. Cheverton, D. Napier and Son Limited, Luton Airport, Luton, Journal of the Royal Aeronautical Society, Vol.63, No.587, November 1959
188. (824) "The Icing of Delta Wings of Unity Aspect Ratio Having Leading Edge Separation". C. K. Rush, NRC LR 268, Laboratory Report, December 1959
189. (332) "Special FAR 23 Section 34". Federal Aviation Authority
190. (360) P. E. Berghausen, R. J. Good, F. Kraus, B. Podolsky and W. Soller, WADC TR 53-461 and WADC TR 55-44,

Also references : 15 60 67 69 71 85 203 255 945

3.2.3.2 1961 Onwards

191. (821) "The Problem of Determining Icing Patterns on Full-Scale Delta Wings". J. W. Flower, A.R.C. 22696, February 1961
192. (825) "Icing Tests of a 10ft Delta Wing of Unity Aspect Ratio Having Leading Edge Separation". C. K. Rush, NRCC LR 337, Aeronautical Report, National Research Council of Canada, Ottawa, Canada, January 1962
193. (826) "Ice Shedding Tests on a 10ft Sharp-Edged Delta Wing at Low Angles of Attack". C. K. Rush, NRCC LR 364, Aeronautical Report, National Research Council of Canada, Ottawa, Canada, December 1962
194. (827) "Some Notes on the Observance of Runback of Water from a Heated Wing Leading-Edge Under Artificial Icing Conditions and the Possible Application of Results to Future Designs". F. J. Bigg, RAE IM ME.165, Royal Aircraft Establishment, Farnborough, July 1964
195. (970) "Aircraft Icing". NASA Conference Publication 2086". FAA-RD-78-109, NASA Lewis Research Center, Cleveland, Ohio, July 19-21, 1978
196. (322) "Frost Formation on an Airfoil: A Mathematical Model I". Mark A. Dietenberger, Prem Kumar and James Luers, University of Dayton Research Institute, Dayton, Ohio, NASA Contract NAS8-31294, 1979
197. (25) "Rime Ice Accretion and Its Effect on Airfoil Performance. PhD Thesis. Final Report". Michael B. Bragg, Department of Aeronautical and Astronautical Engineering, Ohio State University, Columbus, Ohio, NASA CR 165599, March 1982
198. (65) "An Experimental Study of Airfoil Icing Characteristics". Robert J. Shaw and Ray G. Sotos, NASA TM 82790, 1982
199. (584) "Ice Shapes and the Resulting Drag Increase for a NACA 0012 Airfoil". William Olsen, Robert Shaw and James Newton, NASA Lewis Research Center, Cleveland, Ohio, Presented at the 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984, NASA TM-83556, January 12, 1984
200. (935) "Measurement of Local Convective Heat Transfer Coefficients of Four Ice Accretion Shapes". M. E. Smith, et al, Tennessee University, NASA-CR-174680, N84-25646, May 1984
201. (101) "Effect of Geometry on Airfoil Icing Characteristics". Michael B. Bragg, The Ohio State University, Columbus, Ohio. Journal of Aircraft, Vol.21, No.7, July 1984

202. (112) "Experimental and Analytical Investigation into Airfoil Icing". M. B. Bragg, G. M. Gregorek and J. D. Lee, ICAS-84-1.10.4, The Ohio State University, Columbus, Ohio, U.S.A. 43220, AIAA

Also references : 6 28 54 56 62 63 94 152 773 1083

3.2.3.3 Date Unknown

203. (439) "Comparison of Heat Transfer from Airfoil in Natural and Simulated Icing Conditions". Thomas F. Gelder and James P. Lewis, NACA TN 2480,

Also references : 7 35 54 55 74 77 85 94 123 147
150 157 200 211 215 226 318
405 543

3.2.4 Propeller

204. (1012) "Kinetic Temperature of Propeller Blades in Conditions of Icing". J. K. Hardy and C. D. Brown, Royal Aircraft Establishment, Farnborough, Hampshire, Report No. Mech. Eng. 2
205. (94) "Icing Analysis of Two Propeller Sections". M. B. Bragg and G. M. Gregorek, AARL TR 8302, Ohio State University, May 1983

Also references : 2 91 250 443

3.2.4.1 Spinner

Also reference : 415

3.2.5 Engine And Intake

206. (627) "Icing of Carburettor Air Induction Systems of Airplanes and Engines". Journal of Aeronautical Sciences, October 1941
207. (628) "Icing of Carburettor Air Induction Systems of Airplanes and Engines". Skogland, Journal of Aeronautical Sciences, October 1941
208. (843) "The Occurrence and Prevention of Throttle Ice in Carburettors in the Absence of Fuel". H. G. Colliver, Royal Aircraft Establishment, Farnborough, RAE TN Eng.305, June 1944
209. (979) "Protection of Turbine Engines Against Ice". J. K. Hardy, MoS Reference RES/ENG.7291, December 6, 1946
210. (679) "The Canadian Turbine Icing Report". Aeroplane, January 1947
211. (668) "Turbine Engine Icing Problems". A. G. Elliot, Rolls Royce Limited, Royal Aeronautical Society Reprint, American Conference, September 3-5, 1947
212. (669) "Turbine Engine Icing Problems". A. G. Elliot, Rolls Royce Limited, Aeroplane, September 5, 1947
213. (670) "Turbine Engine Icing Problems". A. G. Elliot, Rolls Royce Limited, Flight International, September 11, 1947
214. (666) "First Interim Report on Icing Investigation of Turbojet Engines - Preliminary Icing Experiments with an Axial Flow Unit on the Test Stand". Samolenez and Macauley, National Research Council of Canada, Ottawa, Canada, Report No.M.E.159, September 1947
215. (845) "Turbine Engine Icing Problems". A. G. Elliott, Royal Aeronautical Society Preprint, September 1947
216. (980) "Turbine Icing Standards for Design". MoS Reference 7 Aircraft 2667RDT1, October 9, 1947
217. (671) "Turbine Engine Icing Problems". October 1947
218. (687) "The Protection of Gas Turbine Air Intakes Against Sand and Ice". C. L. Cowdrey, Napier Report No.CDH/Design/1843, July 21, 1948
219. (835) "Preliminary Results of Natural Icing of an Axial-Flow Turbojet Engine". L. W. Acker, NACA TIB 1860, RM E8C18, August 1948

220. (695) "The Stratofreighter Air Duct and Anti-Icing Systems". H. W. Perry, Aircraft Engineering, November 1948
221. (704) "A.S.Z. 109 Build 14B. Cold Weather Testing of Trainer Mamba at the NRC Laboratories". A. V. Starling, Experimental Department (Gas Turbines), National Research Council of Canada, Ottawa, Canada, May 12, 1949
222. (846) "Gas Turbine Icing Tests on Mount Washington, New Hampshire". P. M. Bartlett, SAE Preprint No.510, September 1950
223. (839) "Aircraft Gas Turbine Engine Icing". M. S. Kuhring, NRCC ME 181, July 1950
224. (493) "Gas Turbine Icing Tests at Mount Washington, New Hampshire". Bartlett and Dickey, Air Worlds, Vol.3, No.4, January-February, 1951
225. (836) "Icing Tests on Armstrong Siddeley Double Mamba Engine". G. G. Levy, NAE LR 52, April 1953
226. (830) "Anti-icing Tests on Mamba 6 at Lowther Hill and Continued Investigation of Suitability of Site". Armstrong Siddeley Motors Limited, Winter 1954-1955
227. (832) "Flight Analysis Report No.Q 51 - Ground and Flight Tests of an Engine Air Intake Incorporating De-icing Mats on a Gannet A.S. Mk.1 Aircraft". Fairey Aviation Company Limited, March 1955
228. (829) "The Icing of Compressor Blades and Their Protection by Surface Heating". G. L. Shires and G. E. Munns, R and M No.3041, June 1955
229. (833) "Anti-Icing Test on British Gas Turbine Engines Carried out in Collaboration with the NAE of Canada at their Ottawa Laboratories". Ministry of Supply Report, Winter 1957-1958
230. (834) "Report on Anti-Icing Tests on British Gas Turbine Engines Carried out at the Engine Laboratory, Ottawa, of the N.R.C.C.". Ministry of Supply reference M 141/RC, Winter 1957-1958
231. (976) "Helicopter Icing and De-Icing Flight Trials on a Bristol Sycamore Type 171, Mark 3". J. M. H. Heines, D. L. Bailey and J. R. Stallabrass, National Research Council of Canada, Report LR-221, May 1958
232. (844) "Tests on Several Propeller-Turbine Intakes to Assess Their Liability to Collect Ice Particles". A. G. Kurn, Royal Aircraft Establishment, Farnborough, RAE TN Aero.2569, June 1958

233. (840) "Britannia Engine Icing Investigation - Laboratory Tests Under Simulated Conditions". D. J. Day et al., Royal Aircraft Establishment, Farnborough, RAE Mech.Eng.22, November 1959
234. (847) "Testing of Behaviour of Inlet Flaps of the AUBISQUE by-pass Engine in Icing Conditions". Propeller Test Centre, Saclay, Test Note No.307/ZT/65, Note No.83/SE/ZT/65 (translation).

Also references : 426 676 689 691

3.2.6 Helicopter Rotor Blade

235. (1010) "Report on the Computation of Water Drop Trajectories About a 6 Percent Airfoil at Zero and Four Degrees Angles of Attack". F. E. Lenbarr, Northrop Aircraft Incorporated, Hawthorne, California, October 6, 1952
236. (791) "Rate and Extent of Water Droplet Impingement with Respect to the Icing Protection of the Bell HTE-4 Helicopter Rotor". F. W. Pruden and R. L. Wardlow, NRC Laboratory Memo. LT/38, National Research Council of Canada, Ottawa, Canada, October 1952
237. (373) "Preliminary Helicopter Icing Flight Trials". E. O. Robertson, NRC, NAE Laboratory, NRC LR 106, July 1954
238. (374) "Some Aspects of Helicopter Icing". J. R. Stallabrass, National Research Council, Annual General Meeting of the C.A.I., Ottawa, Canada, May 28, 1957. Canadian Aeronautical Journal, Vol.3, No.8, pp.273-283, October 1957
239. (789) "Canadian Research in the Field of Helicopter Icing". J. R. Stallabrass, NRCC Report 'A', May 1958
240. (800) "Summary of Studies of Helicopter Rotor Icing". G. E. Bartlett, ASTIA No.234,755, WADD TR 59-660, P.90756, September 1959
241. (1020) "US Army Helicopter Icing Tests". Warren E. Griffith and Marvin L. Hanks, US Army Aviation Engineering Flight Activity, Edwards Air Force Base, California 93523, Report SFTE-1974, 1974
242. (906) "Artificial Icing Tests, Lockheed Advanced Ice Protection System Installed on a UH-1H Helicopter". R. K. Merrill and L. Kronenberger, Army Aviation Engineering Flight Activity, Edwards Air Force Base, California, June 1975

243. (1019) "Design for Maximum Survival in Icing". K. T. McKenzie and D. R. Shepherd, Westland Helicopters Limited, Yeovil, Somerset, Presented at Symposium "Icing on Helicopters", Royal Aircraft Establishment, November 26, 1975
244. (896) "Notes of a Visit to Witness Icing Tests of a Bell 214 Helicopter in the Main Chamber of the Climatic Laboratory at Eglin Air Force Base". J. H. Mason, Defense Research and Development Staff, Air Group, Washington D.C., USA, INF-SHEET-A-3-76, January 12-14, 1976
245. (1018) "Wessex Mk.5 XT768 Lucas Ice Protection System, Helicopter Icing Trials in Denmark". Westland Helicopters Limited, Yeovil, Somerset, February-March 1976
246. (1016) "FAA May Reexamine Icing Certification". Aviation Week and Space Technology, pp.66, November 19, 1979
247. (238) "Technical Analysis of the 1976 Lynx Icing Trial". J. E. Clark, Tirstrup, Denmark, WHL Report, WER 141-06-00137
248. (6) "Helicopter Rotor Ice Accretion and Protection Research". J. T. Cansdale, Royal Aircraft Establishment, Farnborough, Hampshire, England, The Sixth European Rotorcraft and Powered Lift Aircraft Forum, Bristol, England, September 16-19, 1980
249. (1015) "Helicopter Icing Review". A. A. Peterson and L. U. Dadone, Boeing Vertol Company, Philladelphia, Pennsylvania, September 1980
250. (1143) "Development for Helicopter Flight in Icing Conditions". David Gibbings, Westland Helicopters Limited, Yeovil, Somerset, England, AGARD Subsystems Testing and Flight Instrumentation, April 1981
251. (595) "Wind Tunnel Study of Icing and De-Icing on Oscillatory Rotor Blades". D. Guffond, Proceedings of the Forum of European Helicopters. ONERA TP 1982-11, September 1982
252. (1014) "US Army Helicopter Icing Developments". Robert N. Ward, SAE 821504, Aerospace Congress and Exposition, Anaheim, California, October 25-28, 1982
253. (150) "High Speed Ice Accretion on Rotorcraft Airfoils". R. J. Flemming and D. A. Lednicer, AHS A 83 39 04 0000, May 1983
254. (327) "Photogrammetric of the Build-up on a U.S. Army UH-1H Helicopter Main Rotor in Hover Flight". R. L. Palko and P. L. Cassady, AEDC TR 83 43, September 1983

255. (1144) "Rotorcraft Icing Technology: An Update". R. Ward and H. W. Chambers, Army Aviation Engineering Flight Activity, Edwards Air Force Base, California, Army Aviation Research and Development Command, St.Louis, Montana, AGARD Flight Mechanics and System Design Lessons from Operational Experience, October 1983
256. (54) "Experimental Investigation of Ice Accretion on Rotorcraft Airfoils at High Speeds". R. J. Flemming and D. A. Lednicer, Sikorsky Aircraft, Stratford, Connecticut, AIAA-84-0183, AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984
257. (262) "Documentation of Ice Shapes on the Main Rotor of a UH-1H Helicopter in Hover". J. D. Lee, AARL, The Ohio State University, Columbus, Ohio, AARL Vol.21, pp.84,85, January 1984
258. (158) "Chinook's Trial by Ice". Flight International, April 28, 1984, pp1160-1163
259. (932) "Further Studies of Helicopter Rotor Ice Accretion and Protection". R. W. Gent and R. H. Markiewicz, Royal Aircraft Establishment, Farnborough, Hampshire, 11th European Rotorcraft Forum, The City University, London, September 1985
260. (1102) "Icing Clearance Criteria for UK Military Helicopters". M. G. Battersby and P. A. Knowles, Aircraft and Armament Experimental Establishment, Boscombe Down, November 1985
261. (462) "Icing and De-Icing Test on a 1/4 Scale Rotor in the ONERA S1MA Wind Tunnel". D. P. Guffond, O.N.E.R.A., Chatillon Cedex, France. AIAA-86-0480. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986
262. (117) "Getting to Grips with Icing". George Marsh. Defence Helicopter World, December 1985/ January 1986
263. (1104) "Rotorcraft Icing - Progress and Potential". AGARD-AR-223, September 1986
264. (1083) "Correlation of Icing Relationships with Airfoil and Rotorcraft Icing Data". Robert J. Flemming and David A. Lednicer, United Technologies Corporation, Stratford, Connecticut, Journal of Aircraft, Vol.23, No.10, pp.237, October 1986
265. (1087) "In-Flight Ice Accretion Characteristics of Rotor Blade Airfoil Sections". D. Belte, US Army Aviation Engineering Flight Activity, Edwards Air Force Base, California, AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987

266. (84) "Helicopter Airworthiness Development - Post HARP".
R. B. Stratton, Rotorcraft Committee Royal Aeronautical Society,
Aerospace Journal, pp.24, April 1987

Also references : 7 20 55 109 123 142 152 157 328
334 856 857 887 888 907 933 1094
1145

3.2.7 Aircraft

267. (250) "The Formation of Ice Upon Exposed Parts of an Airplane in Flight". Thomas Carroll, NACA TN 293, 1928
268. (249) "The Formation of Ice Upon Airplanes in Flight". Thomas Carroll, NACA TN 313, 1929
269. (247) "Ice Formation on Aircraft". C. G. Andrus, Aeronautical Meteorology, 2nd Edition, Chapter 13, The Ronald Press Company, W. R. Gregg, 1930
270. (254) "The Icing of Airplanes". R. O. Steiner, Meteorological Zeitschrift Vol.47, 1930
271. (74) "Distribution of Temperatures Over an Airplane Wing with Reference to the Phenomena of Ice Formation". Edmond Brun, NACA TM 883, 1938
272. (1191) "Ice Formation on Aircraft and Its Prevention". UK Air Ministry, Pamphlet Number 83, pp.30, 1938
273. (77) "Ice Formation on Wings". L. Ritz, NACA TM 888, 1938
274. (318) "French Committee for the Study of Ice Formation". Report on Ice Formation on Aircraft NACA TM 919, 1939
275. (200) "Aerodynamic Heating and the Deflection of Drops by an Obstacle in an Air Stream in Relation to Aircraft Icing". Arthur Kantrowitz, Langley Memorial Aeronautical Laboratory, NACA TN 779, Washington, October 1940
276. (625) "Icing Problems in Operation on Transport Aircraft". R. L. McBrien, S.A.E. Journal, September 1941
277. (76) "The Formation of Ice on Aircraft". W. Bleeker, NACA TM 1027, August 1942

278. (201) "The Icing of Aircraft". M. Robitzsch, NACA TM 1028, September 1942
279. (651) "Contribution to the Problem of Ice Formation". A.A.F. Translation No.533, May 1946
280. (276) "The Limitations and Mathematical Basis for Predicting Aircraft Icing Characteristics from Scale Model Studies". Myron Tribus, Young and L. M. K. Boelter, Section V of Army Air Forces Technical Report 5529, pp.63-78, November 6, 1946
281. (667) "In Flight Icing of Highly Electrified Aircraft". R. Gunn, Journal of Aeronautical Sciences, September 1947
282. (675) "N.A.C.A. Research Ends. Ice Hazards". R. Mc.Larren, Aviation Week, December 22, 1947
283. (769) "A Pilots Guide to Icing". January 18, 1952
284. (617) "Physical Causes of Icing of Aircraft". G. Drometeoizdat, 1957
285. (812) "An Assessment of the Icing Problem on the Supersonic Transport Aircraft". D. J. Day, A.R.C./22,181, September 1960
286. (578) "Progress Toward the Development of an Aircraft Icing Analysis Capability". R. J. Shaw, NASA Lewis Research Center, Cleveland, Ohio, NASA TM 83562, January 1964
287. (582) "Development Study: The Use of Scale Models in an Icing Wind Tunnel to Determine the Ice Catch on a Prototype Aircraft with Particular Reference to Concorde". E. T. Jackson, British Aircraft Corporation (Operating) Limited, SST/B75t/RMMcK/242. Filton Division, Bristol, England, July 1967
288. (338) "Hoar Frost on Aircraft Surfaces". P. A. S. Langston, Heathrow BEA-Engineering Technical Note 3P/570, November 18, 1968
289. (891) "Simulated Icing Tests on a Sea King Helicopter Fuselage". B. P. Marlow, National Gas Turbine Establishment, Pyestock, Hampshire, International Helicopter Icing Conference, Ottawa Canada, May 23-26, 1972
290. (211) "A Theoretical and Experimental Means to Predict Ice Accretion Shapes for Evaluating Aircraft Handling and Performance Characteristics". Raymond W. Wilder, AGARD Advisory Report 127, pp.5-1 to 5-20, November 1978
291. (135) "An Integrated Approach to the Problem of Aircraft Icing". D. W. Newton. Journal of Aircraft, Vol.15, pp.374-380, 1978

292. (1306) "Investigation of Air Transportation Technology at Massachusetts Institute of Technology, 1986". Robert W. Simpson, NASA Langley Research Center, Joint University Program for Air Transportation Research, 1986, April 1986
293. (1325) "Ice Formation on Aircraft". Final Report, J. F. Gayet, Clermont-Ferrand University, France, December 1986
294. (1114) "Airplane Icing Information". B. Vonnegut et al., University of Michigan, Lecture Notes
295. (1187) "Ice Accretion on Aircraft". UK Air Ministry
296. (1176) "Ice Formation in Aircraft". Ernesto Montiel Rodriguez, Instituto Nacional de Tecnica Aeroespacial, Esteban Terradas, Torrejon de Ardoz, Spain, Seccion de Instrumentos de a Bordo, Proteccion y Salvamento

Also references : 7 43 55 56 89 123 152 157 214 248
443 448 454 539 1016

3.2.8 Icing Wind Tunnel Components

297. (574) "Study of Ice Accretion on Icing Wind Tunnel Components". James E. Newton and William Olsen, NASA Lewis Research Center, Cleveland, Ohio. AIAA-86-0547. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986

3.2.9 Droplet Size Effects

298. (14) "Droplet Size Distribution Effects on Aircraft Ice Accretion". R. John Hansman Jr., Massachusetts Institute of Technology, Cambridge, Massachusetts, Journal of Aircraft, Vol.22, No.6, pp.503, June 1985, AIAA-84-0108, AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984

Also reference : 136 817 1025

3.2.10 Testing Technique And Equipment

299. (630) "Icing Problems in Aircraft Induction Systems".. L. B. Kimball, S.A.E. Journal, February 1942
300. (634) "Icing in Induction Systems". L. B. Kimball, Aircraft Engineering, March 1943
301. (1037) "An Investigation of Aircraft Heaters VIII - a Simplified Method for the Calculation of the Unit Thermal Conductance Over Wings". R. C. Martinelli, A. G. Guibert, E. H. Morrin and M. K. Boelter, University of California, NACA ARR, March 1943
302. (426) "Spray Nozzles for the Simulation of Cloud Conditions in Icing Tests of Jet Engines". Goltizine, Sharp and Badham, NRC Report No.Me186, National Research Council of Canada, Ottawa, Canada, August 28, 1950
303. (1025) "A Photographic Study of Freezing of Water Droplets Falling Freely in Air". Robert G. Dorsch and Joseph Levine, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, NACA Washington Report RM E51L17, February 25, 1952
304. (848) "Some Aspects of Icing Simulation". C. K. Rush, NAE LT 29, July 1952
305. (869) "Note on the Flight Testing and Assessment of Icing Protection Systems". D. Fraser, NAE LR 50, March 1953
306. (1024) "The Freezing out of Water Droplets in an Icing Wind Tunnel". D. Napier and Son Limited, Flight Development Establishment, Luton Airport, C. J. Cowlin, August 28, 1953
307. (260) "Analysis of Model Testing in an Icing Wind Tunnel". H. H. Haugher, K. G. Englar and W. W. Reaser, Douglas Aircraft Company Incorporated, Report SM-14993, May 1954
308. (244) "A Dye-Tracer Technique for Experimentally Obtaining Impingement Characteristics of Arbitrary Bodies and a Method for Determining Droplet Size Distribution". Uwe H. von Glahn, Thomas F. Gelder and William H. Smyers Jr., NACA TN 3338, 1955
309. (581) "Model Testing in an Icing Wind Tunnel". P. J. Sibley and R. E. Smith Jr., Lockheed Aircraft Corporation. Report LR10981, 1955
310. (1109) "Use of Truncated Flapped Airfoils for Impingement and Icing Tests of Full-Scale Leading Edge Sections". U. H. von Glahn, NACA TIL 5021, RM E56E11, July 1956

311. (245) "Use of Truncated Flapped Airfoils for Impingement and Icing Tests of Full-Scale Leading-Edge Sections". Uwe H. von Glahn, NACA RM E56E11, 1956
312. (375) "Adverse Weather Tests of the YH-40 Helicopter". A. R. Wicker, W. G. Mauser and C. V. Turvey, WADC TN 59-271, August 1959
313. (170) "Scale Model Analogy for Icing Tunnel Testing". E. D. Dodson, Boeing Airplane Company, Transport Division. Document D66-7976, March 1962
314. (1022) "Use of the K0 Correlation in Preliminary Design and Scale Model Icing". Frederick R. Weiner, Research and Development Group, North American Aviation Incorporated, Los Angeles Division, March 12, 1963
315. (924) "Report No.66-CEV-SE-VT-75 on Tests Carried Out by CEV on Gazelle SA 341 B No.1009 in Canada". Direction Technique Des Constructions Aeronautique, Centre D'essais en Vo, January-February 1973
316. (885) "Ice Makers, Sprayers, Canberra". G. M. Smith, J. H. M. Cochraine, June 1973
317. (492) "Analytical Study of Icing Simulation for Turbine Engines in Altitude Test Cells". C. E. Willbanks and R. J. Schultz, AEDC-TR-73-144 (AD770069), November 1973
318. (592) "Diffuse Reflectance Spectroscopy in Environmental Problem-Solving". R. W. Frei and J. N. MacNeil, CRC Press, Cleveland, Ohio, 1973
319. (903) "Helicopter Icing Spray System". A. R. Todd, Army Aviation Engineering Flight Activity, Edwards Air Force Base, California, Presented at Helicopter Icing Symposium, NATO Army Armaments Group, Panel X, London, November 6-7, 1978
320. (213) "Scaling Wake Particle Interactions for Aerial Applications Research". Allen I. Ormsbee, Michael B. Bragg and Mark D. Maughmer, University of Illinois, Urbana, Illinois, AIAA Aircraft Systems Meeting. AIAA-80-1873, Anaheim, California, August 4-6, 1980
321. (275) "Verification and Application of the Icing Scaling Equations". G. A. Ruff, Sverdrup Technology Incorporated. AIAA-86-0481. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986

322. (575) "An Experimental Method for Measuring Droplet Impingement Efficiency on Two-and Three-Dimensional Bodies". M. Papadakis and G. W. Zumwalt, Wichita State University, Wichita, Kansas. J. J. Kim, R. Elangovan, G. A. Freund Jr., W. Seibel and M. D. Breer, Boeing Military Airplane Company, Wichita, Kansas. AIAA-86-0406. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986
323. (1063) "Cold Weather Trials for Military Aircraft". H. D. Judkins, Aerospace Journal, Vol.14, No.5, Royal Aeronautical Society, May 1987
324. (340) "Techniques of Frost Prediction and Methods of Frost and Cold Protection". A. Bagdonas, J. C. Georg and J. F. Gerber, WMO 487
325. (1089) "Altitude Test Facility". Lucas Aerospace Limited, Fabrications Division, Engineering Laboratories, Hargher Clough, Burnley, Lancashire.
326. (1013) "Simulated Flight Icing Tests with a Tanker Aircraft". P. W. T. Schumacher, U.S.A.F. Aeronautical Systems Division.
327. (1009) "Proposed Tests to Compare the Ice Accretion Produced by Subjecting a Number of Typical Aircraft Shapes to Mixed Icing Conditions, the Ice Crystals Being Produced by (A) Ice Nozzle and (B) Ice Block Chopping Technique". Altitude Test Facility, Lucas Laboratories, Hargher Clough, Burnley, Lancashire, Report No.B49363

Also references : 1 126 152 502 582 748 787 788
795 798 805 806 807 856 896
899 1075

3.2.11 General

328. (622) "Ice Formation in Carburettors". Clothier, Journal of the Royal Aeronautical Society, September 1935
329. (726) "Icing Problems". A. Swertstern, November 1951
330. (879) "Modern Icing Technology". M. Tribus, University of Michigan, Lecture Notes, Project M992-E, Air Research and Development Command, USAF, Chapter 4, January 1952

331. (237) "An Analysis of the Effects of Certain Variables in Determining the Form of an Ice Accretion". Thomas A. Dickey, Aeronautical Engineering Laboratory, AEL 1206, Naval Air Experimentation Station, May 29, 1952
332. (772) "B.E.A. Icing Trials", D. Mason, British European Airways, Shell Aviation News, September 1952
333. (863) "Experimental Investigation of Radome Icing and Icing Protection". James P. Lewis and R. J. Blade, NACA TIB 3568, RM E52J31, March 1953
334. (512) "Water Drop Collisions with Solid Surfaces". O. G. Engel, Research Paper 2951, Journal of Research at the National Bureau of Standards, Vol.54, No.5, pp.281-298, 1955
335. (864) "Icing Problems and Recommended Solutions". E. A. Brun, AGARDograph 16, November 1957
336. (850) "Flight in Ice-Forming Conditions". British Civil Airworthiness Requirements Sub/section D4-7, A.R.B., March 1959
337. (545) "An Investigation of Heat and Mass Transfer by Free Convection from Humid Air to a Metal Plate Under Frosting". C. A. Whitehurst, PhD Thesis, Agricultural and Mechanical College of Texas, College Station, Texas, 1962
338. (854) "Use of the Ké0î Correlation in Preliminary Design and Scale Model Icing". F. R. Weiner, Conference Paper, North American Aviation Incorporated, International Icing Conference, Napier and Son, September 1964
339. (544) "Heat Transfer to a Cryogenic Surface Under Frosting Conditions". M. E. Weber, Sc.D Thesis Chemical Engineering, M.I.T., Cambridge, 1964
340. (533) "Field and Laboratory Observations of Ice Crystal Growth from the Vapour". J. Hallett, Journal of Atmospheric Science, Vol.22, pp.64-89, 1965
341. (404) "Frost Deposition on Cold Surfaces". P. L. Thibaut Brian, Robert C. Reid and Yatish T. Shah, Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139. Journal of Industrial Engineering Chemistry, Fundamentals Vol.9, No.3, pp.375-380, 1970
342. (403) "Prediction of Growth Parameters of Frost Deposits in Forced Convection". J. White and C. J. Cremers, AIAA/ASME 1974 Thermophysics and Heat Transfer Conference, Boston, Massachusettes, July 15-17, 1974

343. (402) "Frost Formation with Varying Environmental Parameters". B. W. Jones and J. D. Parker. Transport ASM Journal of Heat Transfer, May 1975
344. (1154) "Carburetor Ice: A Review". Richard L. Newman, Crew Systems Consultants, Yellow Springs, Ohio, Backup Document for AIAA Synoptic, Journal of Aircraft, October-November 1980
345. (1121) "Prediction of Ice/Frost Growth on Insulated Cryogenic Tanks". P. J. Huffman and M. A. Dietenberger, University of Dayton Research Institute, Dayton, Ohio, Engineers Notes, pp.41, July-August 1983
346. (579) "Analysis and Verification of the Icing Scaling Equations". G. A. Ruff, AEDC TR 85-30, November 1985
347. (1304) "Experimental Evidence for Modifying the Current Physical Model for Ice Accretion on Aircraft Surfaces". W. Olsen and E. Walker, NASA-TM-87184, 1986
348. (1311) "Upcoming Flight Tests Aim to Refine Artificial Icing Techniques". Aviation Week and Space Technology, pp.71, February 8, 1988
349. (1309) "Fuel-Induced Icing". Flight International, pp.36, April 2, 1988
350. (1294) "Ice Simulation : A Two Dimensional Wind Tunnel Investigation of a NACA 652A215 Wing Section with Single Slotted Flap. Part 2 : Configurations Typical for Transport Aircraft". U. Clareus, FFA-TN-AU-995, Pt.2
351. (456) "Laboratory Investigation of Icing in the Carburetor and Supercharger Inlet Elbow of an Aircraft Engine - I - Description of Setup and Testing Technique". Donald R. Mulholland, Vern G. Rollin and Herman B. Galvin. NACA MR E5L13

Also reference : 492 581 580 632 749 753 779 786

3.3. Icing Effect On Performance

3.3.1 Propeller

- 352. (26) ".The Effect of Ice Formation on Propeller Performance". Carr B. Neel Jr. and Loren G. Bright, NACA TN 2212, October 1950
- 353. (111) "Analytical Determination of Propeller Performance Degradation Due to Ice Accretion". Thomas Lloyd Miller, Texas A and M University, College Station, Texas, December 1984

Also references : 83,95,159

3.3.1.1 Rime Ice

- 354. (220) "Performance Degradation of Propeller/Rotor Systems Due to Rime Ice Accretion". K. D. Korkan, Texas A and M University, College Station, Texas, L. Dadone, Boeing Vertol Company, Philadelphia, Pennsylvania, and R. J. Shaw, NASA Lewis Research Center, Cleveland, Ohio, AIAA-82-0286, AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, January 11-14, 1982
- 355. (90) "Performance Degradation of Propeller/Helicopter Rotor Systems Due to Rime Ice Accretion". K. D. Korkan, The Second Icing Analysis, Workshop, NASA Lewis Research Center, February 8, 1983
- 356. (5) "Performance Degradation of Propeller Systems Due to Rime Ice Accretion". K. D. Korkan, Texas A and M University, College Station, Texas. L. Dadone, Boeing Vertol Company, Philadelphia, Pennsylvania, R. J. Shaw, NASA Lewis Research Center, Cleveland, Ohio. Journal of Aircraft, Vol.21, No.1, pp.44-49, January 1984

3.3.1.2 Simulated Ice

- 357. (219) "The Effect of Simulated Icing on Propeller Performance". Blake W. Corson Jr. and Julian D. Maynard, NACA TN 1084, 1946

Also reference : 95 906

3.3.1.3 De-Icer Effect On Performance

- 358. (37) "Analysis of Propeller Efficiency Losses Associated with Heated-Air Thermal De-Icing". Blake W. Corson Jr. and Julian D. Maynard, NACA TN 1112, July 1946
- 359. (95) "Comparative Tests on Propellers with Simulated Ice and with De-Icing Overshoes in 24ft Tunnel". A. B. Haines, Royal Aircraft Establishment, Farnborough, Hampshire, RAE TN Aero. 1847, December 1946
- 360. (665) "Effect of Performance of De-Icing A.S. Mamba Engine". A.S.M. Experimental Department, (Flight Section), August 20, 1947
- 361. (700) "Effect of Performance of Anti-Icing A.S. Mamba Engine". A.S.M. Experimental Department (Flight Section) Report, December 17, 1948
- 362. (69) "Effect of Pneumatic De-Icers and Ice Formations on Aerodynamic Characteristics of an Airfoil". Dean T. Bowden, NACA TN 3564, 1956
- 363. (1301) "Effects of Aircraft De-Icing/Anti-Icing Fluids on Airfoil Characteristics". Eugene G. Hill, Von Karman Institute for Fluid Dynamics, "Influence of Environmental Factors on Aircraft Wing Performance", February 1987

Also reference : 95

3.3.2 Aerofoil

- 364. (1113) "Effect of Ice and Frost Formation on Drag of NACA Airfoil for Various Modes of Thermal Ice Protection". V. H. Gray and U. H. von Glahn, NACA TN 2962, June 1953
- 365. (70) "Effect of Ice and Frost Formations on Drag of NACA 651-212 Airfoil for Various Modes of Thermal Ice Protection". Vernon H. Gray and Uwe H. von Glahn, NACA TN 2962, 1953
- 366. (1108) "Effect of Ice Formations on Section Drag of Swept NACA 63A-009 Airfoil with Partial-Span Leading Edge Slat for Various Modes of Thermal Ice Protection". U. H. von Glahn and V. H. Gray, NACA TIB 4005, RM E53130, March 1954

367. (68) "Effect of Ice Formations on Section Drag of Swept NACA 63A-009 Airfoil with Partial-Span Leading-Edge Slat for Various Modes of Thermal Ice Protection". Uwe H. von Glahn and Vernon H. Gray, NACA RM E53J30, 1954
368. (71) "Correlations Among Ice Measurements, Impingement Rates, Icing Conditions and Drag Coefficients for Unswept NACA 65A004 Airfoil". Vernon H. Gray, NACA TN 4151, 1957
369. (67) "Aerodynamic Effects Caused by Icing of an Unswept NACA 65A004 Airfoil". Vernon H. Gray and Uwe H. von Glahn, NACA TN 4155, 1958
370. (1297) "Drag in Particle-Laden Gas Flow". Lundberg Kriebel, Stanford University, AD 291 178, 1962
371. (63) "Prediction of Aerodynamic Penalties Caused by Ice Formations on Various Airfoils". Vernon H. Gray, NASA Lewis Research Center, Cleveland, Ohio, NASA Office of Technical Services. NASA TN D 2166, Department of Commerce, Washington D.C. 20230, February 1964
372. (218) "The Calculation of Compressible Transitional Turbulent, and Relaminarizational Boundary Layers Over Smooth and Rough ... Extended Mixing-Length Hypothesis". B. K. Hodge and J. C. Adams, AEDC-TR-77-96, 1978
373. (86) "Wind Tunnel Investigation of Airfoil Performance Degradation Due to Icing". M. B. Bragg, and G. M. Gregorek, AIAA 12th Aerodynamic Testing Conference. AIAA-82-0582, Williamsburg, Virginia, March 22-24, 1982
374. (92) "Airfoil Performance Degradation". M. B. Bragg, The Second Icing Analysis Workshop, NASA Lewis Research Center, February 8, 1983
375. (113) "Statistical Study of an Airfoil Glaze Ice Drag Coefficient Correlation". K. D. Korkan, T. L. Miller, Texas A and M University, College Station, Texas. R. J. Shaw, NASA Lewis Research Center, SAE Business Aircraft Meeting. SAE 830753, Wichita, Kansas, April 1983
376. (1136) "Study of Aerospace Materials, Coatings, Adhesions and Processes. Aircraft Icing Processes. Final Scientific Report, 15 Jul. 1982 - 14 Sep. 1983". E. M. Rodriguez, September 14, 1983
377. (576) "Detailed Measurements of the Flowfield in the Vicinity of an Airfoil with Glaze Ice". M. B. Bragg and W. J. Coirier, Ohio State University, Columbus, Ohio, AIAA-85-0409. 23rd Aerospace Sciences Meeting, Reno, Nevada, January 14-17, 1985

378. (577) "Progress in the Development of a Navier-Stokes Solver for Evaluation of Iced Airfoil Performance". M. G. Potapczuk and P. M. Gerhart, AIAA-85-0410. 23rd Aerospace Sciences Meeting, Reno, Nevada, January 14-17, 1985
379. (1086) "Airfoil Aerodynamics in Icing Conditions". M. B. Bragg, G. M. Gregorek, and J. D. Lee, Ohio State University, Columbus, Ohio, Journal of Aircraft, Vol.23, No.1, pp.76, September 17, 1985

Also references : 94 104 220 584 579 1109

3.3.2.1 Rime

380. (215) "Rime Ice Accretion and its Effect on Airfoil Performance". M. B. Bragg, Ph.D. Dissertation, The Ohio State University, 1981
381. (28) "Aerodynamic Characteristics of Airfoils with Ice Accretions". M. B. Bragg and G. M. Gregorek, The Ohio State University, Columbus, Ohio, AIAA-82-0282, AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, January 11-14, 1982
382. (104) "Predicting Airfoil Performance with Rime and Glaze Ice Accretions". M. B. Bragg, The Ohio State University, Columbus, Ohio, AIAA 22nd Aerospace Sciences Meeting, AIAA-84-0106, Reno, Nevada, January 9-12, 1984
383. (914) "Analysis of Data from Wind Tunnel Tests on the Sensitivity of RAE 9645 and NACA 0012 Aerofoils to Surface Protruberances". R. H. Markiewicz, Royal Aircraft Establishment, Farnborough, Hampshire, December 1985

Also reference : 27

3.3.2.2 Simulated Ice

384. (421) "Effects of a Simulated Ice Formation on the Aerodynamic Characteristics of an Airfoil". Beverly G. Gulick, NACA ACR (WR L-292), May 1938

385. (345) "Low Speed Aerodynamic Characteristics of NACA 0012 Aerofoil Section, Including the Effects of Upper-Surface Roughness Simulating Hoar Frost". N. Gregory and C. L. O'Reilly, Aeronautical Research Council, Fluid Motion Sub-Committee, ARC31 719, NPL Aero Report 1308, January 1970
386. (87) "Wind Tunnel Evaluation of Airfoil Performance Using Simulated Ice Shapes". M. B. Bragg, R. J. Zaguli and G. M. Gregorek, AARL TR 82-01. NASA CR 167960, Department of Aeronautical and Astronautical Engineering, The Ohio State University, November 1982
387. (148) "Results of an Experimental Program Investigating the Effects of Simulated Ice on the Performance of the NACA 63A415 Airfoil with Flap. Final Report". R. J. Zaguli, M. B. Bragg and G. M. Gregorek, Department of Aeronautical and Astronautical Engineering, Ohio State University, Columbus, Ohio, NASA CR 168288, January 1984
388. (51) "Experimental Aerodynamic Characteristics of an NACA 0012 Airfoil with Simulated Ice". K. D. Korkan, E. J. Cross Jr. and C. C. Cornell, Texas A and M University, College Station, Texas. Journal of Aircraft. Vol.22, pp.130-132, February 1985
389. (81) "Experimental Study of the Aerodynamic Characteristics of a NACA 0012 Airfoil with Simulated Ice". K. D. Korkan, E. J. Cross Jr., C. C. Cornell, Texas A and M University, College Station, Texas
390. (259) "Aerodynamic Measurements of an Airfoil with Simulated Glaze Ice". M. B. Bragg and W. J. Coirer, The Ohio State University, Columbus, Ohio. AIAA-86-0484. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986

Also references : 114 151 914 1022

3.3.3 Helicopter Rotor

391. (1133) "Nozzle Tests for Simulating Heavy Rain in a Wind Tunnel - Final Report, February 1983 - February 1984". Dayton University, Ohio, James K. Luers and Ira B. Fiscus, Wright-Patterson Air Force Base, Ohio, AFWAL-TR-83-3131, January 1984
392. (53) "Aerodynamic Evaluation of a Helicopter Rotor Blade with Ice Accretion in Hover". J. D. Lee, AIAA-84-0608, March 1984

393. (1132) "Preliminary Indications of Water Film Distribution and Thickness on an Airfoil in a Water Spray". Earl C. Hastings Jr. and Leonard M. Weinstein, NASA Langley Research Center, Hampton, Virginia, NASA-TM-85796, July 1984
394. (16) "Performance Degradation of Helicopter Rotor in Forward Flight Due to Ice". K. D. Korkan, Texas A and M University, College Station, Texas. L. Dadone, Boeing Vertol Company, Philadelphia, Pennsylvania. R. J. Shaw, NASA Lewis Research Center, Cleveland, Ohio. Journal of Aircraft, Vol.22, No.8, pp.713-718, August 1985
395. (1135) "Droplet Size Distribution and Liquid Volume Concentration in a Water Spray : Predictions and Measurements". Instituto Superior Tecnico, Lisbon, Portugal, Advisory Group for Aerospace Research and Development, NATO, G. P.Pita, Combustion Problems in turbine Engines, AGARD, Propulsion and Energetics Panel, 62nd Symposium, Cesme, Turkey, October 3-6, 1983
396. (1134) "Performance of an Alpha-Vane and Pitot Tube in Simulated Heavy Rain Environment - Final Report". Dayton University, Ohio, James K. Luers and Ira B. Fiscus, NASA-CR-176353, October 1985
397. (1127) "Heavy Rain Penalties - A Comparison of Theory to Measurement". J. K. Luers, University of Dayton, Research Institute, Dayton, Ohio, AIAA-85-0256, 1985
398. (1128) "Subscale Testing of High Lift Airfoils Under Heavy Rain". A. J. Bilman, Continuum Dynamics Incorporated, Princeton, New Jersey, AIAA-85-0257, 1985
399. (1129) "Two-Dimensional Wind Tunnel Tests of a Transport-Type Airfoil in a Water Spray". R. E. Dunham Jr., G. M. Bezos and G. L. Gentry Jr., NASA Langley Research Center, Hampton, Virginia, and W. E. Melson Jr., NASA Wallops Flight Facility, Wallops Island, Virginia, AIAA-85-0258, 1985
400. (1130) "Measurements of Water Film Characteristics on Airfoil Surfaces from Wind Tunnel Tests with Heavy Rain". E. C. Hastings Jr. and G. S. Manuel, NASA Langley Research Center, Hampton, Virginia, AIAA-85-0259, 1985
401. (1131) "The Aerodynamic Effect of Surface Wetting Characteristics on a Laminar Flow Airfoil in Simulated Heavy Rain". R. J. Hansman Jr. and M. F. Barsotti, Massachusetts Institute of Technology, Cambridge, Massachusetts, AIAA-85-0260, 1985

Also references : 220 238 1016 1144

3.3.3.1 Rime Ice

402. (261) "Performance Degradation of Helicopter Rotor Systems in Forward Flight Due to Rime Ice Accretion". K. D. Korkan, R. J. Shaw and L. Dadone, AIAA-83-0029, 1983

3.3.3.2 Natural Icing Encounter

403. (975) "Icing and De-Icing Flight Tests on an Alouette Helicopter During the Season 1964-65". National Research Council of Canada, Report LR-429, Department of Mechanical Engineering, NRC, Ottawa, Canada, March 1965
404. (1021) "Requirements for the Operation of Naval Helicopters in Icing Conditions". Aircraft Department, Ministry of Defense (Navy), July 1969
405. (919) "Airworthiness of Helicopters in an Icing Atmosphere". H. E. Le Sueur, International Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
406. (972) "Icing Trials in Canada During Winter 1972/73 - Sea King Helicopter XV642". A. Wilson and C. J. Green, Aircraft and Armament Experimental Establishment, Boscombe Down, January 1973.
407. (973) "Icing Trials in Canada During Winter 1972/73 - Sea King Helicopters XV762 and XT768". A. Wilson and C. J. Green, Aircraft and Armament Experimental Establishment, Boscombe Down, January 1973.
408. (978) "Icing Problems on Helicopter Rotors". Royal Aircraft Establishment, Farnborough, Hampshire, June 1977
409. (50) "Helicopter Rotor Performance Degradation in Natural Icing Encounter". K. D. Korkan, Texas A and M University, College Station, Texas. L. Dadone, Boeing Vertol Company, Philadelphia, Pennsylvania. R. J. Shaw, NASA Lewis Research Center, Cleveland, Ohio, AIAA. Journal of Aircraft Vol.21, pp.84-85, January 14, 1983
410. (1147) "Evaluation of UH-1H Hover Performance Degradation Caused by Rotor Icing. Final Report, 28 Jan. - 4 Mar. 1983". W. Y. Abbot, D. Belte, R. A. Williams and F. W. Stellar, Army Aviation Engineering Flight Activity, Edwards Air Force Base, California, August 1983

- 411. (934) "Aerospaciales Experience on Helicopter Flight in Icing Conditions". Denis Trivier and Gaston Avedissian, Societe Nationale Industrielle Aerospatiale, Presented at the AAAF 9th European Rotorcraft and Powered Life Craft Forum, Stresa, Italy, SNIAS-832-210-107, N84-25707, September 13-15, 1983
- 412. (1050) "Airworthiness Problems on Helicopters Due to Ice Formation". K. T. McKenzie, Westland Helicopters Limited, Helicopter Icing Symposium, Aircraft and Armaments Experimental Establishment, Boscombe Down

3.3.3.3 During Ground Run-Up

- 413. (191) "The Effect of Icing During Helicopter Ground Run-Up". J. R. Stallabrass and R. D. Price, NRC MET 491, Ottawa, Canada, April 1967

Also references : 1143 1146

3.3.3.4 Simulated Ice

- 414. (971) "Artificial Icing Tests UH-1H Helicopter- Part 1". Warren E. Griffith, Raymond B. Smith, Larry K. Brewer, Marvin L. Hanks and James Reid, U.S. Army, January 1974
- 415. (114) "Experimental Study of Performance Degradation of a Model Helicopter Main Rotor with Simulated Ice Shapes". K. D. Korkan, E. J. Cross Jr., and C. C. Cornell, Texas A and M University, College Station, Texas, Reno, Nevada, AIAA-84-0184, AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984
- 416. (52) "Performance Degradation of a Model Helicopter Main Rotor in Hover and Forward Flight with a Generic Ice Shape". K. D. Korkan, E. J. Cross Jr. and T. L. Miller, Texas A and M University, College Station, Texas, AIAA-84-0609, March 1984
- 417. (151) "Performance Degradation of a Model Helicopter Rotor with a Generic Ice Shape". K. D. Korkan, E. J. Cross Jr. and T. L. Miller, Texas A and M University, College Station, Texas. AIAA Journal of Aircraft, Vol.21, No.10, pp.823-830, October 1984
- 418. (326) "Wind Tunnel Tests of Rotor-Blade Models with Replications of Ice Formations". J. D. Lee and J. Berger, NASA Lewis Research Center, NASA CR X, 1984

3.3.4 Aircraft Or Wing

419. (252) "The Jeopardizing Action of Ice Formation on Airplanes". E. Hebner, The German Meteorological Service Report No.25, Lindberg Aeronautical Observatory, District of Beeskow, 1928
420. (251) "Danger of Ice Formation on Airplanes". W. Kopp, NACA TM 499, 1929
421. (88) "Effect of Ice Formations on Airplane Performance in Level Cruising Flight". G. Merrit Preston and Calvin C. Blackman, NACA TN 1598, 1948
422. (725) "Weight Comparison of De-Icing Systems". McBain, Aeronautical Digest, September 1951
423. (871) "The Effect of Icing on Aircraft Equipped with Vortex Generators". A. D. Wood and D. G. Gould, NAE LR 220, April 1958
424. (1048) "Vanguard icing Incident. - 6th October 1961". P and D Report M140, British European Airways, December 1961
425. (1051) "C.A.B. Accident Report in Respect to Continental Airlines Viscount 812 Crash at Kansas City, January 29, 1963". Section 8 - Aircraft Accidents and Aviation Safety, Civil Air Attache Newsletter, Washington, June 20, 1964
426. (990) "Airworthiness Standards: Transport Category, Airplanes. Ice Protection" Federal Aviation Agency, Federal Aviation Regulations, Part 25 Section 25 1419, Change 9, October 1966
427. (147) "Wind Tunnel Investigations of Simulated Hoar Frost on a 2-Dimensional Wing Section With and Without High Lift Devices". B. Ljungstroem, Aeronautical Research Institute of Sweden, FFA, AU-902, 1972
428. (126) "The Elaboration of Ice Simulator Techniques for the Assessment of Icing Effects on Aerodynamic Characteristics of Aircraft". A. Ivaniko, O. K. Trunov and V. Yelistratov, State Research Institute for Civil Aviation, USSR, 3rd. Meeting of the Working Group, September 1974
429. (1043) "Methods for Predicting the Influence of Ice on Aircraft Flying Characteristics". M. Ingleman-Sundberg, Sweden and O. K. Trunov, USSR, Report No. JR-1, The Swedish Soviet Working Group on Scientific-Technical Co-operation in the Field of Flight Safety, 6th Meeting, Item 2.2, 1977
430. (339) "Tests of the Effect of Simulated Hoar Frost Deposits on the Take-off Performance of a Model of a Transport Aircraft (Hawker Syddeley Trident 3B)". D. J. Weeks, RAE TR 71178

431. (1175) "Methods of Testing Aircraft Performance Under Icing Conditions and Ice-Tection Systems". Martin Friendlander, AGARD Subsystem Testing and Flight Test Instrumentation, April 1981
432. (159) "Aircraft Icing Hazards". Robert I. Stanfield, Flight Safety Foundation, Incorporated, 5510 Columbia Pike, Arlington, Virginia 22204, USA, Air Taxi/Commuter Safety Bulletin, September/October 1981
433. (89) "Evaluation of AEROICE". Mark Dieteriberger, Air Force Flight Dynamics Laboratory. Contract F33615-79-C-3030 Requisition 81-02, WPAFB, 1981
434. (62) "Predicting Aircraft Performance Degradation Due to Ice Accretion". M. B. Bragg and G. M. Gregorek, The Ohio State University, Business Aircraft Meeting and Exposition. SAE 830742, Wichita, Kansas, April 12-15, 1983
435. (263) "Performance Evaluation of the XV-15 Tilt Rotor Aircraft in a Natural Icing Encounter". K. D. Korkan, J. C. Narramore, L. Dadone and R. J. Shaw, AIAA-83-2534, October 1983
436. (180) "Performance Degradation of a Typical Twin Engine Commuter Type Aircraft in Measured Natural Icing Conditions". Richard J. Ranaudo, Kevin L. Mikkelsen and Robert C. McKnight, NASA Lewis Research Center, Cleveland, Ohio. Porter J. Perkins, ANALEX Corporation, Cleveland, Ohio, AIAA-84-0179, AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984
437. (97) "Effects of Icing on Performance of a Research Airplane". William A. Cooper, Wayne R. Sand, Marcia K. Politovich and Donald L. Veal, University of Wyoming, Laramie, Wyoming. AIAA Journal of Aircraft, Vol.21, No.9, pp.708-715, March 10, 1984
438. (1085) "Icing Flight Research: Aerodynamic Effects of Ice and Ice Shape Documentation with Stereo Photography". Kevin L. Mikkelsen, Robert C. McKnight and Richard J. Ranaudo, NASA Lewis Research Center, Cleveland, Ohio, and Porter J. Perkins Jr., Sverdup Technology Incorporated, Middleburg Heights, Ohio, AIAA-85-0468, NASA Technical Memorandum 86906, Prepared for the 23rd Aerospace Sciences Meeting, Sponsored by AIAA, Reno, Nevada, January 14-17, 1985

439. (1151) "The Measurement of Aircraft Performance and Stability and Control After Flight Through Natural Icing Conditions". Richard J. Ranaudo, Kevin L. Mikkelsen, Robert C. McKnight, Robert F. Ide, Andrew L. Reehorst, Jerry L. Jordan, William C. Schinstock and Stewart J. Platz, NASA Lewis Research Center, Cleveland, Ohio, Presented at the 3rd Flight Testing Conference, Las Vegas, Nevada, April 2-4, 1986, Cosponsored by AIAA, CASI, DGLR, IES, ITEA, SETP and SFTE, Prepared in cooperation with Kohlman Systems Research Incorporated, Lawrence, Kansas, AIAA-86-9758, NASA-TM-87265, April 2-4, 1986
440. (160) "Operating Safely in Adverse Weather Environments". Joseph W. Stickle and Albert W. Hall, pp.195-208, Low Speed Aerodynamics Division. NASA Langley Research Center
441. (1044) "The Hazards of Tail Stall Due to Icing can be Reduced". M. Ingleman-Sundberg, Sweden and O. K. Trunov, USSR, The Swedish Soviet Working Group on Scientific-Technical Co-operation in the Field of Flight Safety
442. (1042) "The Ice Hazard on Airplanes". William C. Geer, ITHACA, New York, AER-54-4, pp.33

Also references : 249 578 850 1016

3.3.4.1 Wing De-Icer

443. (422) "The Drag of Inflatable Rubber De-Icers". Russell G. Robinson, NACA TN 669, October 1938
444. (424) "Profile-Drag Investigation of an Airplane Wing Equipped with Rubber Inflatable De-Icer". Lewis A. Rodert and Alun R. Jones, Langley Memorial Aeronautical Laboratory, NACA ACR, December 1939
445. (1166) "Analysis and Testing of the Diamond One Wing Anti-Icing System". K. E. Yoeman, Key Industries Corporation, San Antonio, Texas, AIAA-85-0414, 1985

Also references : 68 440

3.3.5 Engine Air Intake Equipment

- 446. (720) "Effect of Heat and Power Extraction on Turbojet Engine Performance. III - Analytical Determination of Effects of Shaft Power Extraction". Koutz, Hensley and Rim, NACA TN2202, October 1950
- 447. (1023) "Some Simulated Icing Techniques for the Testing of Aircraft Engines". P. T. Sharp, D. Napier and Son Limited, Flight Development Establishment, Luton, Bedfordshire, DEV/TN/234/781, December 1957
- 448. (1312) "Observation of Ice/Water Formations on a Model Intake Section Subjected to Simulated Cloud Conditions". S. J. Downs, Rolls Royce Reprint, May 6, 1986
- 449. (187) "Engine Snow Ingestion in the Bell 206A Jet Ranger Helicopter". J. R. Stallabrass, NRC 11893, Canada
- 450. (459) "The Effect of Liquid and Ice Particles on the Erosion of a Supercharger-Inlet Cover and Diffuser Vanes". Vern G. Rollin. NACA MR E6E31
- 451. (1155) "Engine Performance Comparison Associated with Carburetor Icing During Aviation Grade Fuel and Automotive Grade Fuel Operation. Final Report". William Cavage, James Newcomb and Keith Biehl, FAA, Atlantic City, New Jersey, Technical Center, FAA Project 184-320-120, DOT/FAA/CT-82/110, May 1983

Also references : 109 152 158 456 700 1154

3.4 De-Icers

3.4.1 Gas Heated

3.4.1.1 Propeller

- 452. (417) "The Prevention of Ice Formation on Propellers". William C. Clay, NACA ACR, October 1937
- 453. (636) "Airplane Anti-Icing Construction". Aircraft Engineering, February 1944
- 454. (36) "Investigation of the Effect of a Tip Modification and Thermal De-Icing Air Flow on Propeller Performance". Blake W. Corson Jr. and Julian D. Maynard, NACA TN 1111, July 1946
- 455. (38) "A Flight Investigation of the Thermal Performance of an Air Heated Propeller". John F. Darsow and James Selna, NACA TN 1178, April 1947
- 456. (39) "A Method for Estimating Heat Requirements for Ice Prevention on Gas-Heated Hollow Propeller Blades". V. H. Gray and R. G. Campbell, NACA TN 1494, December 1947
- 457. (64) "The Effect of Tip Modification and Thermal Deicing Air Flow on Propeller Performance as Determined from Wind Tunnel Tests". W. H. Gray and R. E. Davidson, Langley Memorial Aeronautical Laboratory, Langley Field, Virginia, NACA TN 1540, February 1948
- 458. (419) "Investigation of Effectiveness of Air-Heating a Hollow Steel Propeller for Protection Against Icing. III - 25 - Percent Partitioned Blades". Donald R. Mulholland and Porter J. Perkins, NACA TN 1588, May 1948
- 459. (204) "Investigation of Effectiveness of Air-Heating a Hollow Steel Propeller for Protection Against Icing - I - Unpartitioned Blades". Donald R. Mulholland and Porter J. Perkins, NACA TN 1586
- 460. (583) "Investigation of Effectiveness of Air-Heating A Hollow Steel Propeller for Protection Against Icing - II - 50-Percent Partitioned Blades". Porter J. Perkins and Donald R. Mulholland, NACA TN 1587

Also references : 37 64 83 452

3.4.1.2 Engine And Intake

461. (838) "The Anti-Icing of Compressor Blades by Surface Heating. Part 1. Stator Blades". G. L. Shires, National Gas Turbine Establishment, December 1950
Also references : 706
462. (981) "Anti-icing Systems of Gas Turbine Engines". C. D. Brown, December 16, 1947
463. (698) "Inlet Icing and Effectiveness of Hot Gas Bleedback for Ice Protection of Turbojet Engine". Saari Flemming, NACA R.M. No.E8J250, November 26, 1948
464. (705) "Effect of Hot Gas Bleedback Ice Prevention on Performance of a Turbojet Engine with Fixed Area Tail Pipe Nozzle". R. O. Dietz and R. P. Krebs, NACA Research Memo No.E9B23, May 16, 1949
465. (982) "The Protection of Jet Engines Against Atmospheric Icing". FN/AGB.1/DD, July 13, 1949
466. (774) "Aircraft Gas Turbine Ice Prevention. The Design and Development of Hot Air Surface Heated Systems". C. K. Rush and D. Quan, Canadian Aeronautical Institute, Preprint No.7/10, May 1957

3.4.1.3 Wing

3.4.1.3.1 1930 - 1950 -

467. (257) "Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil". Theodore Theodorsen and William C. Clay, NACA TR 403, 1931
468. (423) "A Preliminary Study of the Prevention of Ice on Aircraft by the use of Engine-Exhaust Heat". Lewis A. Rodert, NACA TN 712, June 1939
469. (425) "A Flight Investigation of Exhaust-Heat De-Icing". Lewis A. Rodert and Alun R. Jones, NACA TN 783, November 1940
470. (271) "A Preliminary Report on Flight Tests of an Airplane Having Exhaust-Heated Wings". Lewis A. Rodert and Lawrence A. Clousing, NACA ACR, April 1941

471. (272) "A Flight Investigation of the Thermal Properties of an Exhaust Heated Wing De-Icing System on a Lockheed 12-A Airplane". Lewis A. Rodert and Lawrence A. Clousing, Ames Aeronautical Laboratory, Moffet Field, California, NACA ARR, June 1941
472. (273) "A Flight Investigation of the Thermal Properties of an Exhaust-Heated-Wing De-Icing System on a Lockheed 12-A Airplane (Supplement 1)". Lewis A. Rodert and Lawrence A. Clousing, NACA ARR, June 1941
473. (457) "A Flight Investigation of the Thermal Properties of an Exhaust-Heated-Wing De-Icing System on a Lockheed 12-A Airplane (Supplement 2)". Lewis A. Rodert and Lawrence A. Clousing. NACA
474. (414) "Preliminary Investigation and Design of an Air-Heated Wing for Lockheed 12-A Airplane". Lewis A. Rodert and Richard Jackson, NACA ARR (WR A-34), April 1942
475. (427) "A Description of the Ju 88 Airplane Anti-Icing Equipment". Lewis A. Rodert, and Richard Jackson, Ames Aeronautical Laboratory, Moffet Field, California, NACA RB, August 1942
476. (521) "A Method for Determining the Rate of Heat Transfer from a Wing or Streamline Body". Charles W. Frick Jr. and George B. McCullough, NACA ACR, December 1942
477. (428) "Development of Thermal Ice-Prevention Equipment for the B-24D Airplane". Alun R. Jones and Lewis A. Rodert, NACA ACR (WR A-35), February 1943
478. (429) "Development of Thermal Ice-Prevention Equipment for the B-17F Airplane". Alun R. Jones and Lewis A. Rodert, NACA ARR 3H24 (WR A-51), August 1943
479. (431) "Flight Tests of Thermal Ice-Prevention Equipment in the XB-24F Airplane". Carr B. Neel and Alun R. Jones, NACA RMR (WR A-7), October 1943
480. (408) "Hot Air De-Icing - Heat Transfer in the Double Skin". Ditton Laboratory Staff, RAE TN S.M.E. 208, January 1944
481. (406) "Investigation of Wing De-icing by Means of Hot Air". K. C. Hales and G. Mann, RAE TN S.M.E. 255, July 1944
482. (639) "New De-Icing System Applies Exhaust Heat to Plane's Wings and Empennage". S.A.E. Journal, October 1944
483. (323) "An Analysis of the Dissipation of Heat in Conditions of Icing from a Section of the Wing of the C-46 Airplane". J. K. Hardy, RAE Report 831, pp.1-10

484. (450) "An Investigation of a Thermal Ice-Prevention System for a C-46 Cargo Airplane I - Analysis of the Thermal Design for Wings, Empennage, and Windshield". Carr B. Neel Jr., NACA ARR 5A03
485. (444) "An Investigation of a Thermal Ice-Prevention System for a C-46 Cargo Airplane II - The Design, Construction, and Preliminary Tests of the Exhaust-Air Heat Exchanger, Richard Jackson, NACA ARR 5A03a
486. (243) "An Analysis of the Dissipation of Heat in Conditions of Icing from a Section of the Wing of the C-46 Airplane". J. K. Hardy, NACA ARR 4I11a, 1944
487. (241) "An Investigation of a Thermal Ice-Prevention System for a C-46 Cargo Airplane III - Description Thermal Ice-Prevention Equipment for Wings, Empennage, and Windshield". Alun R. Jones and Ray J. Spies Jr., NACA ARR 5A03b, 1945
488. (648) "Heat Recovery as Applied to the Heating and Anti-Icing of Aircraft". J. J. Draney, S.A.E. Journal, February 1946
489. (449) "An Investigation of a Thermal Ice-Prevention System for a C-46 Cargo Airplane IV - Results of Flight Tests in Dry-Air and Natural-Icing Conditions". James Selna, Carr B. Neel Jr. and E. Lewis Zeiller. NACA ARR 5A03c
490. (440) "An Investigation of a Thermal Ice-Prevention System for a C-46 Cargo Airplane V - Effect of Thermal System on Airplane Cruise Performance". James Selna, NACA ARR 5D06
491. (446) "An Investigation of a Thermal Ice-Prevention System for C-46 Cargo Airplane VI - Dry Air Performance of Thermal Systems at Several Twin and Single-Engine Operating Conditions at Various Altitudes, James Selna and Harold L. Kees, NACA ARR 5C20
492. (442) "An Investigation of a Thermal Ice Prevention System for a C-46 Cargo Airplane VII - Effect of Thermal System on the Wing-Structure Stresses as Established in Flight". Alun R. Jones and Bernard A. Schlaff, NACA ARR 5G20
493. (433) "An Investigation of a Thermal Ice-Prevention System for a Twin-Engine Transport Airplane". Alun R. Jones, Ames Aeronautical Laboratory, Moffet Field, California, NACA Report 862 (Based on Previously Issued Reports, ARR's 5A03, 5A03a, 5A03b, 5A03c, 5C20, 5D06, 5G20), 1946
494. (677) "Interim Report on the Effect of an Aircraft Wing Structure of De-icing by Direct Application of Exhaust Gases". Crease and Graham, Thornton Research Centre, (Engineering Division) Report No.M.1/48, Investigation No.4137, January 1947

495. (434) "An Investigation of a Thermal Ice-Prevention System for a Cargo Airplane, VIII - Metallurgical Examination of the Wing Leading-Edge Structure After 225 Hours of Flight Operation of the Thermal System". Maxwell Harris and Bernard A. Schlaff, NACA TN 1235, April 1947
496. (661) "De-Icing of Aeroplane by Mixed Gs". P. Wenthien, M.A.P. Volken R. and T. No.823, G.D.C./p29T, June 1, 1947
497. (436) "An Investigation of a Thermal Ice-Prevention System for a Cargo Airplane, IX - The Temperature of the Wing Leading-Edge Structure as Established in Flight". Bernard A. Schlaff and James Selna, NACA TN 1599, June 1948
498. (437) "Corrosion Tests of a Heated Wing Utilizing an Exhaust-Gas-Air Mixture for Ice-Prevention". George H. Holdaway, NACA TN 1791, January 1949
499. (764) "Note on the Use of Exhaust Gas for Wing Heating". J. K. Hardy, R.A.E. Technical Memo No.Mech.Eng.25, June 1949
500. (405) "The Effect on an Aircraft Wing Structure of De-Icing by Direct Application of Exhaust Gases (Summary Report)". Jackson and Graham, Thornton Research Report No.M29/49, March 27, 1950
501. (767) "Improvements in Heat Transfer for Antiicing of Gas - Heated Airfoils with Internal Fins and Partitions". V. H. Gray, NACA Technical Note 2126(7.3), July 1950

Also references : 15 202 246 255 323 412 413 435
436 629 650

3.4.1.3.2 1951 Onwards -

502. (224) "Preliminary Results of Cyclical De-icing of a Gas Heated Airfoil". Vernon H. Gray, D. T. Bowden and U. von Glahn, NACA RM E51J29, 1952
503. (964) "A Very Approximate Analysis of Total Heat Loads for Wing Anti-Icing on Various Aircraft". Blackburn and General Aircraft Limited, Note No.YED.481, May 28, 1958
504. (236) "Comparison of Several Methods of Cyclic De-Icing of a Gas Heated Airfoil". Vernon H. Gray and D. T. Bowden, NACA/TIB/3632 RM E53C27, June 1953

505. (106) "Thermodynamic Performance of an Airplane Wing Leading Edge Anti-Icing System". R. Ross, Ross Aviation Associates, Sedgwick, Kansas. AIAA Journal of Aircraft, Vol.21, No.7, pp.536-537, February 3, 1984

Also reference : 70 938 945 708 852

3.4.1.3.3 Date Unknown -

506. (452) "Design Outline of Anti-Icing Equipment Employing Heated Air". Lewis A. Rodert. NACA ARR

Also reference : 440

3.4.1.4 Other Components

507. (635) "Anti-icing System Uses Engine Exhaust Heat". H. W. Perry, Flight International, December 1943
508. (650) "Heat Requirements for Instruments and Aerofoils During Icing Storms on Mount Washington". A.S.M.A. Paper No.46-A-90, April 1946
509. (880) "Design Manual for Windshield Jet Air Blast and Ice Removal". H. R. Meline and I. D. Smith, WADC TR 58-444, November 1958
510. (455) "Tests of a Thermal Ice-Prevention System for a Wing Leading-Edge Landing-Light Installation". Wesley H. Hillendahl. NACA MR A4L11
511. (453) "Thermodynamic Design of Double-Panel Air-Heated Windshields for Ice Prevention". Jerome L. Kushnick. NACA ARR

Also references : 413 450 452 639 881

3.4.2 Electro-Thermal

3.4.2.1 Propeller

512. (317) "Interim Report on Flight Tests of Thermal-Electric Propeller De-Icing". J. L. Orr, National Research Council of Canada, Report MD 25, November 7, 1942
513. (208) "Tests of Thermal-Electric De-Icing Equipment for Propellers". Richard Scherrer and Lewis A. Rodert, NACA ARR 4A20 (WR A-47), January 1944
514. (207) "An Analytical Investigation of Thermal-Electric Means of Preventing Ice Formations on a Propeller Blade". Richard Scherrer, NACA ACR 4H31 (WR A-17), August 1944
515. (1282) "Electrical Heating Device". E. P. Newton, Honorary Advisory Council for Scientific and Industrial Research, March 17, 1948
516. (420) "Icing and De-Icing of a Propeller with Internal Electric Blade Heaters". James P. Lewis and Howard C. Stevens, NACA TN 1691, August 1948
517. (961) "Airscrew De-Icing". Flight International, pp.291, March 14, 1952
518. (876) "Intermittent Heating for Aircraft Ice Protection with Application to Propellers and Jet Engines". M. Tribus, ASME Paper 50-A-55, June 1952
519. (1292) "Rubber in Aircraft". E. W. Russell, India Rubber Journal, Vol.126, pp.28, 1954
520. (831) "Anti-Icing Test on Double Mamba Mk.100". Lowther Hill, Armstrong Siddeley Motors Limited, Winter 1955-1956
521. (946) "Propeller De-Icing-Electrothermal Mats for Viscounts". Aviation Week, pp.287, March 1957
522. (692) "Canada Develops Electro-Thermal De-Icers". Canada Aviation, October 1948
523. (944) "An Investigation Utilizing an Electrical Analogue of Cyclic De-Icing of Hollow Steel Propellers with Internal Electric Heaters". C. B. Neel, NACA TN 3025, October 1953
524. (1274) "Electrical De-Icing Overshoes for e.g. Airscrew Blades or Aerofoils". J. A. Chilman, A. G. Mapp and H. Newport, Rotol Limited, April 21, 1960

- 525. (1285) "De-Icing Aircraft Propellers". B. F. Goodrich Company, December 13, 1972
- 526. (447) "De-Icing Effectiveness of External Electric Heaters for Propeller Blades". James P. Lewis, NACA TN 1520

Also references : 36 413 415 1166

3.4.2.2 Engine And Intake

- 527. (963) "Investigation of Power Requirements for Ice Prevention and Cyclical De-icing of Inlet Guide Vanes with Internal Electric Heaters". Uwe von Glahn and Robert E. Blatz, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, december 1, 1950
- 528. (962) "Napier De-Icing System". Machinery Journal, Vol.84, pp.619, March 19, 1954
- 529. (959) "Electric De-Icing". The Aeroplane Journal, pp.330, March 19, 1954
- 530. (952) "De-Icing Elements". Aircraft Production Journal, pp.506, December 1955
- 531. (960) "Electrothermal De-Icing". Wiggin Nickel Alloys, No.31, pp.2-4, Henry Wiggin and Company Limited, Wiggin Street, Birmingham, 1955
- 532. (951) "Inlet De-icing System May Save Weight". Aviation Week, pp.101, February 13, 1961
- 533. (948) "Melting Ice at 30000 Feet"., Copper Journal, C.D.A. Publication No.19, pp.11, December 1963
- 534. (1028) "Arrangement for the Removal of Ice from a Casing". I. A. Levin, A. Y. Levin, N. E. Fedorou, I. A. Rogou and E. E. Afanasou, U.S.S.R. Certificate of Authorship 213590, November 15, 1965

Also references : 861 862

3.4.2.3 Helicopter Rotor Blade

535. (1347) "An Investigation of a Rotor Blade Thermal Ice Prevention System for the H-5 Helicopter". E. F. Katzenberger, Sikorsky Aircraft Division, United Aircraft Corporation, 19th Annual Meeting IAS, IAS Preprint No.333, January 29-February 1, 1951
536. (759) "Rotor Blade De-Icing". Flight International, October 19, 1951
537. (188) "Flight Tests of an Experimental Helicopter Rotor Blade Electrical De-Icer". J. R. Stallabrass, Low Temperature Laboratory, Division of Mechanical Engineering, National Research Council of Canada Aeronautical Report NRC LR 263, Ottawa, Canada, November 1959
538. (190) "A Comparison Between the Spanwise and Chordwise Shedding Methods of Helicopter Rotor Blade De-Icing". J. R. Stallabrass and G. A. Gibbard, Low Temperature Laboratory, Division of Mechanical Engineering, National Research Laboratories, Ottawa, Canada, NRC LR 270, January 1960
539. (383) "Electrical De-Icing of Helicopter Blades". R. D. Crick, Paper Presented at Napier Aircraft Ice Protection Conference, London, May 1961
540. (987) "Icing Flight Tests of an Electrothermal Rotor Blade De-Icing System on a Westland Wessex Helicopter". J. J. Samolewicz, National Research Council of Canada, Report LR-321, File CM4-A3-R26, Laboratory Order 13885A, for the British Ministry of Aviation, Aircraft and Armament Experimental Establishment, Boscombe Down, September 1961
541. (857) "Electrical De-Icing for Helicopters". Paper Presented at the Helicopter Forum, Buckeburg, Germany, May 1962
542. (1026) "Protection of Helicopters Against Frosting". T/21147/MHN/1, Report No.1, October 15, 1968
543. (1027) "Some Thoughts on Helicopter Icing Protection Systems". B. D. Lazelle, Engineering and Heating Systems Division, Lucas Aerospace Limited, Electrical Group, Presented at the International Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
544. (989) "Ice Protection Investigation for Advanced Rotary-Wing Aircraft". J. B. Werner, USAAMRDL Technical Report 73-38, US Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, Lockheed California Company, Burbank, California, August 1973

545. (1201) "Laminates with Low Adhesion For Ice". J. H. Sewell, UK Ministry of Defense, June 30, 1974
546. (910) "Ice Protection System as Proposed for the AH-1Q Improved Main Rotor Blade". G. I. Hackenberger, Kaman Aerospace Corporation, Bloomfield, Connecticut, Presented at Staying Power Symposium, Fort Rucker, Alaska, July 8-10, 1975
547. (1030) "The Development of an Advanced Anti-Icing/De-Icing Capability for U.S. Army Helicopters. Vol.2 - Ice Protection System Application to the UH-1H Helicopter". Lockheed-California Company, Burbank, California, November 1975
548. (992) "Proposed System Changes and Trials Objectives for Season 1976/77- Wessex HU Mk.5 Heated Rotor Blade System Development". Westland Helicopters Limited, Yeovil, Somerset, May 1976, Re-issued for Season 1977/78, July 2, 1977
549. (904) "Tests with the Main Rotor Blades of a Wessex Helicopter Partially Degraded to Simulate Icing Effects". J. Bradley, Aircraft and Armament Experimental Establishment, Boscombe Down, AAE - NOTE - 2106, September 7, 1977
550. (933) "Wessex Mk.5 XT768 Heated Rotor Blade Trials - Denmark 1977/78 - Technical Report". D. R. Shepherd, Westland Helicopters Limited, Yeovil, Somerset, December 5, 1977
551. (905) "UK Rotor Blade Ice Protection Programme, a Review of Progress". D. R. Shepherd, Westland Helicopters Limited, Helicopter Icing Symposium, NATO Army Armaments Group, Panel X, London, November 6-7, 1978
552. (901) "Application of the Spanwise Shedding Rotor Blade De-Icing Concept". P. F. Kitchens, Army Research and Technology Laboratory, Fort Eustis, Virginia, Helicopter Icing Symposium, NATO Army Armaments Group Panel X, London, November 1978
553. (900) "Research Study into Helicopter De-Icing Using Solid State Switching and Control, Vol.1 (Final Report)". D. C. Williams, S. B. Smith, Lucas Aerospace Limited, Hemel Hempstead, UK, February 1980
554. (920) "Research Study into Helicopter De-Icing Using Solid State Switching and Control, Vol.2 (Final Report)". D. C. Williams, S. B. Smith, Lucas Aerospace Limited, Hemel Hempstead, UK, February 1980
555. (156) "One Dimensional Treatment of Thermal Transients in Electrically De-Iced Helicopter Rotor Blades". R. W. Gent and J. T. Cansdale, Royal Aircraft Establishment, RAE TR 80159, December 1980

556. (20) "U.K. Developement of a Rotor De-Icing System". J. E. Clark, 6th. European Rotorcraft and Powered Lift Aircraft Forum, Bristol, 1980
557. (926) "HC-Mk1 (Chinook) Heated Rotor Blade Icing Test - Part 1 - Test Vehicle, Test Site Approach and Summary of Testing". K. Lunn, Experimental Operations, Boeing Vertol Company, Philadelphia, Pennsylvania, and R. Curtis, Rotary Wing Engineering Trials, Aeroplane and Armament Experimental Establishment, Boscombe Down, 10th European Rotorcraft Forum, The Hague, Netherlands, August 28-31, 1984
558. (931) "HC-Mk1 (Chinook) Heated Rotor Blade Icing Test - Part 2 - Analysis of Atmospheric Conditions, Aircraft and Systems Characteristics". P. Dunford and R. Finch, 10th European Rotorcraft Forum, August 28-31, 1984
559. (1090) "De-Icing the McDonnell Douglas AH-64A". Tom C. Knight and James E. Ritter, McDonnell Douglas Helicopter Company, Mesa, Arizona, Presented at the 42nd Annual Forum of the American Helicopter Society, Washington D.C., June 1986
560. (1032) "A Proposal for a Research Study into Helicopter Rotor De-Icing Using Solid State Control and Switching". Lucas Aerospace Limited, Electrical Division, Report No.EQ4930, Issue 2
561. (1033) "Ice Protection Systems for Aeroplanes and Helicopters". System Description, AEG-Telefunken
562. (996) "Wessex HAS Mk.1 XM837 De-Icing Trials in the National Research Council (Canada) Spray, Rig Electrical De-Icing System". Aircraft and Armament Experimental Establishment, Boscombe Down, England, 9th Part of Report No.AAEE/931, Ministry of Aviation
563. (995) "Electrical Equipment for the Boeing Vertol UTTAS Helicopter Rotor Blade, Tail Rotor and Empennage, Ice Protection System". Lucas Aerospace Limited, Maylands Avenue, Hemel Hempstead, Hertfordshire, APS No.143
564. (991) "A Rotor De-icing System for the Boeing Vertol CH47D Helicopter". P. A. Walsh, K. J. Payne and E. M. Grimshaw, Report TB4601, Lucas Aerospace Limited, Maylands Avenue, Hemel Hempstead, Hertfordshire.

Also references : 6 19 109 114 117 158 462 887 888
893 894 932 933 1104

3.4.2.4 Aerofoil (General)

565. (811) "An Electric De-Icing System for Aircraft". E. W. Gilow, A.I.E.E., Paper 49-218, The Glen Martin Company, Baltimore, Md., July 1949
566. (875) "General Specification for NRC Type W7-1 Heating Pads for Electro-Thermal Wing De-Icing". J. L. Orr, NRC LO 590, National Research Council of Canada, Ottawa, Canada, June 1950
567. (872) "Note on the Heat Requirements for Ice Prevention on a Heated Surface in a Cloud of Ice Crystals". J. L. Orr et al., NRCC Report No. MD-34 CC 91, National Research Council of Canada, Ottawa, Canada, July 1950
568. (822) "Specification for NRC Type W7-2 Heater Pads for Electro-Thermal Wing De-Icing. (Icing Wind Tunnel)". J. H. Milsum, NAE LT 11, Laboratory Memo, October 1951
569. (1269) "Anti-Icing Devices for Aircraft". H. F. L. Jenkins, A. E. T. Neale and R. N. Thomson, Dunlop Rubber Company, December 12, 1951
570. (225) "Preliminary Investigation of Cyclic De-icing of an Airfoil Using an External Electric Heater". James P. Lewis and Dean T. Bowden, NACA RM E51J30, 1952
571. (815) "Specification for Electro-Thermal De-Icing Heater Pads for Aircraft". R. O. Robertson, NAE LR 58, Laboratory Memo, May 1953
572. (969) "Electricity in Aircraft - Part 5. Methods of De-Icing". D. C. Flack, Electrical Journal, pp.432-437, February 5, 1954
573. (967) "De-Icing: A New Electrical Approach". Flight International, pp.290, March 12, 1954
574. (968) "Napier Surface Heater De-Icing". Interavia, No.2923, pp.6, March 12, 1954
575. (957) "Electro-Thermal De-Icing Equipment". The Engineer, pp.420, March 19, 1954
576. (958) "Surface Heaters Formed by Spraying Process - Electro-Thermal De-Icing System for Aircraft". The Engineering Journal, pp.378, March 19, 1954
577. (1034) "New Anti-Icing System Announced". American Aviation, March 29, 1954

578. (806) "Icing Tunnel Tests of Two Electro-Thermal Wing De-Icing Pads". J. H. Milsum, NAE TR 133, March 1954
579. (954) "New Surface Heater for Aircraft De-Icing". Plastics Journal, pp.116, April 1954
580. (955) "De-Icing with Sprayed Metal". Metal Spraying, Vol.4, No.4, April 1954
581. (956) "Napier Sprays on Its Electrical De-Icer". Aviation Week, pp.34, April 5, 1954
582. (998) "Napier Surface Heater De-Icing System". British Aircraft Industry Bulletin, pp.21, April 1954
583. (953) "Flame Spraying Resistance Heater Panels". Machinery Journal, pp.107, July 1954
584. (870) "Note on the Advantages of High Specific Power Inputs for Electro-Thermal De-Icing". D. Fraser and C. K. Rush, NAE LR 149, September 1955
585. (965) "Airfoil Anti-icing System Performance". Convair Engineering and Maintenance Conference, Interavia, 1955
586. (1273) "De-Icing and Anti-Icing Apparatus". R. D. S. Crick and R. A. Roper, D. Napier and Son Limited, July 28, 1957
587. (945) "Electrical or Hot Gas Thermal Ice Protection". J. A. Hay, Vickers Armstrongs (Aircraft) Limited, Journal of the SLAE, October 1958
588. (950) "Molded Circuits". Rogers Corporation, Rogers, Connecticut, Application Report No.6, September 25, 1961
589. (1277) "Surface Heating Resistor". K. Gaiser, E. Kraft, D. Gotz and H. Hauser, December 8, 1971
590. (1278) "Load-Carrying Composite Structure, e.g. the Leading Edge of Aircraft". J. H. McClean, Short Brothers and Harland Limited, August 8, 1972
591. (994) "Continuation of M412 Composite Blade De-Icing Investigation". W. Cresap, Bell Helicopter Textron, Engineering Laboratories Report No.41280M-054, April 2, 1980
592. (997) "Heater Mats". AEG Telefunken
593. (947) "Selecting an Electro-Thermal Ice-Protection System". Art Lambert, PAC Aeronautical Engineering Corporation, Technical Products Division, 11248 Playa Court, Culver City, California

594. (949) "Electrical Heating Element". Electrofilm Incorporated, 7116 Laurel Canyon Boulevard, Unit 21, North Hollywood, California
595. (1093) "A Numerical and Experimental Investigation of Electrothermal Aircraft De-Icing". Kevin L. Leffel, K. Cyril Masiulaniel, Kenneth J. DeWitt and Theo G. Keith Jr., Department of Mechanical Engineering, University of Toledo, Toledo, Ohio

Also references : 68 96 246 413

3.4.2.5 Other Components

596. (795) "Icing Tests on Electrically Heated Pressure Heads at Extreme Low Temperatures". K. R. Honick and W. A. Thompson, RAE/TN/Inst.908, May 1945
597. (796) "Comparative Icing Tests on Standard Mk.VIII M Electrically Heated Pitot Heads and a Manufacturing Variant". K. R. Honick and T. H. Sisson, RAE/TN/I.A.P.973, November 1947
598. (737) "Electrical Windscreen De-Icing". Aeroplane, November 4, 1949
599. (749) "Heating Pad De-Icers, Flaps on B-36 Jets". American Aviation, November 6, 1950
600. (801) "Araldite Sprayed De-Icing Spinner Shop Tests". M. J. W. Rogers, DTA Interim Report No.111, March 1952
601. (96) "Equilibrium Temperature of an Unheated Icing Surface as a Function of Air Speed". Bernard L. Messinger, Lockheed Aircraft Corporation. Journal of the Aeronautical Sciences, January 1953, pp.29-42, Design Session, Annual Summer Meeting, I.A.S. Preprint 342, Los Angeles, June 27-28, 1951, Revised July 2, 1952
602. (851) "An Analytical Study of Heat Requirements for Icing Protection of Radomes". James P. Lewis, NACA TIB 3443, RM E53A22, March 11, 1953
603. (861) "Aircraft Ice Protection Conference". D. Napier and Son, Limited, Lectures and Discussions, June 11, 1958
604. (618) "Aircraft Electrical Ice Protection and Future Developments". Aircraft Ice Protection Conference, 1958

605. (862) "Aircraft Ice Protection Conference". D. Napier and Son, Limited, Lectures and Discussions, June 9, 1959
606. (873) "Icing Protection in Aircraft with Special Consideration of Electrical Systems". German Report, November 1961
607. (988) "General Dynamic Convair Report T66-7, Icing Tunnel Results of C141 Horizontal Stabilizer Cyclic De-Icer System". November 1962
608. (619) "Recent Developments in Aircraft Ice Protection". K. H. Greenly, Aircraft Engineering, Vol.35, No.4, April 1963
609. (918) "Anti-Icing Aspects of Helicopter Windshield Design". P. A. Miller, Sierracin Corporation, Sylmar, California, USA, International Helicopter icing Conference, May 23-26 1972
610. (990) "Installing the Heater Cable Directly into the Redesigned Leading Edge". Aircraft Engineering Journal-Concorde, pp.43, May 1973
611. (1300) "Analysis of an Airplane Windshield Anti-Icing System Using Hot Air". R. Ross, Ross Aviation Associates, Sedgwick, Kansas, Journal of Aircraft, Vol.20, No.11, pp.963-967, November, 1983
612. (1060) "A Heater Made from Graphite Composite Material for Potential De-Icing Application". C-C. Hung, NASA Lewis Research Center, Cleveland, Ohio, M. E. Dillehay and M. Stahl, Ohio State University, Cleveland, Ohio, AIAA-87-0025, Presented at AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987
613. (1061) "Efficient Numerical Simulation of an Electrothermal De-Icer Pad". T. Keith Jr., K. DeWitt and W. Wright, University of Toledo, Toledo, Ohio, AIAA-87-0024, Presented at AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987

Also references : 109 202 453 454 863 948 951 959
983 995

3.4.3 Rubber Boot (Non-Inflatable)

614. (1286) "Aeroplane Propeller De-Icer Shoe". Firestone Tyre and Rubber Company, August 7, 1945

615. (1232) "Preventing the Accumulation of Ice". M. L. Taylor, B. F. Goodrich Company, April 1, 1947
616. (1267) "Electric Heating Elements for De-Icing". R. S. Ely and I. M. Ketcham, December 1, 1948
617. (1268) "Electrically Heated Protective Covering". B. F. Jones and P. E. Coonly, B. F. Goodrich Company, June 22, 1949
618. (1287) "Propeller Blade De-Icing Shoe". G. B. Speir and D. Wehrle, Curtiss-Wright Corporation, April 11, 1950
619. (1202) "Equipment for Attaching Aeroplane Propeller De-Icer Shoes". R. W. Brown, Firestone Tyre and Rubber Company, July 4, 1950
620. (1283) "Electrically Heated Apparatus for Preventing Ice Accumulation". A. M. deLa Rue, B. F. Goodrich Company, August 22, 1951
621. (1203) "Attaching Aeroplane Propeller De-Icer Shoes". R. W. Brown, Firestone Tyre and Rubber Company, July 10, 1951
622. (1205) "Hose, Rubber, Wire-Wound, Synthetic, Ice Eliminating System". US Department of Defense, Washington DC, February 5, 1952
623. (1284) "Compressor Systems Having Electrically Heated Blades". A. G. Elliot, Rolls Royce Limited, October 22, 1952
624. (1213) "Package for Shipping and Storing a Conductive Rubber Heating Element". C. J. Ford, Wingfoot Corporation, June 23, 1953
625. (1270) "Electric Resistance Heaters". W. A. Gurney, Dunlop Rubber Company, December 1, 1954
626. (1212) "Electrically Heated Propeller De-Icer". Wingfoot Corporation, February 23, 1955
627. (1271) "Electrically Heated Protective Coverings". B. F. Goodrich Company, March 2, 1955
628. (1211) "De-Icing Elements". Dunlop Rubber Company and H. Wiggin and Company Limited, London, Vol.17, No.12, pp.506-516, 1955
629. (1279) "Electrically Heated Protective Covering for Aircraft". A. M. de La Rue, B. F. Goodrich Company, June 1, 1956
630. (1289) "De-Icer". W. H. Taylor, Goodyear Tyre and Rubber Company, July 31, 1956

- 631. (1280) "Electrically Heating Element". C. J. Ford and J. L. Nisbet, Goodyear Tyre and Rubber Company, January 10, 1961
- 632. (1275) "Aircraft De-Icer". Goodyear Tyre and Rubber Company, September 13, 1961
- 633. (1276) "Thermal Defrosters". Pneumatiques, Caoutchouc Manufacture et Plastiques Kleber-Colombes, december 1, 1965
- 634. (1281) "Flexible Sheet-Like Electric Heater for Aircraft Wings". H. W. Hesford, August 13, 1968

Also references : 19 20 26 36 95 246 413 447

3.4.4 Thermal (General)

- 635. (672) "Thermal Anti-Icing Survey on Mount Washington". A. Guibert, Trans. of A.S.M.E., November 1947

3.4.4.1 Propeller

- 636. (637) "De-Icing Means for Propellers". Aircraft Engineering, June 1944
- 637. (167) "Numerical Simulation of One-Dimensional Heat Transfer in Composite Bodies with Phase Change". K. J. DeWitt and G. Baliga, NASA CR 165607, 1982
- 638. (18) "Numerical Simulation of Two-Dimensional Heat Transfer in Composite Bodies with Application to De-Icing of Aircraft Components". David Fu-Kuo Chao, The University of Toledo, Toledo, Ohio, NASA Lewis Research Centre, November 1983
- 639. (35) "The Effects of Aerodynamic Heating on Ice Formations on Airplane Propellers". Lewis A. Rodert, NACA TN 799

3.4.4.2 Engine And Intake

- 640. (659) "Preliminary Investigation of Engine and Aircraft De-Icing". A.S.M. Projects Department (Thermodynamics) Report, March 19, 1947

641. (702) "Improvements in or Relating to Apparatus for Preventing or Reducing the Formation of Ice on the Air Ducts of Gas Turbine Engines". F. C. Marchant and J. E. Bell, P.S. 618,224, February 17, 1948
642. (683) "Heated Rubber Used for Intake Anti-Icing". Aviation Week, March 15, 1948
643. (1117) "Ice Protection of Turbojet Engines by Inertia Separation of Water. I. Alternate Duct System". Uwe. H. von Glahn, NACA TIB 1836, RM E8A27, June 1948
644. (1118) "Ice Protection of Turbojet Engines by Inertia Separation of Water. II. Single-Offset-Duct System". Uwe. H. von Glahn, NACA TIB 1838, RM E8A28, June 1948
645. (1119) "Ice Protection of Turbojet Engines by Inertia Separation of Water. III. Annular Submerged Inlets". Uwe. H. von Glahn, NACA TIB 1838, RM E8A29, June 1948
646. (1120) "Experimental Investigation of Hot Gas Bleedback for Ice Protection of Turbojet Engines. I. Nacelle with Offset Air Inlet". E. Callaghan et al., NACA TIB 1846, RM E8D13, July 1948
647. (841) "Anti-Icing of Turbine Engines". Staff of Mechanical Engineering Department, Royal Aircraft Establishment, Farnborough, RAE TN ME 26, July 1948
648. (689) "Protection of Engines Against Ice". J. K. Hardy, R.A.E. Technical Memo No. Mech. Eng. 8, August 1948
649. (691) "Protection of Aircraft Turbine Engines Against Ice Accretion". W. Deacon, NGTE Report No. R30, September 1948
650. (703) "Means for Preventing an Internal Combustion Turbine Unit from Icing (Hot Gases from Jet Pipe)". T. Clarke, Armstrong Siddeley Motors Limited, P.S. 622,627, May 4, 1949
651. (706) "25 Hour Endurance Test to Special Category Conditions on Mamba ASZ107. Build 34A with Engine Anti-Icing System". R. Matthews, A.S.M. Experimental Test Report M.191, June 15, 1949
652. (710) "Improvements in or Relating to Compressor Particularly for use with Aircraft Power Plants (De-Icing Intake to Compressor)". A. V. D. Willgows, United Aircraft Corporation, P.S. 929,044, September 9, 1949
653. (709) "Protection of Aircraft Turbine Engines Against Ice Accretion". W. Deacon, NGTE Report R30, September 1949

654. (763) "Icing Requirements for Reciprocating Engine Induction Systems". Willard, Rollin and Mulholland, NACA Report 982 1950 (6.2), 1950
655. (715) "Jet Engine Icing Protection Systems". Hawthorne, Aviation Operations, July 1950
656. (719) "Development of the Anti-Icing System for the J-47 Gas Turbine". Morrell and Frischhetz, S.A.E. Preprint No.509, August 30, 1950
657. (721) "Military Industrial Research Perfects Turbine Anti-Icing". Perreault, American Aviation, October 1950
658. (766) "Turbine Engine Anti-Icing Atop Mount Washington". Bartlett and Dickey, S.A.E. Journal, January 1951
659. (754) "Anti-Icing of Compressor Blades". May 4, 1951
660. (755) "Blade Anti-Icing". Aviation Week, May 14, 1951
661. (770) "Turbojets Anti-Icing Chaige Heating Investigation on an Axial Flow Engine". Thompson and Smith, N.A.E. (Canada) Laboratory Report No.Lr20, February 6, 1952
662. (761) "Means for Preventing the Formation of Ice on an Aircraft or in a Gas Turbine Engine Therefore". P.S. 676,154, July 23, 1952

Also references : 666 680 684 695 700 704 733
734 735 829 843 876

3.4.4.3 Aircraft

663. (1207) "Methods of Overcoming Ice Trouble on Aircraft". A. Faure, A. M.Ducret and J. R. Rideau, Ministry R.T.P. Les Ailes, No.818, pp.6-7, 1937
664. (1208) "De-Icing Device, Employing a 'Resistant' Coating for Electrical Heating". G. Chamagne, 1937
665. (1209) "Anti-Icing Devices for Aircraft". A. M.Ducret and J. R. Rideau, July 14, 1938

- 666. (430) "Flight Tests of Thermal Ice-Prevention Equipment on a Lockheed 12-A Airplane". Richard Scherrer, NACA ARR 3K10 (WR A-49), September 1943
- 667. (432) "Flight Tests of Thermal Ice Prevention Equipment on the B-17F Airplane". Bonne C. Look, NACA ARR 4B02 (WR A-23), February 1944
- 668. (174) "Thermal De-Icing on the DC-6". Aeronautical Digest, August 1946
- 669. (652) "Some Suggested Specifications for Thermal Ice-Prevention System for Aircraft". L. A. Rodert, Trans of A.S.M.E., October 1946
- 670. (688) "Provision of Heat on Aircraft for Protection Against Ice and for Cabin Heating". L. H. G. Sterne, R.A.E. Technical Note Mech.Eng.19, August 1948
- 671. (756) "Improvements in or Relating to Aircraft De-Icing Apparatus". S.A.B.L., Patent Specification 753,753, May 23, 1951
- 672. (379) "Some Results of Experimental Flights in Natural Icing Conditions and Operation of Aircraft Thermal Ice Protection Systems". O. K. Trunov and M. S. Egorov, Paper Presented at Napier Aircraft Ice Protection Conference, Luton, May 1960

Also references : 159 200 659

3.4.4.4 Wing

- 673. (520) "Report on the Development and Application of Heated Wings". Myron Tribus and J. R. Tessman, AAF TR 4972, Office of Technical Services, U.S. Department of Commerce PB 18122, January 1946
- 674. (15) "Icing Problems and the Thermal Anti-Icing System". F. L. Boeke and R. A. Paselk North American Aviation Incorporated, The Los Angeles Meeting, I.A.S., Los Angeles, August 16-17, 1945. Revised and Resubmitted May 11, 1946
- 675. (678) "Transfer of Heat Internally in a Heated Wing". J. K. Hardy and Morris, R.A.E Report Mech.Eng.4, January 1947
- 676. (435) "The Calculation of the Heat Required for Wing Thermal Ice Prevention in Specified Icing Conditions". Carr B. Neel Jr., Norman R. Bergrun, David Jukoff and Bernard A. Schlaff, NACA TN 1472, December 1947

677. (1110) "The Calculation of the Heat Required for Wing Thermal Ice Prevention in Specified Icing Conditions". Carr B. Neel Jr., Norman R. Bergrun, David Jukoff and Bernard A. Schlaff, Ames Aeronautical Laboratory, Moffet Field, California, December 1947

3.4.4.5 Aerofoil

678. (696) "Analysis of Heat Transfer Over a Small Cylinder in Icing Conditions on Mount Washington". Tribus and Young, Trans. of A.S.M.E., November 1948
679. (852) "Intermittent Heating of Airfoils for Ice Protection Utilizing Hot Air". H. H. Hauger, Extr. Trans. A.S.M.E., pp.287-298, February 1954
680. (881) "A Process for the Design of Air-Heated Ice Prevention Systems". Carr B. Neel, NACA/TN/3130, June 1954
681. (708) "Heat Requirements for Ice Protection of a Cyclically Gas-Heated 36 deg. Swept Airfoil with Partial-Span Leading Edge Slat". Vernon H. Gray and Uwe von Glahn, NACA/TIL/5094, RM E56B23, February 1956

Also references : 68 70 236 673 945

3.4.4.6 General Component

682. (673) "Heat Requirements for Instruments and Aerofoils During Icing Storms on Mount Washington". V. J. Schaefer, Trans. of A.S.M.E., November 1947
683. (674) "Thermal De-Icing". Aviation Week, December 15, 1947
684. (682) "Thermal Fin Effect in Heat Anti-Icing Corrugations". J. Jones, Journal of Aeronautical Sciences, March 1948
685. (686) "A New Thermal De-Icer". Aeroplane, July 2, 1948
686. (699) "A Comparison Between Two Anti-Icing Methods". A.S.M. Experimental Department, (Aerodynamics) Report, December 3, 1948
687. (740) "Anti-Icing Heat Requirements of a Turbo Jet Inlet Mount Washington Tests". W.A.C. Serial Report No.1461, 1949

688. (712) "Operation Results of Thermal Anti-Icing". Beard and North, S.A.E. Preprints No.403, January 13, 1950
689. (714) "Thermal Anti-Icing is Here to Stay". Beard and North, S.A.E. Journal, May 1950
690. (741) "Thermal De-Icing of Aircraft Windscreens". Wiggin Nickel Alloys, Henry Wiggin and Company Limited, Wiggin Street, Birmingham 1950
691. (768) "An Investigation of Aircraft Heaters XXXVIII. Determination of Thermal Performance of Rectangular and Trapezoidal Shaped Inner Skin Passages for Anti-Icing Systems". Boelter, Sanders and Romie, NACA Technical Note 2524 (18), November 1951
692. (701) "Instrument Heating for Aircraft Ice Protection Applications to Properties of Jet Engines". Myron Tribus, Trans. of A.S.M.E., November 1951
693. (697) "Further Remarks on Intermittent Heating". F. Weiner, Trans. of A.S.M.E., November 1951
694. (793) "Automatic Controllers for Aircraft Ice Protection Systems". E. H. Bowler and G. M. Wright, NAE/LR/67, July 1953
695. (781) "Ice Prevention in a Cloud of Ice Crystals". C. K. Rush, N.A.E. Note 14, 1956
696. (620) "Some Problems of Aircraft and Helicopter Ice Protection". O. K. Trunov, Aircraft Ice Protection Conference, 1961
697. (21) "Thermal Aspects of De-Icer Design". J. R. Stallabrass, International Helicopter Icing Conference, Ottawa, 1972
698. (1092) "Ice Protection Thermal Modelling Techniques". Andrew A. Peterson, Ruth Cholod Johnson and Alfred D. Cipolloni, Boeing Vertol Company, Philadelphia, Pennsylvania, Presented at the 42nd Annual Forum of the American Helicopter Society, Washington D.C., June 1986
699. (454) "Flight Investigation of a Stall-Warning Indicator for Operation Under Icing Conditions". Alun R. Jones and John A. Zalovcik. NACA ARR

Also references : 40 121

3.4.5 Pneumatic Boot

700. (1196) "Pneumatic De-Icers". B. F. Goodrich Company, Rubber Age, New York, 1932
701. (1224) "Apparatus for Preventing the Accumulation of Ice on the Surface of Aeroplanes or Other Vehicle". B. F. Goodrich Company, March 16, 1939
702. (1214) "Apparatus for Preventing Ice Accumulation on Aircraft Surfaces". M. L. Taylor, B. F. Goodrich Company, February 2, 1940
703. (1225) "Airplane Wing Slot Operating Apparatus". C. T. Sears, B. F. Goodrich Company, August 7, 1942
704. (1216) "Inflation Units for Preventing Ice Accumulation on Airfoil Surfaces". C. T. Sears and M. L. Taylor, September 9, 1942
705. (1217) "Apparatus for Prevention of Ice Accumulation". B. F. Goodrich, October 27, 1942
706. (1218) "Apparatus for Prevention of Ice Accumulation". B. F. Goodrich, November 19, 1942
707. (1226) "Apparatus for Improving Wing Slot Operation". C. T. Sears, B. F. Goodrich Company, December 29, 1942
708. (1252) "Preventing Ice Accumulation". M. R. Bell and C. S. Stebbins, B. F. Goodrich Company, May 25, 1943
709. (1227) "System of Inflation and Apparatus for De-Icing Equipment". M. L. Taylor and C. T. Sears, B. F. Goodrich Company, December 21, 1943
710. (1193) "De-Icers and Design". B. F. Goodrich Company, Akron, 1943
711. (638) "Pneumatic De-Icers. Taylor Made to Satisfy Specific Plane Need". S.A.E. Journal, July 1944
712. (1228) "Protective Covering for Aircraft Surfaces". W. H. Hunter, B. F. Goodrich Company, December 18, 1945
713. (1229) "Protective Covering for Aircraft Surfaces". W. H. Hunter, B. F. Goodrich Company, February 5, 1946
714. (1231) "Protective Covering for Preventing Accumulation of Ice on Aerofoils". E. E. Heston, B. F. Goodrich Company, April 1, 1947

715. (1233) "Inflatable Shoe for Aircraft". W. H. Hunter, B. F. Goodrich Company, April 1, 1947
716. (1235) "Protective Apparatus for Preventing Accumulation of Ice on Airfoils". E. E. Heston, B. F. Goodrich Company, March 2, 1948
717. (1221) "Preventing Ice Accumulation on a Surface Exposed to Ice-Forming Conditions in an Air Flow". B. F. Goodrich Company, September 16, 1948
718. (1236) "Ice Removing Covering for Aircraft". R. G. Campbell, B. F. Goodrich Company, March 30, 1948
719. (1237) "De-Icing Equipment for Aerofoils". J. O. Antonson, B. F. Goodrich Company, April 27, 1948
720. (1256) "De-Icing Systems for Aircraft". Bendix Aviation Corporation, July 13, 1948
721. (1238) "Apparatus for Preventing Accumulation of Ice on Aerofoils". E. E. Heston, B. F. Goodrich Company, August 3, 1948
722. (1222) "Apparatus for Preventing the Accumulation of Ice on a Surface". B. F. Goodrich Company, March 1, 1949
723. (1257) "De-Icers". Bendix Aviation Corporation, April 11, 1949
724. (1261) "Inflatable Ice Removing Apparatus for Aircraft". J. J. Minshall, Borg-Warner Corp., November 29, 1949
725. (1194) "BTR De-Icers for Aircraft". British Tyre and Rubber Company Limited, Booklet, London, 1949
726. (1241) "Protective Covering for Aerofoils". T. C. Harper, B. F. Goodrich Company, May 2, 1950
727. (1242) "Apparatus for Preventing Accumulation of Ice Upon Surfaces". H. E. Greene, B. F. Goodrich Company, January 2, 1951
728. (1262) "Inflatable Ice Eliminating Apparatus". D. Gregg, Bendix Aviation Corporation, January 30, 1951
729. (1244) "Protective Cover to Prevent Ice Accumulations". T. C. Harper, B. F. Goodrich Company, July 10, 1951
730. (1246) "Inflatable Covering for Surfaces". C. F. Totheroh, B. F. Goodrich Company, September 18, 1951
731. (1195) "Improved De-Icer on Navy Plane". Rubber Age (N.Y.), B. F. Goodrich Company, U.S. Navy Bureau of Aeronautics, 1951

732. (1247) "Preventing Ice Accumulation on Aerofoils". B. F. Jones, B. F. Goodrich Company, June 3, 1952
733. (1248) "Fluid Pressure Operated Inflation Control Valve". A. W. Spicer, B. F. Goodrich Company, December 30, 1952
734. (1197) "Application of Pneumatics for Aircraft De-Icing System". B. F. Goodrich Company and Bendix Aviation Corporation, Eclipse Pioneer Division, Applied Hydraulics, Vol.5, No.3, pp.102, 1952
735. (1249) "Building Continuous Tubing". M. Kuts, B. F. Goodrich Company, January 31, 1956
736. (599) "The Physics of the Mechanical Removal of Ice from Aircraft". D. L. Loughborough, Aeronautical Engineering Review, Vol.11, No.2, February 1956
737. (1206) "De-Icing System, Pneumatic Boot, Aircraft General Specification for". US Department of Defense, Washington DC, 1956
738. (1250) "Inflatable Ice-Removing Apparatus for Aircraft". J. C. Hess, B. F. Goodrich Company, October 25, 1960
739. (1263) "Inflatable De-Icing Boot". US Department of the Air Force, February 7, 1961
740. (1215) "Control of Inflatable Units, e.g. Airfoil Inflatable Units for Preventing Ice Accumulation". B. F. Goodrich Company, June 23, 1962
741. (1258) "Aircraft Engine Intake". E. H. E. Martin, R. N. Thomson and D. Norbury, Dunlop Company Limited, November 15, 1967
742. (1251) "Aircraft De-Icing Shoe". P. W. Kageorge and G. E. Uden, B. F. Goodrich Company, February 27, 1968
743. (1204) "Inflatable Vane". T. S. Braveman, June 21, 1968
744. (1259) "Inflatable Aircraft Fairing". G. C. Jennings, Marston Excelsior Limited, November 27, 1968
745. (1260) "Inflatable Intake for Aircraft". E. H. E. Martin, Dunlop Company Limited, April 16, 1969
746. (1265) "De-Icing Device". R. O. Kline, Goodyear Tyre and Rubber Company, November 30, 1971
747. (1192) "Ice, Peril of the Air". Rubber Developments, Vol.25, No.3, pp.87, 1972

- 748. (1223) "Pneumatic De-Icers for Aircraft". B. F. Goodrich Company, September 26, 1973
- 749. (166) "Pneumatic Boot for Helicopter Rotor Deicing". B. J. Blaha and P. L. Evanich, NASA CP 2170, 1980
- 750. (1137) "JUH-1H Pneumatic Boot De-Icing System Flight Test Evaluation. Final Report, 16 Nov. 1981 - 30 May 1983". L. A. Haworth, R. G. Oliver and R. Woratschek, USAAEFA-81-11, May 1983

Also references : 10 69 109 117 159 246 413 422 424

3.4.6 Freezing Point Depressant

- 751. (1253) "Preventing the Formation of Ice on Aircraft". G. R. Shaw and M. F. Pring-Rowe, July 24, 1940
- 752. (418) "An Investigation of the Characteristics of a Propeller Alcohol Feed Ring". Carr B. Neel Jr., NACA RB 4F06 (WR A-50), June 1944
- 753. (638) "The New T.K.S. Airframe De-Icing System". September 1944
- 754. (644) "The New T.K.S. Airframe De-Icing System". September 29, 1945
- 755. (242) "Kinetic Temperature of Wet Surfaces. A Method of Calculating the Amount of Alcohol Required to Prevent Ice and Derivation of the Psychrometric Equation". J. K. Hardy, Royal Aircraft Establishment, Farnborough, Hampshire, Reports and Memoranda No.2830, NACA ARR 5G13, September 1945
- 756. (649) "De-Icing for To-Day TKS Fluid System". Flight International, April 1946
- 757. (1230) "Propeller Blade Protective Device". W. H. Hunter, B. F. Goodrich Company, June 11, 1946
- 758. (1255) "Anti-Icer System". Bendix Aviation Corporation, December 20, 1946
- 759. (1199) "Ice Preventing Means for Propellers". J. de Stefano, February 10, 1948

760. (1189) "Study of Wing De-Icer Performance on Mount Washington". D. L. Loughborough et al, 1948
761. (738) "Porous Leading Edge De-Icing". Aeroplane, November 4, 1949
762. (739) "Sintered Products Developments in Powder-Metallurgy, Porous Metal De-Icer Panels". Aircraft Production, December 1949
763. (943) "Vickers Viking Fluid De-Icing Trials 1950". Project Development Department of Bristol European Airways, Published by TKS (Aircraft De-Icing) Limited, Drayton House, Gordon Street, London WC1, 1950
764. (752) "Porous Panel Anti-Icing System". Aviation Week, January 8, 1951
765. (760) "Contract No.6/Eng/4744/CB 12CB Methanol Anti-Icing Tests for Mamba Apollo", A.S.M. Mechanical Engineering Department Report T.539, February 19, 1952
766. (941) "Fluid De-Icing, An Up-to-date Perspective". TKS (Aircraft De-Icing) Limited, Drayton House, Gordon Street, London WC1, September 1953
767. (1190) "Fight Against Frosting in Aircraft". R. Anthoine, 1952
768. (837) "Comparison of Alcohols as Aero Gas Turbine Anti-Icing Fluids". G. W. Benson and F. G. Kitson, NAE LR 125, February 1955
769. (1200) "Propeller Blade De-Icing Means". A. O. Smith Corporation, February 8, 1955
770. (895) "Wessex Mk.1 Rotor Fluid de-Icing System Tests". D. E. Golding, Westland Helicopters Limited, Yeovil, October 1961
771. (621) "Fluid De-Icing". D. C. Tanner, Aircraft Ice Protection Conference, 1961
772. (942) "Fluid TKS De-Icing". TKS (Aircraft De-Icing) Limited, Drayton House, Gordon Street, London WC1, 1961
773. (1264) "De-Icing Boot for Preventing Accumulation of Ice Formations on Edge Portions of Vehicles, e.g. Aircraft". H. H. Son Gullberg, H. H. Son Gullberg Incorporated, July 7, 1970
774. (168) "Icing Tunnel Tests of a Glycol-Exuding Porous Leading Edge Ice Protection System on a General Aviation Airfoil". D. L. Kohlman, W. G. Schweikhard and A. E. Albright, Kansas University Center for Research, Incorporated, NASA CR 165444, 1981

- 775. (44) "Experimental and Analytical Investigation of a Freezing Point Depressant Fluid Deicing System". A. E. Albright, NASA CR 174758, September 1984
- 776. (11) "Flight Testing a Liquid Ice Protection System on a Single-Engine Airplane". Richard L. Newman, Crew Systems Consultants, Yellow Springs, Ohio, General Aviation Aircraft Meeting and Exposition, Wichita, Kansas, SAE 850923, April 16-19, 1985
- 777. (874) "Fluid T.K.S. De-Icing". T.K.S. (Aircraft De-Icing) Limited
- 778. (1198) "Preventing or Removing Ice Formation on or from Aircraft Propeller Blades". B. F. Goodrich Company
- 779. (1188) "Distributing De-Icing Liquids on Surfaces Subject to Ice Formation". Tecalemit Limited, C. C. S. Le Clair

Also references : 36 95 109 159 202 255 274 280 412
413 458 460 938 1167

3.4.7 Ice-Phobic

- 780. (256) "Refrigerated Wind-Tunnel Tests on Surface Coatings for Preventing Ice Formation". M. Knight, NACA TN 339, 1930
- 781. (274) "A Flight Investigation of the Distribution of Ice-Inhibiting Fluids on a Propeller Blade". Lewis A. Rodert, NACA TM 727, 1939
- 782. (1290) "Prevention of Ice Formation on Aircraft". H. J. Strausz, September 22, 1942
- 783. (1220) "Protective Coverings for Aircraft". B. F. Goodrich Company, April 10, 1947
- 784. (1219) "Removing Ice from Surfaces Subjected to Icing Conditions". B. F. Goodrich Company, December 1, 1947
- 785. (1239) "Reducing Adhesion of Ice to Rubbery Surfaces". E. G. Haas, B. F. Goodrich Company, May 24, 1949
- 786. (1240) "Preventing Accumulation of Ice on Aircraft Surfaces". D. L. Loughborough, B. F. Goodrich Company, May 24, 1949

- 787. (1245) "Preventing Ice Accumulation on Aircraft Surfaces". J. M. Davies, B. F. Goodrich Company, September 11, 1951
- 788. (1291) "Surface Having Low Adhesion to Ice". R. Smith-Johannsen, General Electric Company, November 11, 1952
- 789. (1210) "Rubber in the Fight Against Icing". H. J. Ensink, Rubber, pp.122-124, 1953
- 790. (985) "Development of an Ice-Shedding Coating for Helicopter Rotor Blades". J. H. Sewell, Royal Aircraft Establishment, Farnborough, Hampshire, Report TR71238, December 1971
- 791. (882) "Evaluation of the Ice Shedding Potential of a Water-Absorbing Polyurethane Material". M. J. Oliver, Royal Aircraft Establishment, Farnborough, Hampshire, RAE TM 344, April 1980
- 792. (929) "Ice Shedding Coatings for Helicopter Airframes". J. H. Sewell, Royal Aircraft Establishment, Farnborough, Hampshire, RAE MAT STR 1027, October 1983
- 793. (927) "Development of an Ice Shedding Coating for Helicopter Rotor Blades". J. H. Sewell, Royal Aircraft Establishment, Farnborough, Hampshire
- 794. (458) "Investigation of the Ice-Inhibiting Characteristics of Compounds Applied Prior to Flight". Lewis A. Rodert.
- 795. (986) "Improved Ice-Shedding Pastes for Application to Helicopter Rotor Blades". J. H. Sewell, Royal Aircraft Establishment, Farnborough, Hampshire, Report TR82002 - Polyethylene Glycol (PEG)

Also references : 19 36 91 109 202 240 255 288 290
319 333 335 412

3.4.8 Electro-Impulse

- 796. (162) "British Patent Specification No. 505,433". Rudolf Goldschmidt, May 5, 1939
- 797. (1266) "Composite Product Based on Rubber". R. Asche and J. J. Hubscher, March 17, 1949
- 798. (585) "Electro-Impulse De-Icing System". I. A. Levin, Tech. Air., pp.6, September 1971

799. (586) "USSR Electric Impulse De-Icing System Design". I. A. Levin, Aircraft Engineering, pp.7, July 1972
800. (983) "Aircraft Protection - Russian Patent, Electric Impulse System". R. Piercy, Reference Research/1826/RP, Memorandum, September 12, 1972
801. (940) "Preliminary Specification for the Electro-Impulse De-Icing System". Lucas Aerospace Limited, Electrical Group, Engineering and Heating Systems, The Airport, Luton, Beds., July 3, 1973
802. (939) "Electrical Interference Aspects of a Proposed Electrical Impulse De-Icing System". D. R. Marshall, British Aircraft Corporation, Commercial Aircraft Division, Weybridge, Surrey, September 10, 1973
803. (938) "Trade-Off Between Electro-Impulse, Hot Air and Fluid Ice Protection Systems". John. W. Nicol, British Aircraft Corporation, Systems Department report, October 8, 1973
804. (937) "Electro-Impulse De-Icing System, Survey of Initial Assessments". L. Parker, British Aircraft Corporation, Systems Department Report, October 9, 1973
805. (936) "Electro-Impulse De-Icing Development Tests". I. Higgins and M. Jarman, British Aircraft Corporation, Aircraft Laboratories, Weybridge, Surrey, October 10, 1973
806. (921) "Electro-Impulse De-Icing Tests on a Conventionally Constructed Specimen of Wing Leading Edge". British Aircraft Corporation, Weybridge, UK, June 1977
807. (46) "Electro-Impulse De-Icing: Concept and Electrodynamic Studies". R. L. Schrag and G. W. Zumwalt, Wichita State University, Wichita, Kansas, AIAA 22nd. Aerospace Sciences Meeting. AIAA-84-0021, Reno, Nevada, January 9-12, 1984
808. (47) "Electro-Impulse De-Icing: Structural Dynamic Studies, Icing Tunnel Tests and Applications". W. D. Bernhart and G. W. Zumwalt, AIAA 22nd. Aerospace Sciences Meeting. AIAA-84-0022, Reno, Nevada, January 9-12, 1984
809. (9) "Flight and Wind Tunnel Tests of an Electro-Impulse De-Icing System". G. W. Zumwalt, Wichita State University, Wichita, Kansas. A. A. Mueller, Cessna Aircraft Company, Wichita, Kansas, AIAA/NASA General Aviation Technology Conference, Hampton, Virginia, AIAA-84-2234, July 10-12 1984

810. (119) "Flight Evaluation of an Electro-Impulse De-Icing System on a Light General Aviation Airplane". A. A. Mueller, D. R. Ellis and D. C. Bassett, AIAA/AHS/ASEE Aircraft Design Systems and Operation Meeting. AIAA-84-2495, San Diego, California, October 31- November 2, 1984
811. (120) "Icing Tunnel Test of Electro-Impulse De-Icing of an Engine Inlet and High Speed Wings". G. W. Zumwalt, Wichita State University, Wichita, Kansas, AIAA 23rd. Aerospace Sciences Meeting. AIAA-85-0466, Reno, Nevada, January 14-17, 1985
812. (587) "De-Icing of Aerodynamic Surfaces Using Electromechanical Impulses". G. J. Lewis, PhD Thesis, Nottingham University, May 1985
813. (589) "Analysis and Tests for Design of an Electro-Impulse De-Icing System". G. W. Zumwalt, R. L. Schrag, W. D. Bernhart and R. A. Friedberg, NASA CR 174919, May 1985
814. (588) "Electromagnetic Impulse De-Icing Applied to a Nacelle Nose Lip". G. W. Zumwalt, AIAA-85-1118. AIAA/SAE/ASME 21st Joint Propulsion Conference, Monterey, California, July 8-10, 1985
815. (8) "The Structural Dynamics of Electro-Impulse De-Icing on the Lear Fan Kelvar Composite Leading Edge". T. Paramasivam and Glen W. Zumwalt, Aeronautical Engineering Department, Wichita State University, Wichita, Kansas, SAE 850917
816. (572) "Designing an Electro-Impulse De-Icing System". G. W. Zumwalt and R. A. Friedberg, Wichita State University, Wichita, Kansas. AIAA-86-0545. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986
817. (573) "The Electrodynamic Operation of Electro-Impulse De-Icing Systems". G. J. Lewis, Rolls-Royce Limited, Derby, England. AIAA-86-0547. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986
818. (1309) "Theoretical Analysis of the Electrical Aspects of the Basic Electro-Impulse Problem in Aircraft De-icing Applications". R. A. Henderson and R. L. Schrag, Wichita State University, NASA-CR-176808

Also reference : 109

3.4.9 Microwave

819. (1303) "The Interaction of Radio Frequency Electromagnetic Fields with Atmospheric Water Droplets and Applications to Aircraft Ice Prevention". R. J. Hansman Jr., Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, NASA-CR-169246, Flight Transportation Laboratory,

See reference : 109

3.4.10 Acoustic

3.4.11 Hybrid

820. (19) "Hybrid Heater/Paste and Heater/Flexible Coating Schemes for De-Icing Helicopter Rotor Blades". J. H. Sewell, Royal Aircraft Establishment, Farnborough, Hampshire, England, G. Osborn, Naval Aircraft Materials Laboratory, Gosport, England, 4th. European Rotorcraft and Powered Lift Aircraft Forum, Associazione Italiana Aeronautica ed Astronautica Associazione Industrie Aerospaziali, Paper 53, Stresa, Italy, September 13-15, 1978

Also references : 109 255

3.4.12 Mechanical

821. (468) "Mechanical De-Icer Equipment". Anonymous, Aviation Engineering Section of the Aeronautical Digest, Vol.27, No.2, pp.34-35, August 1935
822. (1254) "Ice Eliminating Systems". Bendix Aviation Corporation, February 1, 1944
823. (1234) "Aerodynamic Brake". W. H. Hunter, B. F. Goodrich Company, October 14, 1947
824. (1243) "Protective Covering for Ice Removal from Airfoils". A. M. La Rue, B. F. Goodrich Company, June 12, 1951
825. (984) "Investigation of Mechanical Shock De-Icing - Interim Report". P. E. Sandorff, June 28, 1973

- 826. (913) "Evaluation of the AFC321 Ice Deflector Shield". J. Krukowski, United Aircraft Corporation, Sikorsky Aircraft Division, Connecticut, February 1975
- 827. (1059) "Flight Evaluation of a Flexible Substrate Leading Edge Material for the Protection of Helicopter Main Rotor Blades in Natural Icing Conditions". G. V. Ray and J. Bradley, Aircraft and Armament Experimental Establishment, Boscombe Down, February 1976
- 828. (898) "Development of De-Icing Equipment for Aircraft Blade Antennas". P. J. Ives, A-91-A-705 FR, H. R. Smith Technical Developments Limited, Witney, UK, February 1983
- 829. (603) "Mechanical Ice Release Process. Part 1: Self Shedding From High Speed Rotors". Kazuhiko I. Itagaki, CRREL Report 83-26, DA Project 4A1-61102-AT-24, October 1983
- 830. (164) "U.K. Patent Application GB 2 155 883 A. De-Icing Apparatus". John Harold Sewell, The Secretary of State for Defence (United Kingdom), Whitehall, London SW1A 2HB, D. J. McCormack, Procurement Executive, Ministry of Defence, Patents 1A(4), Room 2014, 20th Floor, Empress State Building, Lillie Road, London SW6 1TR, 2 October 1985

Also reference : 599

3.4.13 General De-Icing Method

- 831. (1148) "Piezoelectric De-Icing Device Patent Application". Robert C. Fink and Bruce A. Banks, NASA Lewis Research Center, Cleveland, Ohio, Filed February 25, 1983
- 832. (1163) "Thermal Analysis Techniques for Design of V/Stol Aircraft Ice Protection". A. A. Peterson, Boeing Vertol Company, Philadelphia, Pennsylvania, AIAA-85-0340, 23rd Meeting, Reno, Nevada, 1985

3.4.13.1 Aircraft

- 833. (255) "The Prevention of the Ice Hazard on Airplanes". W. C. Geer and Merit Scott, NACA TN 245, 1930

834. (320) "An Investigation of Methods for the De-Icing of Aircraft". J. C. Hunsaker, F. G. Keyes, H. G. Houghton, C. A. Johnson and J. V. Dotson, Progress Report to the National Academy of Sciences. Report 1, Massachusetts Institute of Technology, 1940
835. (626) "New Developments in Ice Elimination Equipment". Gregg and Taylor, Bendix Aviation Corporation, September 1941
836. (631) "Anti-Icing Systems". Harold. C. Webb, Aeronautical Digest, February 1942
837. (1047) "Aircraft Cabin Conditioning and De-Icing". R. Graham, Royal Aircraft Establishment, Farnborough, Hampshire, and W. M. Widgery, Westland Aircraft Limited, Report on Visit to USA and Canada between April and July 1945, Report M235, July 1945
838. (474) "Anti-Icing Equipment for Aircraft". General Specifications (Heated Surface Type) Army Air Forces Specification R-40395, A.A.F., April 21, 1942
839. (633) "Electronic Controls of De-Icing Equipment". Aeronautical Digest, November 1942
840. (640) "Recent Trends in Airplane Ice-Prevention Technique". S.A.E. Journal, December 1944
841. (415) "A Flight Investigation of the Ice-Prevention Requirements of the United States Naval K-Type Airship", Wesley H. Hillendahl, NACA MR A5J19a (WR A-4), October 1945
842. (518) "Protection of Aircraft Against Ice". J. K. Hardy, Report S.M.E. 3380, British R.A.E., July 1946
843. (1107) "Protection of Aircraft Against Ice". J. K. Hardy, Royal Aircraft Establishment, Farnborough, Hampshire, RAE Report SME/3380, July 1946
844. (654) "Protection of Aircraft Against Ice". December 1946
845. (660) "Cold Cure (an Account by Vickers on the De-Icing of the Vickers Viking), Aeronautics, April 1947
846. (663) "A Review of Some German Developments in Airplane Anti-Icing". M. Tribus, A.S.M.E. Trans., July 1947
847. (1116) "Protection of Aircraft Against Ice. - Note on a Visit to U.S.A." J. K. Hardy, Royal Aircraft Establishment, Farnborough, Hampshire, RAE Technical Memo, Mech.Eng.10, September 1948

848. (731) "Viscount De-Icing Trials". Engineer, February 10, 1950
849. (742) "De-Icing the Viscount". Flight International, February 16, 1950
850. (743) "Viscount De-Icing". Aeroplane, February 17, 1950
851. (745) "De-Icing the Vickers Viscount". Shell Aviation News, April 1950
852. (746) "The Simplicity of the Comet. A Contract in Cabin Air and De-Icing Systems for the Comet". The Havell Gazette, 1950
853. (723) "Rubber in Aircraft". J. F. Garner and J. F. Powell, British Rubber Development, February 1951
854. (724) "The Icing Problem - from the Airframe Designer's Angle. How Ice Forms, Means of Prevention and Dispersal". Schaetzle, Flight International, August 31, 1951
855. (802) "Results of Recent Rotor Blade De-Icing Tests on Mount Washington". Proceedings of the Great Lakes Regional Dinner Meeting. Part 1, January 1952
856. (853) "Simple Graphical Solution of Heat Transfer and Evaporation from Surface Heated to Prevent Icing". V. H. Gray, NACA TN 2799, October 1952
857. (816) "Note on the Heat Requirements for Ice Prevention on a Heated Surface in a Cloud of Ice Crystals". C. K. Rush, NRC LT 16 Laboratory Memo, December 1952
858. (868) "Icing Protection for a Turbojet Transport Airplane: Heating Requirements, Methods of Protection and Performance Penalties". T. F. Gelder et al., NACA TN 2866, January 1953
859. (469) "Convair Model 340 Airfoil Anti-Icing System Test. Plane N-73104". A. F. Bullard, United Airlines Incorporated, Engineering Department, Report F-345, May 1953
860. (820) "A Design Manual for Thermal Anti-Icing Systems". Harold. H. Sogin, WADC TR 54-313, PB 121135, December 1954
861. (819) "Methods Used to Assess the Heat Required and the Penalties Involved for Protecting Aircraft Against Icing Conditions". H. E. Le Sueur, S and T Memo No.9/56, January 1957
862. (803) "Solutions for Helicopter Rotor Blade Icing". D. A. Richardson, Presented at the Annual General Meeting, IAS Preprint No.810, January 1958

- 863. (141) "Progress Toward the Developement of an Aircraft Icing Analysis Capability". R. J. Shaw, AIAA 22nd. Aerospace Sciences Meeting. AIAA-84-0105, Reno, Nevada, January 9-12, 1984
- 864. (890) "Evaluation of Prototype Aircraft De-Icing Equipment". D. A. Grocott, Aircraft and Armamnet Experimental Establishment, Boscombe Down
- 865. (1036) "An Introduction to Aircraft Ice Protection Systems". T. W. Harpre, De-Icing Department, Aviation Division, Dunlop Company Limited
- 866. (1124) "Aircraft Icing Avoidance and Protection". National Transportation Safety Board, NTSB-SR-81-1, United States Government, Washington D.C. 20594

Also references : 412 413 416 945

3.4.13.2 Wing

- 867. (681) "Wing De-Icer Performance on Mount Washington". Loughborough and Green, Aircraft Engineering, March 1948
- 868. (732) "Note on the Rig Testing of the Wing Anti-Icing Equipment for the Apollo Aircraft". Experimental Department (Gas Turbines), National Research Council of Canada, Ottawa, Canada, June 14, 1949
- 869. (707) "Apollo Wing Anti-Icing Tests, 25 Hour Endurance Test on A.S.M. Combustion Chambers with 1st Stage Film Cooling Deleted and Turbine Injection Starting Tests on Z116. Build Nos.19,20,20a,21". P. H. Newton, Experimental Department (Gas Turbines) Test Report No.M.201, August 3, 1949
- 870. (143) "Wing Leading Edge Anti-Icing Analysis-Final Report". R. Ross and J. G. Stone, RAA 81 2, Ross Aviation Associates, Sedgwick, Kansas, March 1981

Also reference : 1166

3.4.13.3 Helicopter Rotor Blade

871. (722) "H-5, Rotor Antiicing System, Katzenberger, Interavia No.3, 1951
872. (387) "Tests of an Experimental Helicopter Deicing System on an H-13 Helicopter. Part IV". F. Burpo, Bell Helicopter Corporation Report 502 099 002, September 15, 1959
873. (385) "Summary of Ice Protection System Developement and Testing for Helicopter Rotors". J. F. Van Wyckhouse, Bell Helicopter Company, Report 529 099 001, August 1961
874. (792) "Wessex H.A.S. Mk1 XM331 de-Icing Trials in the NRC Spray Rig Fluid De-Icing System". E. G. Wilson, Report No.AAEE/931, 13th part, Aircraft and Armament Experimental Establishment, Boscombe Down, November 1961 - January 1962
875. (894) "Some of the More Practical Aspects of Developing the All-Weather Helicopter". A. Wilson, Aircraft and Armaments Experimental Establishment, Boscombe Down, International Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
876. (907) "Equipment of All Weather Helicopters Seen Under the Aspect of Icing Conditions". H. Hermes, Telefunken, Hamberg, Germany, Presented at Staying Power Symposium, Fort Rucker, Alaska, July 8-10, 1975
877. (912) "Ice Protection Systems for the YUH-61A (UTTAS) Helicopter". R. N. Stevens, Boeing Vertol Company, Philadelphia, Pennsylvania, Presented at Staying Power Symposium, Fort Rucker, Alaska, July 8-10, 1975
878. (902) "Rotor Blade De-Icing System on the Messerschmitt-Bolkow-Blohm Helicopter BO-105". H. Melcher, Bundesministerium Fur Verteidigung, Germany, Helicopter Icing Symposium, NATO Army Armaments Group Panel X, London, November 6-7, 1978
879. (928) "Development of New Ice-Shedding Schemes". J. H. Sewell, Royal Aircraft Establishment, Farnborough, Hampshire, UK, Helicopter Icing Symposium, NATO Army Armaments Panel X, London, November 6-7, 1978
880. (915) "Stagnation Point Positions for Aerofoil Sections". National Physical Laboratory, Teddington, Middlesex, UK, NPL-AERO-194, RAE 100-104, H. B. Squire, October 1980

- 881. (1099) "Development of the Chinook Helicopter Rotor Blade De-Icing System" Kenneth Lunn, Boeing Vertol Company, Philadelphia, Pennsylvania, Presented at the Royal Aeronautical Society, London, January 14, 1986
- 882. (1094) "Application of Rotor Icing Analysis to the Design of a Rotorcraft De-Icing System". Robert J. Flemming, Sikorsky Aircraft Division, United Technologies Corporation, Stratford, Connecticut, Presented at the 42nd Annual Forum of the American Helicopter Society, Washington D.C., June 1986
- 883. (1091) "Helicopter De-Icing System Development and Qualification Flight in Natural Icing Versus Simulation and Analysis". Kenneth Lunn, Philip J. Dunford and George E. Henschke, Boeing Vertol Company, Philadelphia, Pennsylvania, Presented at the 42nd Annual Forum of the American Helicopter Society, Washington D.C., June 1986
- 884. (884) "Rotary Wing Ice Protection". M. E. Southgate

Also references : 84 114 117 189 462 595 603 976

3.4.13.4 General Component

- 885. (1293) "Icing of Aircraft". B. C. Haynes, Safety Bulletin, Civil Aeronautics Board, Washington D.C., pp.6, 1943
- 886. (641) "German De-Icing Technique". Reports on Development, Devices, etc., December 1944
- 887. (642) "Removal Repair and Storage of De-Icers". Commercial Aviation, June 1945
- 888. (646) "Correct Servicing Determines De-Icer Efficiency Part 2". Aviation, November 1945
- 889. (656) "De-Icing To-Day". Flight International, December 19, 1946
- 890. (344) "A Thermal De-Icing Installation". Aeroplane, January 24, 1947
- 891. (657) "Protection of Aircraft Against Ice". J. K. Hardy, Journal of the Royal Aeronautical Society, March 1947
- 892. (762) "De-Icing and De-Frosting". Shell Aviation News, May 1949

893. (866) "Ice Protection for Turbojet Transport Airplane - Determination of Heat Requirements Icing". P. T. Hacker et al., I.A.S. S.M.F. Fund Paper No.FF-1, March 1950
894. (867) "Ice Protection for Turbojet Transport Airplane - Thermal Anti-Icing Systems for High-Speed Aircraft". P. T. Hacker et al., I.A.S. S.M.F. Fund Paper No.FF-1, March 1950
895. (713) "Windscreen De-Icing". A. C. Waine, Aeronautics, May 1950
896. (750) "Economical De-Icing". Flight International, November 23, 1950
897. (751) "Economics of De-Icing". Aeroplane, November 24, 1950
898. (717) "Investigation of Aerodynamic and Icing Characteristics of Water-Inertia-Separation Inlets for Turbojet Engines". Glahn and Blatz, NACA Research Memo No.E50E03, 1950
899. (758) "Python Anti-Icing Tests at NRC 1950-51". National Research Council of Canada, Ottawa, Canada, September 21, 1951
900. (728) "Development of the Ambassador De-Icing System". H. Newbigin, Aircraft Engineering, August 1952
901. (149) "Criteria for the Design, Assessment and Control of Icing Protection Systems". D. Fraser, K. G. Pettit and E. H. Bowler, Institute of Aerospace Sciences Preprint 369, 1952
902. (473) "Meteorological Design Requirements for Icing Protection Systems". Don Fraser, University of Michigan Airplane Icing Information Course, Lecture 12a, NAE/LR/49, March 1953
903. (808) "Beverley C Mk.1. Protection Against Ice". Blackburn and General Aircraft Limited, September 23, 1953
904. (814) "An Approximate Method for Estimating the Transient Heat Flow Distribution in a De-Icing Pad". R. L. Wardlaw, January 1954
905. (809) "Anti-Icing Investigation with Viking VL.229". D. Napier and Son, Limited, S and T Memo No.2/56, March 1956
906. (1272) "Preventing or Removing Ice Formations". S. H. Taylor, F. S. Fidlán and D. S. Mountain, National Research Development Corporation, October 8, 1955

907. (810) "A Note on the Thermal Anti-Icing Tests on the Vickers Viking VL.229 1953 - 1955". H. E. Le Susuri, S and T Memo No.8/56, November 1956 le;(817) "Rain Erosion Part VI. An Assessment of Various Materials and De-Icing Systems". R. B. King, RAE Report No.CPM 10, Royal Aircraft Establishment, Farnborough, June 1964
908. (917) "De-Icing Characteristics of a Reinforced Elastomer Diaphragm on a Two-Foot Dish Antenna". J. R. Stallabrass, Mechanical Engineering Department, National Research Council of Canada, Ottawa, Canada, February 1972
909. (908) "Ice Protection Systems Experience S-51 to the UTTAS". K. M. Rosen, United Aircraft Corporation, Sikorsky Aircraft Division, Connecticut, USA, Staying Power Symposium, Fort Rucker, Alaska, July 8-10 1975
910. (45) "Development of Deicing System". Pravada, February 1980
911. (1180) "E-2C Passive Detection System (PDS) Nose Radome Anti-Icing Demonstration Test Program". R. Kreis, Grumman Aerospace Corporation, Bethpage, New York, also Lancaster, California, Society of Flight Test Engineers, 1982, pp.261-270, September 19-22, 1982
912. (321) "Ice Prevention and Removal". pp.528-533

Also references : 202 227 632 655 864 869

3.5 Test Instrumentation, Equipment And Procedure

3.5.1 Instrumentation

3.5.1.1 Temperature

- 913. (629) "Report on Temperature Measurements on the Wing of a He.177 with Hot Air De-Icing System". Gattingen, Aeronautical Laboratory, R.T.P. Translation No.2533 (Tl.1165), October 1941
- 914. (778) "Temperature Measurements on a Beaufort Aircraft During Summer at Alice Springs and Melbourne". G. J. Dailey and F. A. Dale, Report ACA-26, July 1946
- 915. (153) "Temperature, Its Measurement and Control in Science and Industry". G. E. Glawe, Reinhold Publishing Corporation Vol.3, Part 2, Ed. 1st., pp.601-605, New York, 1962

Also references : 20 38 97 109 180 188 448 797 1052

3.5.1.2 Dew Point

- 916. (264) "A Dew-Point Recorder for Measuring Atmospheric Moisture". C. W. Thornthwaite, Monthly Weather Review, Vol.68, No.11, pp.315-318, November 1940
- 917. (268) "Psychrometric Tables for Obtaining the Vapour Pressure, Relative Humidity, and Temperature of the Dew Point". C. F. Marvin, W. B. Report 235, Weather Bureau, U.S. Department of Commerce, 1941
- 918. (265) "Preliminary Report on an Improved Dew-Point Hygrometer". D. R. Storey, National Research Council of Canada Report MD 23, September 3, 1942
- 919. (266) "An Improved Dew Point Hygrometer for Use at High Altitude". D. R. Storey, National Research Council of Canada Report MD 28, August 23, 1943
- 920. (1339) "Further Improvements in the Electronic Dewpoint Hygrometer". E. W. Barrett, R. L. Slater and K. E. Newton, Journal of Meteorology, Vol.12, No.4, pp.308-313, August 1955

921. (535) "Hygrometer Developments at the U.S. Naval Research Laboratory". R. E. Ruskin, Chapter 66, "Humidity and Moisture Measurement and Control in Science and Industry", Vol.1, "Principles and Methods of Measurement of Humidity in Gases", New York, Reinhold Publishing Company, pp.704, 1965
922. (192) "An Improved Continuous-Indicating Dew-Point Meter". Frank A. Friswold, Ralph D. Lewis and R. Clyde Wheeler Jr., NACA TN 1215

Also reference : 97 1052

3.5.1.3 Liquid Water Content

923. (1340) "An Electric Hygrometer and Its Application to radio Meteorology". F. W. Dunmore, Bureau of Standards Journal of research, Vol.20, pp.723-744, 1938
924. (407) "Measurement of Free Water in Cloud Under Conditions of Icing". J. K. Hardy, NACA ARR 4111(WR A-15), 1944
925. (1342) "A Spectrophotometer for the Determination of the Water Vapour in a Vertical Column of the Atmosphere". L. W. Foskett and N. B. Foster, Journal of the Optical Society of America, Vol.35, pp.601-610, 1945
926. (1343) "Demountable Rotating Multicylinders for Measuring Liquid Water Content and Particle Size of Clouds in Above and Below Freezing Temperatures". J. J. Schaefer, General Electric Research Laboratory Report, Contract No.W-33-038-ac-951, 1945
927. (1338) "Measurement of Absolute Humidity in Extremely Dry Air". A. W. Brewer, B. Cwilog and G. M. B. Dobson, Proc. Physics Society, London, Vol.60, pp.52-70, 1948
928. (532) "Capillary Collector for Measuring the Deposition of Water Drops on a Surface Moving Through Clouds". B. Vonnegut, Review of Scientific Instrumentation, Vol.20, pp.110-114, 1949
929. (372) "A New Method of Measurement of Cloud-Water Content". J. Warner and T. D. Newnham, C.S.I.R.O. Division of Radiophysics, Australia. Quarterly Journal of the Royal Meteorological Society, Vol.78, pp.46-52, 1952
930. (131) "The Calculated and Measured Performance Characteristics of a Heated-Wire-Liquid-Water-Content Meter for Measuring Icing Severity". C. B. Neel and C. P. Steinmetz, NACA TN 2615, 1952

931. (1341) "The Carbon Film Electric Hygrometer Element". W. J. Smith and N. J. Hoeflich, Bulletin of the American Meteorological Society, Vol.35, pp.60-62, 1954
932. (369) "A Heated-Wire Liquid-Water Content Instrument and Results of Initial Flight Tests in Icing Conditions" Carr B. Neel, NACA RM A54I23, 1955
933. (154) "Impingement of Cloud Droplets on a Cylinder and Procedure for Measuring Liquid Water Content and Droplet Sizes in Supercooled Clouds by Rotating ...". J. J. Brun, W. Lewis, P. J. Perkins J. S. Serofini, NACA Report, 1955
934. (377) "A Continuously Recording Water-Content Meter". H. J. aufm Kampe, H. K. Weickmann and J. J. Kelly, Signal Corps Engineering Laboratories. Journal of Meteorology, Vol.13, pp.64-66, February 1956
935. (543) "On the Measurements of Liquid Water Content and of Ice Accretion in Supercooled Clouds and on Some Errors of These Instruments". V. E. Minervin, Tsient Aeronautical Observatory, (T. Vyp. 17, pp.15), Moscow, 1956
936. (370) "Wind Tunnel Calibrations of Three Instruments Designed for Measurements of the Liquid Water Content of Clouds". G. V. Owens, Cloud Physics Laboratory, Technical Note 6, The University of Chicago, 1957
937. (365) "A Comparative Flight Test of Three Instruments for Measuring Cloud Water Content". E. W. Barrett, Technical Note 14, Cloud Physics Laboratory, The University of Chicago, 1958
938. (788) "The Analysis of Measurements of Free Ice and Ice/Water Concentrations in the Atmosphere of the Equatorial Zone". I. McNaughton, RAE/TN/Mech.Eng.283, May 1959
939. (1052) "Instrumentation and Operations for Gathering Thunderstorm Data with an F-100F During the 1963 National Severe Storm Project". E. B. Underwood, Technical Documentary Report No.ASD-TR-64-77, Directorate of Flight Test, Aeronautical Systems Division, Airforce Systems Command, Wright-Patterson Air Force Base, Ohio, February 1964
940. (547) "Response Calculations for Light-Scattering Aerosol Particle Counters and Photometers". J. R. Hodkinson and J. R. Greenfield, Journal of Applied Optics, Vol.4, pp.1463-1474, 1965

941. (536) "Water Vapour Density Measurements Utilizing the Absorption of Vacuum Ultraviolet and Infrared Radiation". J. E. Tillman, Chapter 43, "Humidity and Moisture Measurement and Control in Science and Industry", Vol.1, "Principles and Methods of Measurement of Humidity in Gases", New York, Reinhold Publishing Company, pp.704, 1965
942. (354) "Measurements of Water-Ice Budget Changes at -5 Degrees Celcius in AgI-Seeded Tropical Cumulus". R. E. Ruskin, U.S. Naval Research Laboratory, Washington D.C.. Journal of Applied Meteorology, Vol.6, pp.72-81, 1967
943. (355) "Comparative Measurements of Cloud Liquid Water Using Heated Wire and Cloud Replicating Devices". Paul A. Spyers-Duran, The University of Chicago. Journal of Applied Meteorology, Vol.7, pp.674-678, 1968
944. (1053) "Method of Determining the Meteorological Parameters Needed for the Preparation of De-Icing Systems". Wolfer, Hamburg Aircraft Factory Limited, Report No.MBB/UH-16-70, December 1970
945. (155) "Comparative Liquid Water Content Measurements of Conventional Instruments with an Optical Array Spectrometer". Robert G. Knollenberg, Department of the Geophysical Sciences, The University of Chicago 60637. Journal of Applied Meteorology, Vol. 11, pp.501-508, April 1972
946. (570) "Measurement of Liquid Water Content with a Heated Wire". C. B. Neel, Proceedings of the 19th International Aerospace Symposium, Vol.19, B, pp.301, Washburn, Ed., (ISBN 0-87664-212-1), 1973
947. (228) "Effects of Airplane Flowfields on Hydrometeor Concentration Measurements". H. G. Norment and R. G. Zalosh, Atmospheric Science Associates, PO.Box 307, Bedford, Massachusetts 01730, AFCRL TR 74 0602. AD A006 690, December 6, 1974
948. (1096) "The Measurement of Water Content by an Evaporator". Thomas G. Kyle, National Center for Atmospheric Research, Boulder, Colorado, 80303, December 27, 1974
949. (546) "Response Calculations for Light-Scattering Aerosol Particle Counters". D. D. Cooke and Kerker Milton, Journal of Applied Optics, Vol.14, pp.734-739, 1975
950. (229) "Effects of Airplane Flowfields on Cloud Water Content Measurements". H. G. Norment, AFCRL TR 75 0231. AD A014 807, April 30, 1975

951. (352) "A New Hot-Wire Liquid Cloud Water Meter". Francis J. Merceret and Terry L. Schricker, National Hurricane Research Laboratory, NOAA, Miami, Florida 33124. Journal of Applied Meteorology, Vol.14, pp.319-326, April 1975
952. (230) "Effects of Airplane Flowfields on Hydrometeor Concentration Measurements. Preprints". H. G. Norment, International Conference on Cloud Physics, pp.591-596, Boulder, Colorado, July 26-30, 1976
953. (232) "Additional Studies of the Effects of Airplane Flowfields on Hydrometeor Concentration Measurements". H. G. Norment, AFGL TR 76 0187. AD-A032 311, August 13, 1976
954. (132) "A Hot Wire Liquid Water Device Having Fully Calculable Response Characteristics". W. D. King, D. A. Parkin and R. J. Handsworth, Division of Cloud Physics, CSIRO, Sydney, Australia. Journal of Applied Meteorology, Vol.17, pp.1809-1813, December 1978
955. (363) "Frequency Response of the CSIRO Liquid Water Probe". S. Bradley and W. D. King. Journal of Applied Meteorology, 1978
956. (364) "Total Droplet Concentrations and Average Droplet Sizes from Simultaneous Liquid Water Content and Extinction Measurements". W. D. King and R. J. Handsworth. Journal of Applied Meteorology, 1978
957. (234) "Collection and Measurement Efficiencies of the EWER Cloud Water Meter for Hydrometeors". Hillyer G. Norment, Atmospheric Science Associates, 363 Great Road, P.O.Box 307, Bedford, Massachusetts 01730, AFGL TR 79 0122, Contract F19628-79-M-0005, May 11, 1979
958. (353) "Response Characteristics of Knollenberg Light-Scattering Aerosol Counters". R. G. Pinnick and H. J. Auvermann. Journal of Aerosol Sciences, Vol.10, pp.55-74, 1979
959. (133) "Calibrations of Johnson-Williams Liquid Water Content Meters in a High Speed Icing Tunnel". J. Walter Strapp and Robert S. Schemenauer, Atmospheric Environment Service, Downsview, Ontario, Canada, M3H5T4. Journal of Applied Meteorology, Vol.21, pp.98-108, March 27, 1981 and September 2, 1981
960. (351) "Calibration of Knollenberg FSSP Light-Scattering Counters for Measurement of Cloud Droplets". R. G. Pinnick, D. M. Garvey and L. D. Duncan, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico 88002. Journal of Applied Meteorology, Vol.20, pp.1049-1057, May 21, 1981

961. (1173) "Cloud Liquid Water Content Measuring Equipment for the Nomad N24 Aircraft Flight Icing Trials of 1978-1979". F. W. Skidmore, Comp. and G. F. Pearce, Comp., Aeronautical Research Laboratories, Melbourne, Australia, September 1981
962. (350) "Comparative Study and Calibration of Sensors for the Measurement of the Liquid Water Content of Clouds with Small Droplets". P. Personne, J. L. Benguier, J. P. Pinty and Y. Pointin, L.A.M.P., University of Clermont II, 63170 Aubiere, France. Journal of Applied Meteorology, Vol.21, pp.189-196, 1982
963. (567) "A Description of FSSP Auxiliary Variables and their Use". D. Baumgardner, Cloud Particle Measurement Symposium: Summaries and Abstracts, NCAA TN 199, pp.54-60, 1982
964. (441) "An Oil-Stream Photomicrographic Aeroscope for Obtaining Cloud Liquid-Water Content and Droplet Size Distributions in Flight". Paul T. Hacker, NACA TN 3592
965. (41) "Instruction Manual J-W LWC Liquid-Water-Content Indicator. Model LWH". Johnson Williams Incorporated, Mountain View, California, Document 61WCO 0621, n.d.
966. (966) "Atmospheric Water Vapour and Icing Sensing Techniques". K. G. Pettit, National Aeronautical Establishment, Canada, AGARD Flight Test Manual, Vol.4, Part 11A10
967. (1122) "Liquid Water Content Devices". Robert E. Ruskin, Naval Research Laboratory, Atmospheric Technology, pp.38

Also references : 11 20 23 61 69 72 97 100 109 110
124 130 180 188 189 244 275 346
347 349 381 395 416 435 448 472
475 478 480 481 483 484 491 494
516 534 567 575 653 799 926
1068 1070 1071 1072 1080 1158

3.5.1.4 Droplet Size

968. (481) "On the Measurement of Drop Size and Liquid Water Content in Fogs and Clouds". H. G. Houghton and W. H. Radford, Papers in Physical Oceanography and Meteorology. Vol.6, No.4, pp.5-31, M.I.T. and Woods Hole Oceanographic Institute, Cambridge and Woods Hole, Massachusetts, November 1938
969. (23) "Cloud Droplet Camera". H. W. Elliot, Division of Mechanical Engineering, National Research Laboratories, Ottawa (Canada), Report MI-701, December 26, 1947

970. (337) "Raindrop Size, Shape and Falling Speed". A. F. Spilhaus, College of Engineering, New York University. Journal of Meteorology, Vol.5, pp.108-110, 1948
971. (80) "The Terminal Velocity of Fall for Water Droplets in Stagnant Air". Ross Gunn and Gilbert D. Kinzer. Journal of Meteorology, Vol.6, pp.243-248, August 1949
972. (744) "Method for Measuring the Size of Water Droplets in Clouds, Fogs and Sprays". NRC Report No.ME.177, National Research Council of Canada, Ottawa, Canada, March 22, 1950
973. (515) "Measurements of Airborne Droplets by the Magnesium Oxide Method". K. R. May, Journal of Scientific Instrumentation, Vol.27, pp.128-130, 1950
974. (514) "Method for Measuring the Size of Water Drops in Clouds, Fogs and Sprays". N. Goltizine, National Aeronautical Establishment of Canada, Note 6, pp.13, 1951
975. (477) "An Instrument Employing a Coronal Discharge for the Determination of Droplet-Size Distribution in Clouds". Rinaldo J. Brun, NACA TN 2458, 1951
976. (485) "Adaption of a Cascade Impactor to Flight Measurement of Droplet Size in Clouds". Joseph Levine and Kenneth S. Kleinknecht, NACA RM E51G05, 1951
977. (478) "Flight Camera for Photographing Cloud Droplets in Natural Suspension in the Atmosphere". Stuart McCullough and Porter J. Perkins, NACA RM E50K01a, 1951
978. (516) "A Cloud Droplet Sampler for Use on Aircraft". P. Squires and C. A. Gillespie, Quarterly Journal of the Royal Meteorological Society, Vol.78, pp.387-393, 1952
979. (479) "Note on Sampling and Photographing Cloud Droplets in Flight". F. J. Bigg and G. C. Abel, RAE TN 156 Mechanical Engineering, September 1953
980. (1322) "Impingement of Water Droplets on a Cylinder in an Incompressible Flowfield and Evaluation of the Rotating Multicylinder Method for Measurement of Droplet-Size Distribution, Volume-Median-Diameter, and Liquid-Water Content in Clouds". R. Brun and H. Mergler, NACA TN 2904, 1953
981. (486) "A Review of Radiation Scattering Methods for Measuring Cloud Droplet Size". D. C. Baxter, Report MD-40. National Research Council of Canada, Ottawa, Canada, April 1954

982. (487) "An Improved Infrared Transmissometer for Cloud Drop Sizing". John C. Johnson, Ralph G. Eldridge and James R. Terrell, Science Report 4, Department of Meteorology, M.I.T.. Contract AF19 (122)-245, July 1954
983. (511) "A Three Slide Cloud Droplet Sampler". E. N. Brown and J. H. Willett, Bulletin of the American Meteorological Society, Vol.36, pp.123-127, 1955
984. (513) "Recent Developments in the Measurement of Precipitation Elements from Aircraft". M. P. Garrod, Meteorological Research Paper 1050, Meteorological Research Commission, London, pp.8, 1957
985. (366) "A Technique for Measuring Precipitation Particles from Aircraft". Edward N. Brown, The University of Chicago. Journal of Meteorology, Vol.15, pp.462-466, 1958
986. (787) "The Measurement of Ice Crystal Sizes in Flight". T. J. Methven, RAE/TN/Mech.Eng.279, January 1959
987. (508) "A Continuously Recording Precipitation Particle Sampler". E. N. Brown, Journal of Meteorology, Vol.18, pp.815-818, 1961
988. (780) "Determination of the Size of Ice Crystals Formed During Condensation of Water in Wind Tunnels and of Their Effect on Boundary Layers". H. Thomann, The Aeronautical Research Institute of Sweden, FFA Report 101, Stockholm, July 1964
989. (509) "Continuous Particle Sampler". P. B. MacCready Jr. and T. C. Todd, Journal of Applied Meteorology, Vol.3, pp.450-460, 1964
990. (510) "An Airborne Continuous Cloud Particle Replicator". P. A. Spyers-Duran and R. R. Braham Jr., Journal of Applied Meteorology, pp.1108-1113, 1967
991. (534) "Cloud Particle Replication in Stormy Tropical Cumulus". J. M. Averitt and R. E. Ruskin, Journal of Applied Meteorology, Vol.6, pp.88-94, 1967
992. (566) "A Cloud Droplet Sampler". A. H. Auer Jr., An information supplement. Internal report to the Bureau of Reclamation from the University of Wyoming, 1969
993. (368) "A New Electro-Optical Technique for Particle Size Measurements". Robert G. Knollenberg and W. Edward Neish, National Center for Atmospheric Research, Boulder, Colorado. Proceedings of the Electro-Optical System Design Conference, pp.594-608, 1969

994. (367) "The Optical Array; An Alternative to Scattering or Extinction for Airborne Particle Size Determination". R. G. Knollenberg. Journal of Applied Meteorology, Vol.9, pp.86-103, 1970
995. (371) "The Relationship Between Imprint Size and Drop Diameter for an Airborne Drop Sampler". R. M. Schechter and R. G. Russ, Naval Research Laboratory, Washington, D.C.. Journal of Applied Meteorology, Vol.9, pp.123-126, 1970
996. (886) "Holographic Determination of Droplet Size and Its Distribution in Ice-Forming Mist". H. Royer, Franco-German Research Institute, St.Louis, france, November 1973
997. (231) "Effects of Airflow on Sampling of Water Drops by Two Instruments Mounted on the Fuselage of a Lockheed C130B Airplane". H. G. Norment, Atmospheric Science Associates, Associates to Scientific Instrument Group, Research Facility Center, NOAA, Miami, Florida, Final Report, on NOAA contract P.O. 01 6 022 11153, December 1, 1975
998. (233) "Effects of Airflow on Sampling of Water Drops from Two Instrument Ports on the Convair 990 Airplane". H. G. Norment, Atmospheric Science Associates Final Report, on NOAA Contract P.O. 01 7 022 12337, June 30, 1977
999. (549) "Airborne Camera Photographs Water Drops, Ice Particles in Clouds". R. F. Stengel, Design News, Vol.33, pp.38-39, 1977
1000. (494) "Performance of the PMS Axially Scattering Spectrometer Probe". R. K. Jeck, Aerosol Measurement, pp.294-311, University of Florida Press, 1979
1001. (347) "Improved Drop Generators for Calibration of Drop Spectrometers and Use in Laboratory Cloud Physics Experiments". Theodore W. Cannon and Walter W. Grotewold, National Center for Atmospheric Research, Boulder, Colorado 80307. Journal of Applied Meteorology, Vol.19, pp.901-905, August 15, 1979 and May 3, 1980
1002. (124) "The 1982 Cloud Particle Measurement Symposium". Darrel Baumgardner and James E. Dye, National Center for Atmospheric Research, P.O.Box 3000, Boulder Colorado 80307, May 4-7, 1982
1003. (129) "The 1982 Cloud Particle Measurement Symposium". D. Baumgardner and J. E. Dye, Bulletin of the American Meteorological Society, Vol.64, pp.366-370, April 1983

1004. (346) "An Analysis and Comparison of Five Water Droplet Measuring Instruments". Darrel Baumgardner, Department of Atmospheric Science, University of Wyoming, Laramie 82071. Journal of Climate and Applied Meteorology, Vol.22, pp.891-910, May 1983
1005. (1185) "Measurement of Water Droplet Distributions in an Icing Wind Tunnel by Holography". Edward M. Gates, Department of Mechanical Engineering, Alberta University, Edmonton, June 1983
1006. (130) "Determination of the Size and Concentration of Cloud Drops with an FSSP". Todd A. Cerni, Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming 82071. Journal of Climate and Applied Meteorology. Vol.22, pp.1346-1355, August 1983
1007. (1156) "Size Velocity Correlation Measurement of Large Drops in a Turbulent Air Flow". H. Burnage et al., ONERA, TP 1985-69, 1985
1008. (1158) "A Stagnation Pressure Probe for Droplet-Laden Air Flow". S. N. B. Murthy and C. M. Ehresman, Purdue University, West Lafayette, Indiana, AIAA-85-0330, 1985
1009. (1317) "Operating Envelopes of Particle Sizing Instrumentation Used for Icing Research - Final Contractor Report". Edward A. Hovenac, Sverdup Technology Incorporated, Cleveland, Ohio, Contract NAS3-24105, NASA-CR-180870, AIAA-88-0291, December 1987
1010. (1080) "Filter Measurement of Ice Nuclei Concentrations and Selected Comparisons". James E. Jiusto, G. Garland and John Zamurs, Atmospheric Sciences Research Center, State University of New York, Albany, New York
1011. (1081) "Ice Nucleus Measurements - Workshop Summary Status". Gabor Vali, University of Wyoming, Laramie, Wyoming 82071
1012. (1088) "A CCN Spectrometer". J. G. Hudson, Desert Research Institute, University of Nevada, Reno Nevada

Also references : 11 14 61 67 97 100 109 110 136
152 180 188 217 228 234 244
349 350 351 354 364 395 398
435 441 445 475 480 483 484
491 548 567 575 653 926
1052 1067 1071 1072 1076
1159

3.5.1.5 Particle Velocity

- 1013. (4) "Laser-Velocimeter Flow-field Measurements of an Advanced Turboprop". J. S. Serafini, NASA Lewis Research Centre, Cleveland, Ohio, J. Sullivan, Purdue University, West Lafayette, Indiana, H. E. Neumann, NASA Lewis Research Center, Cleveland, Ohio, AIAA/SAE/ASME 17th Joint Propulsion Conference AIAA-81-1568, Colorado Springs, Colorado, July 27-29, 1981
- 1014. (197) "Laser Velocimeter Measurements of the Flow Fields Around Single and Counter-Rotation Propeller Models". Dana Morris Dunham and William L. Sellers III, NASA Langley Research Center, Hampton, Virginia. Joe W. Elliot, U.S. Army Structures Laboratory, Langley Research Center, Hampton, Virginia, General Aviation Aircraft Meeting and Exposition, Wichita, Kansas, April 16-19, 1985
- 1015. (1159) "The Droplet Velocity Dispersion Device". M. Dixon, University of Southern California, Los Angeles, California, AIAA-85-0077, 1985

Also references : 1076 1156

3.5.1.6 Ice Accretion

- 1016. (797) "Note on Thermal Ice Detection". F. J. Bigg, RAE Technical Memo Mech.Eng.47, October 1950
- 1017. (378) "An Aircraft Icing Indicator", G. W. Brock, U.S.A.F., A.I.R.L., TN 516, December 1951
- 1018. (805) "Some Tests of a Refrigerated Rotating Cylinder for Measuring Ice Accretion". B. Quan and H. G. Wenham, NAE LR 45, May 1952
- 1019. (380) "Comparative Tests of Two Icing Detectors". D. Fraser, NRC, NAE Test Report, NRC TR 32, June 1952
- 1020. (381) "Thermodynamic Limitations of Ice Accretion Instruments". D. Fraser, C. K. Rush and D. C. Baxter, NRC, NAE Laboratory Report NRC LR 32, August 1952
- 1021. (1344) "Wind Tunnel Testing of the RAE Rotating Disc Icing Meter". C. J. Cowlin, D. Napier and Son Limited, DEV/TR/124/924, 1953

1022. (1345) "The Characteristics of an Orifice-Type Icing Detector Probe". D. Fraser, National Aeronautical Establishment Laboratory Report, LR-71, 1953
1023. (798) "Development and Test of a Cooled Rotating Disc Icing Meter". F. J. Bigg, RAE/TN/Mech.Eng.200, March 1955
1024. (382) "Comparative Tests of Three Icing Detectors". R. L. Wardlaw, NRC, NAE Test Report NRC TR 264, August 1955
1025. (1320) "Completion Report on Development of an Ice Indicator with a Piezo-Electric Sensing Element". E. T. Maciag, M. G. Kullin, Y. T. Tsui and E. G. Thurston, Clevite-Brush Development Company, Contract No.NONR-1494(00), 1955
1026. (1123) "Aircraft Icing Objective Measurement and Classification". International Civil Aviation Organisation, Montreal, Canada, Circular 40-AN/35, 1955
1027. (799) "The Use of Thermal Ice Detectors for Measurement of Ice Crystal Concentration". I. McNaughton and F. J. Bigg, RAE/TN/Mech.Eng.282, September 1959
1028. (376) "Ice Detectors". D. P. Howlett, Paper Presented at Napier Aircraft Ice Protection Conference, London, May 1961
1029. (189) "Review of Icing Protection for Helicopters". J. R. Stallabrass, Low Temperature Laboratory, Division of Mechanical Engineering, National Research Laboratories, Ottawa, Canada, NRC LR 334, March 1962
1030. (1055) "The Leigh Helicopter Ice Detector". Leigh Instruments Limited, Carleton Place, Ontario, Canada, Report TP-951112, June 14, 1974
1031. (235) "Airflow Effects on Riming Measurements by a Wing Tip-Mounted Ice Detector on the M130E Research Airplane". Hillyer G. Norment, AFGL TR 79 0194, August 24, 1979
1032. (899) "Definition of Rotor Head Camera System for Chinook HC Mk.1 Icing Trials". K. Chivers, Aircraft and Armaments Experimental Establishment, Boscombe Down, October 1980
1033. (169) "Development and Test of a Microwave Ice Accretion Measurement Instrument (MIAMI)". B. Magenheimer and J. K. Rocks, NASA CR BATT 92880, 1981
1034. (103) "Microwave Ice Accretion Measurement Instrument (MIAMI)". B. Magenheimer and J. K. Rocks, Ideal Research, Incorporated, 11810 Parklawn Drive, Rockville, Maryland 20852, AIAA 20th Aerospace Sciences Meeting, AIAA-82-0285, Orlando, Florida, January 11-14, 1982

1035. (102) "IRI Microwave Ice Accretion Measurement Instrument (MIAMI)". Ideal Research, Incorporated, 11810 Parklawn Drive, Rockville, Maryland 20852
1036. (384) "Napier Servomechanisms Ice Detector Mk. 2". D. Napier and Son Limited, Spraymat Information Bulletin IB/s.14, Issue 2
1037. (590) "Real-Time Measurement of Ice Growth During Simulated and Natural Icing Conditions Using Ultrasonic Pulse-Echo Techniques". R. J. Hansman Jr. and M. S. Kirby, Massachusetts Institute of Technology, Cambridge, Massachusetts, AIAA-86-0410. AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986
1038. (1057) "All About Ice Detectors". Arthur C. Kohler, Commercial Aviation, pp.58
1039. (1054) "Ice Detectors (Type 1)". Rosemount Engineering Company, Minneapolis, Minnesota, Bulletin 8646
1040. (1058) "Ice Detection System Type T260". Release No.3, Canadian Applied Research Limited, Toronto, Canada
1041. (1056) "An Assessment to Current Icing Severity Instruments". J. E. Clark, Westland Helicopters Limited
1042. (1126) "Measurement of Ice Accretion Using Ultrasonic Pulse-Echo Techniques". R. John Hansman Jr. and Mark S. Kirby, Massachusetts Institute of Technology, Cambridge Massachusetts, Journal of Aircraft, Vol.22, No.6, pp.530

Also references : 11 20 26 54 66 67 71 109 110 152
158 180 190 202 217 395 413 716
776 777 794 813 858 859 860 926

3.5.1.7 Propeller Thrust

1043. (199) "An Electric Thrust Meter Suitable for Flight Investigation of Propellers". Porter J. Perkins Jr. and Morton B. Millenson, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, NACA RM E9C17, Washington, May 9, 1949

Also references : 26 36 180

3.5.1.8 General

1044. (269) "Preparation of Air of a Known Humidity and Its Application to the Calibration of an Absolute-Humidity Recorder". A. C. Walker, Industrial and Engineering Chemistry (Annual Edition), Vol.2, No.2, pp.134-138, April 15, 1930
1045. (645) "De-Icing Test Rig". Aeronautical Digest, November 1, 1945
1046. (480) "Instruments for Measuring Atmospheric Factors Related to Ice Formation on Airplanes". B. Vonnegut, R. M. Cunningham and R. E. Katz, Technical Report 5519, Air Material Command, AAF. (Contract W-33-038-ac-5443 with M.I.T.), August 13, 1946
1047. (655) "Measuring Method for Judging the Efficiency of Thermal De-Icing Installation of Aeroplane". P. Wenthen, M.O.S. Volken Reports and Trans. No.811, December 15, 1946
1048. (676) "Icing Tests on Engine Air Induction Systems". Morris, Jenkins, Colliver, R.A.E. Technical Note No.Mech. Eng.12, January 1947
1049. (680) "Mamba Anti-Icing Rig (Scheme D8318) Interim Report on Work Done to Date". A.S.M. Experimental Department Report (Comb.), January 22, 1947
1050. (664) "Instrumentation for Flight Testing of Thermal Anti-Icing Systems". W. C. Droege, A.S.M.E. Transactions, August 1947
1051. (684) "Mamba Anti-Icing Rig (Scheme D8318) Further Testing of Alternative Method for Mixing". A.S.M. Experimental Department (Comb.) Report, March 23, 1948
1052. (694) "Note on Ice Detectors". R.A.E. Reference ME/1521/JKH/55, November 1948
1053. (729) "Instrumentation for Flight Testing of Thermal Anti-icing Systems". W. C. Droege, A.S.M.E. Paper No.46-A-36, 1949
1054. (483) "A Review of Instruments Developed for the Measurement of the Meteorological Factors Conducive to Aircraft Icing". Alun R. Jones and William Lewis, NACA RM A9C09, 1949
1055. (476) "Nephelometric Instruments for Aircraft Icing Research". K. G. Pettit, Report MD-33, National Research Council of Canada, Ottawa, Canada, August 1950
1056. (757) "Indication, Measurement and Control of Ice Accretion". Journal of the Royal Aeronautical Society, June 1951

1057. (484) "On the Measurement of the Properties of Supercooled Clouds". K. G. Pettit, NAE Report 1954. Quarterly Bulletin of the National Aeronautical Establishment, Ottawa, Canada, April 1 - June 30, 1954
1058. (66) "A Simplified Instrument for Recording and Indicating Frequency and Intensity of Icing Conditions Encountered in Flight". Porter J. Perkins, Stuart McCullough and Ralph D. Lewis, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, NACA RM E51E16, 1951
1059. (1046) "Project Summit Outline of Test facilities at the Mt. Washington Icing Establishment for Season 1956-1957". Smith, Hinchman and Grylls Incorporated, Aeronautical Icing Research Laboratories, Bartlett, New Hampshire, April 1956
1060. (349) "Three New Instruments for Cloud Physics Measurements". R. G. Knollenberg, Preprints from the International Conference on Cloud Physics, American Meteorological Society, pp.554-561, 1976
1061. (1174) "Experimental Comparison of Icing Cloud Instruments". W. Olsen, NASA Lewis Research Center, Cleveland, Ohio, D. Takeuchi, Meteorological Research Incorporated, and K. Adams, Air Force Flight Test Center, NASA Lewis Research Center, Cleveland, Ohio, Presented at the 21st Aerospace Sciences Meeting, Reno, Nevada, AIAA-83-0026, January 10-13, 1983
1062. (1172) "Comparison of Icing Cloud Instruments for 1982-1983 Icing Season Flight Program". Robert F. Ide and G. Paul Richter, NASA Lewis Research Center, Cleveland, Ohio, Presented at the 22nd Aerospace Sciences Meeting, Reno, Nevada, Sponsored by AIAA, January 9-12, 1984
1063. (1168) "Measurement of Heat Transfer for an Accreting Ice Surface in Wind and Flight Tests". R. J. Hansman and M. S. Kirby, Massachusetts Institute of Technology, Cambridge, Massachusetts, AIAA-85-1352, 1985
1064. (1169) "Status of Icing Cloud Instrument Comparisons: 1983-84 Icing Flight Season". R. F. Ide, U.S. Army Research and Technology Laboratories, Cleveland, Ohio, Porter J. Perkins, Sverdup Technology Incorporated, Cleveland, Ohio, and G. P. Richter, NASA Langley Research Center, Hampton, Virginia, AIAA-85-0469, 1985
1065. (1319) "Measurement of Local Convective Heat Transfer Coefficients from a Smooth and Roughened NACA-0012 Airfoil: Flight Test Data". James E. Newton, G. James Van Fossen, Phillip E. Poinsett and Kenneth J. DeWitt (Toledo University, Ohio), 1988, AIAA-88-0287, NASA-TM-100284, Presented at the 26th Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1988

Also references : 125 935 727 775 785 786 793
795 796 924 926

3.5.2 Equipment

1066. (209) "Notes on Possible Equipment and Technique for Experiments on Icing on Aircraft". G. I. Taylor, British A.R.C. R. and M. 2024, January 15, 1940
1067. (560) "The Production of Clouds Containing Supercooled Water Droplets or Ice Crystals Under Laboratory Conditions". Vincent J. Schaefer, Bulletin of the American Meteorological Society, Vol.29, No.4, pp.175-182, April 1948
1068. (730) "Improvements in or Relating to Ice Detecting Apparatus for Air Compressor". Westinghouse Company, P.S.622,554, May 4, 1949
1069. (733) "Rig Testing of Components of Mamba Anti-Icing Scheme on High Pressure Rig". A.S.M. Experimental Department Report (Comb.), July 11, 1949
1070. (734) "Improvements in or Relating to Gas Turbine Power Plants. (Cooling of Lubricating Oil used for De-icing Intake)", International Company, P.S.626,571, July 18, 1949
1071. (735) "Improvements Relating to the Heating of Compressors (Electrical)". D. Napier and Sons Limited, P.S. 629,764, September 28, 1949
1072. (736) "Anti-Icing and Fire Prevention Arrangements on D.H. Ghost Civil Installations". September 29, 1949
1073. (517) "The Production of Sprays and Mists of Uniform Drop Size by Means of Spinning Disc Type Sprayers". W. H. Walton and W. C. Prewett, Proceedings of the Physics Society, Vol.62 B, pp.341-350, 1949
1074. (747) "Equipment of a Canadian Unit to Investigate Icing Phenomena". Flight International, August 28, 1950
1075. (491) "Critical Impact Velocities of Water Droplets as a Problem in Injector-Spray Sampling". Jack H. Rupe, Progress Report 4-80, Jet Propulsion Laboratory, C.I.T., September 29, 1950

1076. (748) "Tests of a Water Spray Rig for Simulating Icing Conditions Ahead of a Turbine Engine in Flight". Mechanical Engineering Department, R.A.E. Technical Note Mech.Eng.58, October 1950
1077. (859) "Orifice Type Ice Detector Preliminary Icing Tunnel Tests of Functioning as Ice Detector, Rate of Icing Meter and Icing Severity Meter". D. Fraser, NAE/LR/3, July 1951
1078. (727) "The Tests of Water Spray Nozzles for Simulating Natural Icing Conditions". J. Randall, Experimental Department (Flight Section), February 14, 1952
1079. (858) "The Characteristics of an Orifice-Type Icing-Detector Probe". D. Fraser, NAE/LR/71, June 1953
1080. (794) "An Aircraft Icing Rate Meter". G. M.Wright, June 1953
1081. (856) "Description of the Spray Rig Used to Study Icing on Helicopters in Flight". D. L. Bailey, Division of Mechanical Engineering, National Research Council of Canada, NAE/LR/186, Ottawa, Canada, January 1957
1082. (860) "Ice Detection System Type T260 Release No.3". Canadian Applied Research Limited, Toronto, Canada, February 1957
1083. (386) "Description of the Spray Rig Used to Study Icing on Helicopters in Flight". D. L. Bailey, NAE Laboratory Report NRC LR 186A, September 1960
1084. (550) "Study of the Vibrating Reed in the Production of Small Droplets and Solid Particles of Uniform Size". W. P. Wolf, Review of Scientific Instrumentation, Vol.32, pp.1124-1129, 1961
1085. (850) "Review of Icing Detection for Helicopters". J. R. Stallabrass, NRCC Aeronautical Report LR/334, Division of Mechanical Engineering, National Research Council of Canada, March 1962
1086. (1142) "Helicopter Icing Spray System Qualification, Final Report, 13 Apr. - 5 Jul. 1973". James S. Hatden, Edward E. Bailes, Joseph C. Watts and Larry K. Brewer, United States Army Aviation Systems Test Activity, Edwards Air Force Base, California, October 1973
1087. (127) "Ice and Landing Surface Demoulding-Replica Fabrication". Goran Lundstrom, Aerodynamics Department, Fluid Technology Laboratory, The Aeronautical Research Institute of Sweden, 1973-07-20, FFA Memo 90, Stockholm, 1973

1088. (548) "A Camera for Photography of Atmospheric Particles from Aircraft". T. W. Cannon, Review of Scientific Instrumentation, Vol.45, pp.1448-1455, 1974
1089. (916) "Airborne Calibration of the Spray Cloud Generated by the Canberra Icing Tanker". Aircraft and Armament Experimental Establishment, Boscombe Down

Also references : 124 127 152 203 209 244 245 268
347 355 510 574 575 785 786 789
903 1122 1162

3.5.3 Procedure

1090. (711) "Some Tricks in Cold Weather Operations". Dymont, S.A.E. Preprint No.40R, January 13, 1950
1091. (716) "A Rapid Method of Estimating the Severity of Icing". Schaetzel, Aircraft Engineering, July 1950
1092. (718) "Some Tricks in Cold Weather Operation". J. L. Dymonts, Air World, July-August, 1950
1093. (786) "Surface Temperature During Icing - A Description of Tests Performed in the Icing Tunnel at Artington During February of 1952 in Co-operation with Napier Icing Team". G. L. Shires, NGTE Report, February 1952
1094. (775) "Report of the First Year's Flying on the Development of Flight Testing Techniques for Finding and Measuring Natural Icing Conditions". G. C. Abel, ARC/CF/221, February 1953
1095. (776) "Report of the Second Year's Flying on the Development of Flight Testing Techniques for Finding and Measuring Natural Icing Conditions". G. C. Abel, ARC/CF/221, March 1953
1096. (475) "Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Cylinder Method". William Lewis, Porter J. Perkins and Rinaldo J. Brun, NACA RM E53D23, 1953
1097. (777) "Report of the Third Year's Flying on the Development of Flight Testing Techniques for Finding and Measuring Natural Icing Conditions". G. C. Abel, ARC/CF/221, January 1955
1098. (785) "The Production of a 20 Micron Water Droplet Spray in a Sub Zero Temperature Airstream". A. P. Johnstone, NGTE M 382, Memorandum, April 1964

1099. (568) "Techniques for Probing Cloud Microstructure". R. G. Knollenberg, "Clouds. Their Formation, Optical Properties and Effects". (P. V. Hobbs and A. Deepak), Eds., Academic Press, pp.495, 1981
1100. (1330) "Measurements of Local Heat Transfer Coefficients on Ice Accretion Shapes". R. V. Arimilli and E. G. Kesbock, Paper AIAA-84-0018, Presented at the 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984
1101. (1162) "An Optical Method for Extracting Water Droplet Impingement Data from Wind Tunnel Experiments". F. M. Dickey and G. A. Freund Jr., Boeing Military Airplane Company, Wichita, Kansas, AIAA-85-0261, 1985
1102. (1310) "New Methods and Materials for Molding and Casting Ice-Formations". Andrew L. Reehorst and G. Paul Richter, NASA Lewis Research Center, Cleveland, Ohio, NASA Technical Memorandum 100126, September 1987

Also references : 127 152 209 244 245 275 560 780
807 854 966 1126

3.6 Meteorology

1103. (1336) "Jelineks Psychrometer -Tafeln". F. M. Exner, Seventh Edition, Leipzig, 1929
1104. (253) "Meteorological Notes on the Formation of Ice on Aircraft". C. G. Andrus, Cleveland Airport, Ohio, December 15, 1929, Monthly Weather Review, January 1930
1105. (248) "Supersaturation and Icing of Airplanes". W. J. Himphreys, Monthly Weather Review, Weather Bureau, Washington, June 1930
1106. (73) "Meteorological Conditions During the Formation of Ice on Aircraft". L. T. Samuels, NACA TN 439, 1932
1107. (1337) "Psychrometric Charts for High and Low Pressures". D. B. Brooks, National Bureau of Standards, U.S. Department of Commerce, Miscellaneous Publication M.146, 1935
1108. (623) "Microscopic Examination of Fog, Cloud and Rain Droplets". Fuchs and Petrjanoff, January 16, 1937
1109. (624) "The Physico-Meteorological Factores Giving Rise to Ice Secretion in the Atmosphere". W. Findeisen, M.O.S. G.D.C. Translation No.10/6189T (T.I.B. Reference T.3454), October 13, 1938
1110. (75) "Meteorological Physical Limitations of Icing in the Atmosphere". W. Findeisen, NACA TM 885, 1938
1111. (78) "Determination of Icing Conditions for Airplanes". David L. Arenberg, Illustrations, Transcripts, Reports and Papers, Meteorology. pp.99-122, 1943
1112. (391) "Supercooled Water Droplets in Rising Currents of Cold Saturated Air". I. Langmuir, General Electric Company, Schenectady, New York, 1944
1113. (653) "Liquid Water Content and Droplet Size in Clouds of the Atmosphere", G. W. Brock, A.S.M.E. Paper No.46-A-45, 6TL. Acc. No.124, December 1946
1114. (658) "Cold Weather No Longer Feared for Aircraft". Forney, Weitzer, Diron, Blayle, S.A.E. Journal, March 1947
1115. (662) "Icing Properties of Non-Cyclonic Winter Stratus Clouds". W. Lewis, N.A.C.A. Technical Note No.1391, July 1947

1116. (258) "A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes". William Lewis, NACA TN 1393, 1947
1117. (470) "A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing". William Lewis, Dwight B. Kline and Charles P. Steinmetz, NACA TN 1424 1947
1118. (539) "Hail Formation, Vertical Currents and Icing of Aircraft". E. Gaviola and F. A. Fuertes, Journal of Meteorology, Vol.4, pp.116, 1947
1119. (1331) "Resolution 166, International Meteorological Organization, Conference of Directors, Washington, 1947
1120. (855) "Royal Canadian Air Force (Research and Development) Report on Winter Operations". RCAF. No.297, Winter Experimental Establishment, Edmonton-Churchill Watson Lake, 1947 - 1948, April 1948
1121. (685) "Icing of Aircraft - the Meteorological Problem". R.A.E. Technical Memo Mech.Eng.6, July 1948
1122. (1324) "The Distribution of Raindrops with Size". J. S. Marshall and W. M. Palmer, Journal of Meteorology, Vol.5, pp.165-166, August 1948
1123. (690) "The Ice Phase in the Atmosphere". H. Weickman, R.A.E. Library Translation No.273, (Volkenrode R. and T. 716), September 1948
1124. (693) "The Physico-Meteorological Factors Giving Rise to Ice Secretion in the Atmosphere". W. Findeisen, M. of S. Trans. G.D.C. 10/6189T. (Lillienthal Report), October 13, 1948
1125. (503) "Supercooled Water - and Ice Clouds". Wilhelm Peppler, Abstracts in Bulletins of the American Meteorological Society, Vol.29, No.9, pp.458, November 1948
1126. (416) "Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment". Alun R. Jones, and William Lewis (U.S Weather Bureau, Ames Aeronautical Laboratory), NACA TN 1855, MARCH 1949
1127. (1097) "The Nature of Ice-Forming Nuclei in the Atmosphere". B. J. Mason, Imperial College of Science and Technology, London, October 6, 1949
1128. (488) "Investigation of Meteorological Conditions Associated with Aircraft Icing in Layer-Type Clouds for 1947-48 Winter". Dwight B. Kline, NACA TN 1793, 1949

1129. (489) "Observations of Icing Conditions Encountered in Flight During 1948". William Lewis and Walter H. Hoecker Jr., NACA TN 1904, 1949
1130. (1333) "The Growth of Cloud Droplets in Uniformly Cooled Air". W. E. Howell, ScD. Dissertation, Massachusetts Institute of Technology, 1948, also Journal of Meteorology, Vol.6, pp.134, 1949
1131. (502) "Canadian Experiments on Artificially Induced Precipitation". John L. Orr and K. G. Pettit, Bulletin of the American Meteorological Society, Vol.31, No.2, pp.56-59, February 1950
1132. (865) "Ice Protection for Turbojet Transport Airplane - Meteorology and Physics of Icing". P. T. Hacker et al., I.A.S. S.M.F. Fund Paper No.FF-1, March 1950
1133. (472) "Liquid Water Content and Distribution of Drops in Cumulus Clouds". V. A. Zaitsev, NRC Technical Report (translation TT-395 by G. Belkov) from Trudy Glavnici Geofizicheskoi Observatorii. Vol.19, No.81, pp.122-132, 1950
1134. (1038) "Analysis of Meteorological Data Obtained During Flight in a Supercooled Stratiform Cloud of High Liquid-Water Content". Porter J. Perkins and Dwight B. Kline, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, NACA, Washington, July 11, 1951
1135. (490) "Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds". Dwight B. Kline and Joseph A. Walker, NACA TN 2306, 1951
1136. (227) "A Summary of Meteorological Conditions Associated with Aircraft Icing and a Proposed Method of Selecting Design Criteria for Ice-Prevention Equipment". Paul T. Hacker and Robert G. Dorsch, NACA TN 2569, 1951
1137. (878) "Ice Accretion on Aircraft". Meteorological Report No.9, 1951
1138. (1332) "Smithsonian Meteorological Tables, Sixth Revised Edition, pp.347-350, Washinton, 1951
1139. (771) "Preliminary Comparison of Meteorological Forecasts of Natural Icing Conditions with Conditions Encountered". G. C. Abel, Aircraft and Armament Experimental Establishment, Boscombe Down, A.A.E.E./RES/266, May 1952
1140. (765) "A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the USA". William Lewis and N. R. Burgrun, NACA/TN/2738, July 1952

1141. (749) "Preliminary Survey of Icing Conditions Measured During Routine Transcontinental Airline Operation". Porter J. Perkins, NACA/TIB/3287, RM E52J06, December 1952
1142. (813) "Occurrence of High Rates of Ice Accretion on Aircraft". A. C. Best, Meteorological Office Professional Notes No.106, 1952
1143. (471) "Physical Properties of Cumulus Clouds". H. K. Weickmann and H. J. aufm Kampe, Journal of Meteorology, Vol.10, No.3, pp.204-211, June 1953
1144. (782) "Annual Report of Operations of North Star Icing Research Aircraft. 1951 - 1952 Season". J. H. Milsum, NAE/TR/91, September 1953
1145. (1335) "Meteorological Instruments". W. E. K. Middleton and A. F. Spilhaus, Third Edition Revised, University of Toronto, 1953
1146. (783) "Second Annual Report of Operations of North Star Icing Research Aircraft. 1952 - 1953 Season". J. H. Milsum and J. R. Stallabrass, NAE/TR/188, November 1954
1147. (753) "Statistical Survey of Icing Data Measured on Scheduled Airline Flights over the United States and Canada from November 1951 to June 1952". Porter J. Perkins, NACA/TIB/4677, RM E55F28a, September 1955
1148. (784) "Third Annual Report of Operations of North Star Icing Research Aircraft. 1953 - 1954 Season". J. H. Milsum, NAE/TR/266, September 1955
1149. (1321) "Wind Tunnel Simulation of Atmospheric Icing Conditions". C. K. Rush and R. L. Wardlaw, National Aeronautical Establishment, Ottawa, Canada, 1955
1150. (779) "Ice Crystals - A New Icing Hazard". O. R. Ballard, Napier and Sons Limited and B. Quan, CAI Preprint No.7/11, A.G.M. of the Canadian Aeronautical Institute, Ottawa, Canada, May 1957
1151. (769) "Icing Frequencies Experienced During Climb and Descent by Fighter-Interceptor Aircraft". Porter J. Perkins, NACA/TN/4314, July 1958
1152. (1095) "Size-Distribution of Ice Crystals in Cumulonimbus Clouds". R. F. Jones, Meteorological Office, London, July 27, 1959
1153. (538) "Measurement of Ice-Crystal Clouds". F. J. Bigg, D. J. Day and I. I. McNaughton, Aircraft Ice Protection Conference, Napier and Son Limited, Luton, England, 1959

1154. (445) "The Physics of Clouds, Rain and Lightning". B. J. Mason, pp.59-78, September 14, 1961
1155. (1298) "Microstructure of Fog". Shifrin, NACA TT F-317, 1964
1156. (121) "Airworthiness Standards: Transport Category Airplanes, Part 25". Federal Aviation Regulations, Federal Aviation Authority, January 2, 1965
1157. (330) "Forecaster's Guide on Aircraft Icing". Air Weather Service Manual 105-39, September 1964 and January 1969
1158. (49) "Microphysics of Clouds and Precipitation". N. R. Pruppacher and J. D. Klett, First Edition, D. Reidel Publishing Company, Dordrecht, The Netherlands, 1970
1159. (40) "A Simplified Criterion to Certify Light Aircraft for Flight in Icing Conditions". David H. Gollings, Piper Aircraft Corporation, and Dennis W. Newton, Pennsylvania State University, SAE 740349, Business Aircraft Meeting, Wichita, Kansas, April 2-5, 1974
1160. (569) "On the Spatial Variability of Droplets in Cloud". J. Warner, Journal of Atmospheric Science, Vol.36, pp.541-545, 1979
1161. (897) "Research on the Effect of Regimes of Generation of the AGI Aerosol on its Ice-Forming Activity". N. S. Kim, Trudy Tsent, Aerol.OBS.No.142, USSR, 1980
1162. (134) "Icing Characteristics of Low Altitude, Supercooled Layer Clouds". R. K. Jeck, FAA RD 80 24, 1980
1163. (348) "Primary Ice Crystal Production in Cumulus Congestus Clouds of Eastern Montana". T. A. Cerni, Preprints from the International Conference on Cloud Physics, American Meteorological Society, pp.346-349, Chicago, 1982
1164. (59) "A New Characterization of Super Cooled Clouds Below 10000 Feet AGL". C. O. Masters, Federal Aviation Administration, Washington, D. C.. DOT/FAA/CT 83/22, 1983
1165. (1140) "A New Characterization of the Icing Environment Below 10,000 Feet AGL from 7,000 Miles of Measurements in Supercooled Clouds". Richard K. Jeck, NASA, Marshall Space Flight Center, 7th Annual Workshop on Meteorology and the Environment, Inputs to Aviation Systems, pp.44-47, April 1984
1166. (1141) "A New Characterization of Supercooled Clouds". Charles O. Masters, NASA, Marshall Space Flight Center, 7th Annual Workshop on Meteorology and the Environment, Inputs to Aviation Systems, pp.49-52, April 1984

1167. (1150) "Icing Climatology for Helicopters". W. T. Roach and D. A. Forrester, Meteorological Office, Bracknell, UK, NATO, October 1984
1168. (1149) "The Aircraft Icing Environment in Wintertime, Low Ceiling Conditions. Final Report". N. B. Guttman, R. K. Jeck, M. R. Henderson and M. D. Mueller, Naval Research Laboratory, Washington D.C., October 28, 1985
1169. (1066) "Turbulence Effect on Cloud Droplet Spectrum During Condensation". A. S. Stepanov, Institute of Experimental Meteorology, Obinsk, USSR
1170. (1067) "Droplet Size Development in Warm Cumulus Clouds". A. N. Dingle and D. D. Harding, University of Michigan, Ann Arbor, Michigan
1171. (1068) "On the Decrease of Droplet Number with Height in the Early Stage of Growth in a Convective Warm Cloud". Yoshihiko Takahashi, Independent Research Laboratory for Meteorology, Tokyo Japan
1172. (1069) "Naturally Occurring Biological Ice Nucleants: A Review". Russell C. Schnell, National Research Council of Canada, Ottawa, Canada, NRC Research Association, NOAA/APCL, Boulder Colorado
1173. (1070) "Ice Crystal Concentrations in Wintertime Clouds". William A. Cooper and Gabor Vali, University of Wyoming, Laramie, Wyoming 82071
1174. (1071) "Cloud Physics Measurements with Polarization Diversity Lidar", Kenneth Sassen, Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming
1175. (1072) "The Measurement of Cloud Droplet Spectra". P. Ryder, Meteorological Office, Bracknell, Berkshire, UK
1176. (1073) "Water Drop Separation Probabilities". C. P. R. Saunders, S. Al-Said and M. Gay, University of Manchester Institute of Science and Technology, Manchester, UK
1177. (1075) "Supersaturation Regime within a Settling Cloud Chamber: Preliminary Results". Klaus M. Weickmann and Richard Barchet, University of Wisconsin, Madison, Wisconsin
1178. (1076) "Collision Efficiencies of Droplets with Diameter Below 40 Microns for Non-Gravitational Velocities". Ryszard Balcer, Institute of Geophysics, University of Warsaw, and Jerzy Czyz, Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland

1179. (1065) "Concentrations of Aitken, Cloud Droplet Condensation and Ice Nuclei Over Selected Oceanic and Continental Sites". Paul A. Allee, Atmospheric Physics and Chemistry Laboratory, Natural Oceanic and Atmospheric Administration, Boulder, Colorado, Robert I. Sax and Emil Delado, National Hurricane and Atmospheric Administration, Coral Gables, Florida
1180. (1062) "Where and When Helicopter Icing Occurs". David A. Forrester, Meteorological Office, Bracknell, UK
1181. (1064) "A Simple Numerical Simulation of the Condensational Growth of Cloud Droplets in Background Air", K. Bonis, E. Koflanouits, A. Meszaros and E. Meszaros, Institute for Atmospheric Physics, Budapest, Hungary
1182. (1326) "Advances in Radar Meteorology". D. Atlas, Advances in Geophysics, Vol.10, pp.318-478, Academic Press, New York
1183. (100) "FAR Part 25 Appendix C". Federal Aviation Authority

Also references : 40 110 125 152 158 159 160 267
269 331 337 354 386 396 409
435 473 534 775 780 977
1025 1063 1077 1078

3.7 Propeller And Aerofoil (Un-Iced)

3.7.1 Propeller

1184. (115) "The Prop-Fan - a New Look in Propulsors". C. Rohrbach and F. B. Metzger, AIAA-75-1208, September 1975
1185. (34) "A Report on the Aerodynamic Design and Wind Tunnel Test of a Prop-fan Model". Carl Rohrbach, Hamilton Standard, Division of United Technologies Corporation, Windsor Locks, Connecticut, AIAA-76-667, AIAA/SAE 12th Propulsion Conference, Palo Alto, California, July 26-29, 1976
1186. (33) "Design and Performance of Energy Efficient Propellers for Mach 0.8 Cruise". D. C. Mikkelson, B. J. Blaha, G. A. Mitchell and J. E. Wikette, NASA TMX 73612, 1977
1187. (118) "Wind Tunnel Performance of Four Energy Efficient Propellers Designed for Mach 0.8 Cruise". R. J. Jeracki, D. C. Mikkelson and B. J. Blaha, NASA TM 79124, 1979
1188. (29) "A Theoretical and Experimental Investigation of Propeller Performance Methodologies". K. D. Korkan and G. M. Gregorek, Ohio State University, Columbus, Ohio, and D. C. Mikkelson, NASA Lewis Research Center, Cleveland, Ohio, AIAA-80-1240, AIAA/SAE/ASME 16th Joint Propulsion Conference, Hartford, Connecticut, June 30-July 2, 1980
1189. (116) "Summary of Advanced Methods for Predicting High Speed Propeller Performance". L. J. Bober and G. A. Mitchell, NASA TM 81409, 1980
1190. (122) "Modern Propellers for Commuter Airlines". J. G. Russell, SAE 820719, Commuter Aircraft and Airline Operations Meeting, Savannah, Georgia, May 24-26, 1982
1191. (22) "Operational Evaluation of a Propeller Test Stand in the Quiet Flow Facility at Langley Research Centre". P. J. W. Block, NASA TM 84523, September 1982
1192. (3) "Large Scale Propeller Testing in the NRC 9 Metre Wind Tunnel in Canada". D. J. Barber, The de Havilland Aircraft of Canada Limited, SAE 830751, Business Aircraft Meeting and Exposition, Wichita, Kansas, April 12-15, 1983
1193. (12) "Techniques of Model Propeller Testing". R. M. Bass, Dowty Rotol Limited, Cheltenham Road, Gloucester, England, SAE 830750, Business Aircraft Meeting and Exposition, Wichita, Kansas, April 12-15, 1983

1194. (1) "Results from Performance and Noise Tests of Model Scale Propellers". Patricia J. W. Block and Ruth M. Martin, NASA Langley Research Center, Hampton, Virginia, SAE 830730, Business Aircraft Meeting and Exposition, Wichita, Kansas, April 12-15, 1983
1195. (13) "Environmental Influences on Testing Composite Propeller Blades". W. J. Colclough, Dowty Rotol Limited, Cheltenham Road, Gloucester, England, SAE 830752, Business Aircraft Meeting and Exposition, Wichita, Kansas, April 12-15, 1983
1196. (145) "Performance Evaluation of Full-Scale Propellers by Wind Tunnel Test". AGARD Fluid Dynamics Symposium Proceedings No.366, Paper 4, Toronto, Canada, October 1-4, 1984
1197. (144) "Aerodynamics and Acoustics of Propellers". AGARD Fluid Dynamics Symposium Proceedings No.366, Paper 5, Toronto, Canada, October 1-4, 1984
1198. (194) "Manufacture of Composite Propeller Blades for Commuter Aircraft". R. McCarthy, Dowty Rotol Limited, Cheltenham Road, Gloucester, England, General Aviation Aircraft Meeting and Exposition, Wichita, Kansas, April 16-19, 1985
1199. (195) "Noise Constraints Effecting Optimal Propeller Designs". Christopher J. Miller, NASA Lewis Research Center, Cleveland, Ohio, John P. Sullivan, Purdue University, West Lafayette, IN, General Aviation Aircraft Meeting and Exposition, Wichita, Kansas, April 16-19, 1985
1200. (198) "The Analysis of Counter-Rotating Propeller Systems". Daniel J. Lesieutre and John P. Sullivan, Purdue University, General Aviation Aircraft Meeting and Exposition, Wichita, Kansas, April 16-19, 1985
1201. (82) "Are propellers coming back - and when?". Bill Sweetman, Nick Cook and Pierre Condom, Interavia No.6, pp.615-620, June 18, 1985
1202. (108) "A Review of Some Recent U.K. Propeller Developements". R. M. Bass and D. G. M. Davis, Dowty Rotol Limited, Cheltenham Road, Gloucester, England, AIAA/SAE/ASME/ASEE 21st. Joint Propulsion Conference, Monterey, California, July 8-10, 1985

Also references : 197 259

3.7.2 Aerofoil

- 1203. (24) "Airfoil Section Characteristics as Affected by Variations of the Reynolds Number". E. N. Jacobs and A. Sherman, NACA Report 586, 1937
- 1204. (179) "A New Series of Airfoil Sections Suitable for Aircraft Propellers". J. Bocci, Aeronautical Quarterly, pp.59-73, February 1977
- 1205. (32) "An Extension to the Method of Garabedian and Korn for the Calculation of Transonic Flow Past an Aerofoil to Include the Effects of a Boundary Layer and Wake". M. R. Collyer, RAE TR 77104, 1977
- 1206. (216) "Fortran Programs for Calculating the Incompressible Potential Flow About a Single Element Airfoil Using Conformal Mapping". C. J. Woan, Aeronautical and Astronautical Research Laboratory, The Ohio State University, TR AARL 80 02, January 1980

3.8 Research Programmes, Previous Bibliographies And Conferences

1207. (202) "Recent Flight Research on Ice Prevention". Lewis A. Rodert, Lawrence A. Clousing and William H. McAvoy, NACA ARR, January 1942
1208. (413) "Survey of Aircraft Anti-Icing Equipment". H. C. Chandler Jr., NACA ARC Report No.5826 Tl.64 (Survey), February 1942
1209. (647) "The Airplane Icing Problems and its Alleviation Through Research". A. R. Jones, Automotive and Aviation Industry, January 15, 1946
1210. (804) "Icing Research with RY3 Aircraft JT 973 Icing Season 1945 - 1946". C. D. Brown, LT Laboratory Note 7 46, National Research Council of Canada, Ottawa, Canada, June 1946
1211. (482) "Basic Icing Research by General Electric Company Fiscal Year 1946". R. D. Bowers ed., Report 5539, Air Material Command, AAF. Contract W-33-038-ac-9151, January 24, 1947
1212. (1115) "NACA Conference on Aircraft Ice Prevention". NACA TIB 1216, June 1947
1213. (140) "Bibliography on Ice Formation and De-Icing". (109 References), Part 1, R.T.P.3 Bibliography No.28, 1930-1941, 1948
1214. (334) "Canadian Research in the Field of Helicopter Icing". J. R. Stallabrass. Journal of the Helicopter Association of Gt. Britain, Vol.12, No.4, pp.169-196, August 1958
1215. (1001) "Aircraft Ice Protection Conference". 1959
1216. (1007) "Aircraft Ice Protection Conference 1960". D. Napier and Son Limited, Luton Division, The Airport, Luton, Bedfordshire, UK, 1960
1217. (807) "A Resume of Simulation Techniques and Icing Activities at the Engine Laboratory of the National Research Council (Canada)". M. S. Chappell, National Research Council of Canada, Aeronautical Report No.NRCC LR 305, May 1961
1218. (1006) "Aircraft Ice Protection Conference 1961". D. Napier and Son Limited, Luton Division, The Airport, Luton, Bedfordshire, UK, 1961
1219. (1005) "Aircraft Ice Protection Conference 1962". D. Napier and Son Limited, Luton Division, The Airport, Luton, Bedfordshire, UK, 1962

1220. (43) "Engineering Summary of Airframe Icing Technical Data". D. T. Bowden, A. E. Gensemer and C. A. Skeen, FAA ADS 4, December 1963
1221. (1049) "Report of the De-Icing Commision in Canada". In-Flight Test Department, Sud-Aviation, March 24, 1966
1222. (1004) "Aircraft Ice Protection". Report of Symposium, FAA Engineering and Manufacturing Division Flight Standards Service, Washington D.C., April 28-30, 1969
1223. (925) "Annual Report 1970", McGill University, MacDonald Physics Laboratory, Montreal, Canada, 1970
1224. (974) "Proceedings of the Helicopter Icing Symposium". Aircraft and Armament Experimental Establishment, Boscombe Down, October 1971
1225. (893) "All Weather Helicopter". K. T. McKenzie, Westland Helicopters Limited, Yeovil, Somerset, UK, International Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
1226. (887) "Helicopter Icing". K. M. McKenzie and L. S. McDonald, Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
1227. (1008) "General Review of Helicopter Icing". J. R. Stallabrass, National Research Council of Canada, Presented at the International Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
1228. (889) "Draft Air Regulations Concerning Conformity to the Technical Clauses of the Icing Clearance of the ...". H. Bouilloud, Service Technique Aeronautique, France, International Helicopter Icing Conference, Ottawa, Canada, May 23-26, 1972
1229. (888) "Notes on the International Helicopter Icing Conference". Ottawa, Canada, May 23-26, 1972, Royal Aircraft Establishment, Farnborough, Hampshire, UK, J. D. Booker
1230. (1003) "Minutes of the AVSCOM Helicopter IFR Conference". U.S. Army Aviation Systems Command, January 30-31, 1973
1231. (909) "Overview of USAAMRDL Helicopter Ice Protection Research and Development". R. I. Adams, Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, Presented at Staying Power Symposium, Fort Rucker, Alaska, July 8-10, 1975
1232. (911) "Summary of Findings and Recommendations - Anti-Ice/De-Ice Session of Staying Power Symposium". J. Kishi, Army Aviation Test Board, Fort Rucker, Alaska, Presented at Staying Power Symposium, July 8-10, 1975

1233. (923) "United States Army Aviation Centre", Staying Power Symposium", Army Aviation Centre, Fort Rucker, Alaska, July 1975
1234. (922) "Memorandum of Work in Progress: De-Iced Puma Subject: De-Iced Puma 04 - Test Methods". Centre D'Essais en Vol, Note de Travail Puma Degivre, September 1976
1235. (152) "Aircraft Icing". NATO AGARD Fluid Dynamics Panel. Paper No. 127, Government Conference Center, Ottawa, Canada, September 30, 1977
1236. (110) "Icing Testing for Aircraft Engines". North Atlantic Treaty Organisation, Advisory Group for Aerospace Research and Development, Conference Proceedings, AGARD-CR-236, April 3-4, 1978
1237. (607) S. F. Ackley, G. E. Lemieux, K. Itagaki and J. O'Keefe, Symposium on Snow and Ice Control Research, Hanover, New Hampshire, May 15-19, 1978
1238. (1017) "Symposium on Helicopter Icing". Held at the Royal Aircraft Establishment, NATO Army Armaments Group Panel X (Inter Service Group) on Air Vehicles for Tactical Air Mobility, Helicopter Icing Sub-Group, November 6-7, 1978
1239. (214) "Techniques and Facilities Used at the Onera Modane Centre for Icing Tests". C. Armand, F. Charpin, G. Fasso and G. Leclere, NATO AGARD-AR-127, pp.A6-1 to A6-23, November 1978
1240. (594) "Icing Test Facilities and Test Techniques in Europe". M. Pierre and X. Vaucheret, AGARD AR 127, 1978
1241. (1002) "Royal Air Force Icing Programme - Blade De-Icing System Preliminary Requirements". J. T. Rubis, Boeing Vertol Company, Philadelphia, Pennsylvania, October 30, 1979
1242. (999) "Helicopter Rotor Ice Accretion and Protection Research". J. T. Cansdale, Royal Aircraft Establishment, Farnborough, Hampshire, UK, Technical Memo EP645, October 1980
1243. (142) "Rotorcraft Icing Research Requirements". A. A. Peterson, L. Dadone, D. Bevan and W. Olsen, 37th Annual Forum of the American Helicopter Society, May 1981
1244. (7) "NASA Lewis Research Center Icing Research Program". Peggy L. Evanich, NASA Lewis Research Center, NASA Marshall Space Flight Center, Proceedings of the 5th Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems, No.82-21148, pp.64-75, December 1981

1245. (933) "Rotorcraft Icing - Status and Prospects". AGARD-AR-166, NATO, August 1981
1246. (165) "Commercial Aviation Icing Research Requirements". L. P. Koegeboehn, NASA CR 165336, 1981
1247. (55) "Selected Bibliography of NACA-NASA Aircraft Icing Publications". J. J. Reinmann, NASA TM 81651, 1981
1248. (157) "Aircraft Icing Research at NASA". R. J. Shaw, J. J. Reinmann and W. A. Olsen, NASA TM 82919, June 1982
1249. (329) "Photogrammetric Development and Application at AEDC". Richard L. Palko and Patrick L. Cassady, Calspan Field Services Incorporated, AEDC Division, Arnold Air Force Station, Tennessee. AIAA 12th Aerodynamic Testing Conference, AIAA-82-0610, Williamsburg, Virginia, March 21-24, 1983
1250. (123) "NASA Lewis Research Center's Program on Icing Research". J. J. Reinmann, R. J. Shaw and W. A. Olsen, NASA Lewis Research Center, NASA TM 83031, 1983
1251. (443) "Review of Recent Research on Interior Noise of Propeller Aircraft". John S. Mixon and Clemans A. Powell, NASA Langley Research Center, Hampton, Virginia, AIAA-84-2349 AIAA/NASA 9th Aeronautics Conference, Williamsburg, Virginia, October 15-17, 1984
1252. (1138) "Overview of FAA's Aircraft Icing Program". Loni Czekalski, NASA, Marshall Space Flight Center, 7th Annual Workshop on Meteorology and the Environment, Inputs to Aviation Systems, pp.26-29, April 1984
1253. (1139) "The NASA Altitude Wind Tunnel (AWT): Its Role in Advanced Icing Research and Development". Bernard J. Blaha and Robert J. Shaw, Presented at the 23rd Aerospace Sciences Meeting, Reno, Nevada, Sponsored by AIAA, January 14-17, 1985
1254. (593) "Overview on Icing Research at ONERA". D. Guffond, J. Cassaing and L. Brunet, AIAA-85-0335. AIAA 23rd Aerospace Sciences Meeting, January 1985
1255. (1161) "FAA's Engineering and Development Aircraft Icing Program". L. Czekalski, FAA Technical Center, Atlantic City, New Jersey, AIAA-85-0015, 1985
1256. (1167) "A Summary of NASA's Research on the Fluid Ice Protection System". A. E. Albright, General Dynamics Corporation, Fort Worth, Texas, AIAA-85-0467, 1985

1257. (1146) "The UH-1H Helicopter Icing Flight Test Program: An Overview". R. J. Shaw and G. P. Richter, NASA Lewis Research Center, Cleveland, Ohio, AIAA-85-0338
1258. (1177) "NASA's Aircraft Icing Analysis Program". R. J. Shaw, NASA Lewis Research Center, Cleveland, Ohio, NASA-TM-88791, International Conference of the Aeronautical Sciences, London, September 7-12, 1986
1259. (1029) "Rotorcraft Icing, Progress and Potential". AGARD-AR-223, September 1986
1260. (109) "Rotorcraft Icing Status and Prospects". North Atlantic Treaty Organisation, Advisory Group for Aerospace Research and Development, AGARD-AR-166, Flight Mechanics Panel
1261. (818) "Icing Flight Development". B. T. Cheverton Royal Aeronautical Society Preprint
1262. (1000) "5th International Aircraft Ice Protection Conference". Sponsored by the Engineering and Heating Systems Division of Lucas Aerospace Limited, Luton, Bedfordshire, UK
1263. (1302) "NASA's Rotorcraft Icing Research Program". Robert J. Shaw, John J. Reinmann and Thomas L. Miller, NASA Lewis Research Center, Cleveland, Ohio
1264. (1031) "Forty Years of Helicopter Ice Protection Experience at Sikorsky Aircraft". K. M. Rosen and M. L. Potash

Also references : 160 180 213 374 416 782 783 784
789 796 799 891

3.9 Computational Fluid Dynamic Icing

3.9.1 Two-Dimensional Particle Trajectory*9.1

1265. (85) "A Method of Constructing the Paths of Raindrops of Different Diameters Moving in the Neighbourhood of (1) a Circular Cylinder, (2) An Aerofoil, Placed in a Uniform Stream of Air; and a Determination of the Rate of Deposit of the Drops on the Surface and the Percentage of Drops Caught". Muriel Glauert, NACA RM 2025, A.R.C. Technical Report, November 10, 1940
1266. (1098) "Prediction of the Rate of Formation of Ice, and the Rate of Heating Necessary to Prevent Ice". J. K. Hardy and G. Mann, Royal Aircraft Establishment, Farnborough, Hampshire, RAE TN Aero.1010 (Misc), August 1942
1267. (1106) "Rate of Catch of Supercooled Water on Aerofoils and Cylinders in Flight Under Conditions of Icing". J. K. Hardy et al., Royal Aircraft Establishment, Farnborough, RAE SME TN 207, January 1944
1268. (1334) "A Mathematical Investigation of Water Droplet Trajectories". I. Langmuir and K. Blodgett, A.A.F. Technical report 5417, February 1946
1269. (30) "A Mathematical Investigation of Water Droplet Trajectories". Irving Langmuir and Katherine B. Blodgett, U.S. Army Air Forces Technical Report 5418, (Contract No.W-33-038-ac-9151), General Electric Company, 1946
1270. (519) "Icing Report by the University of California, Fiscal Year 1946". R. D. Bowers, AAF Technical Report 5529, November 1946
1271. (79) "A Method for Numerically Calculating the Area and Distribution of Water Impingement on the Leading Edge of an Airfoil in a Cloud". Norman R. Bergrun, NACA TN 1397, 1947
1272. (203) "Determination of Rate, Area, and Distribution of Impingement of Waterdrops on Various Airfoils from Trajectories Obtained on the Differential Analyzer". A. G. Guibert, E. Janssen, and W. M. Robbins, University of California, NACA RM 9A05, 1950
1273. (359) P. E. Berghausen, R. J. Good, F. Kraus, B. Podolsky and W. Soller, Applied Science Research Laboratory, Progress Reports, Army Air Force Contract AF33(616)-231, University of Cincinnati, 1950-55

1274. (222) "An Empirical Method Permitting Rapid Determination of The Area, Rate, and Distribution of Water-Drop Impingement on an Airfoil of arbitrary Section at Subsonic Speeds". Norman R. Bergrun, NACA TN 2476, 1951
1275. (362) H. P. Messner and G. H. Baldauf, Transport America Society Mechanical Engineers, Vol.697, 1951
1276. (498) "Comments on Methods of Calculating Water Catch and a Correlation of Some New Data". H. Drell and P. J. Valentine, Report 8552, Lockheed Aircraft Corporation, April 16, 1952
1277. (497) "Determination of Drop Trajectories by Means of an Extension of Stoke's Law". P. Sherman, J. S. Klein and M. Tribus, Engineering Research Institute, (Air Research and Development Command, USAF, Contract AF 18(600)-51, Project M992-D), University of Michigan, Michigan, April 1952
1278. (773) "Impingement of Spherical Water Droplets on a Wedge at Supersonic Speeds in Air". Tribus and Guibert, Journal of Aeronautical Sciences, June 1952
1279. (501) "Preliminary Report on the Computation of Water Drop Trajectories About a 6 Percent Airfoil". F. E. Lenherr and J. E. Thomson, TDM 67, Northrop Aircraft Incorporated, August 14, 1952
1280. (1112) "Analytical Investigation of Icing Limit for Diamond Shaped Airfoil in Transonic and Supersonic Flow". E. E. Callaghan and J. S. Serafini, NACA TN 2861, January 1953
1281. (1105) "A Method for Rapid Determination of the Icing Limit of a Body in Terms of the Stream Conditions". E. E. Callaghan and J. S. Serafini, NACA TN 2914, March 1953
1282. (877) "Calculations of the Catch of Water by a Jet Engine During High-Speed Flight in Cloud". D. A. J. Miller, NAE LR 78, June 1953
1283. (499) "A Modified Method of Determining the Rate of Ice Accretion of an Airfoil in an Icing Condition". Herman Schwartz, Technical Note WCT 54-106, Directorate of Flight and All-Weather Testing, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, October 1954
1284. (828) "A Theoretical Analysis of the Icing Limit for a NACA 0004 Airfoil". Richard R. Perez and Thomas R. Shafer, WADC TN 57-106, AD 118263, Wright Air Development Center, Air Research and Development, U.S.A.F., Wright-Patterson Air Force Base, Ohio, April 1957

1285. (1101) "The Motion of a Wire Through Ice". J. W. Telford and J. S. Turner, CSIRO Radiophysics Laboratory, Sydney, Australia, December 28, 1962
1286. (226) "A Method for Determining Cloud-Droplet Impingement on Swept Wings". Robert G. Dorsch and Rinaldo J. Brun, NACA TN 2931, 1953
1287. (1039) "Determination of Capture Probabilities of Precipitation Particles with the Strobolume". Roland List, November 1963
1288. (1316) "A User's Guide to a Program for Computing Viscous Transonic Flows Past Aerofoils (Garabedian and Korn Method)". M. R. Collyer, Royal Aircraft Establishment, Farnborough, Hampshire, September, 1976
1289. (210) "Trajectory Scaling Laws for a Particle Injected into the Wake of an Aircraft". Allen I. Ormsbee and Michael B. Bragg, Aviation Research Laboratory, University of Illinois, Report ARL-1, June 1978
1290. (1314) "Improvements to the Viscous Garabedian and Korn (VGK) Method for Calculating Transonic Flow Past an Aerofoil". M. R. Collyer and R. C. Lock, Royal Aircraft Establishment, Farnborough, Hampshire, Technical Report 78039, August 1978
1291. (171) "Computer Modeling of Atmospheric Ice Accretion". S. F. Ackley and M. K. Templeton, CRREL 79 4, Army Cold Regions Research and Engineering Laboratory, 1979
1292. (31) "Helicopter Rotor Blade Icing: A Numerical Simulation". M. M. Oleskiw and E. P. Lozowski, 3rd. WMO Scientific Conference on Weather Modification, Clermont-Ferrand, July 1980
1293. (27) "An Analytical Approach to Airfoil Icing". M. B. Bragg, G. M. Gregorek and R. J. Shaw, AIAA-81-0403, NASA Lewis Research Center, Cleveland, Ohio. AIAA 19th Aerospace Sciences Meeting, January 1981
1294. (57) "Mathematical Modelling of Ice Accretion on Airfoils". Charles D. MacArthur, John L. Keller and James K. Luers, University of Dayton Research Institute, Dayton, Ohio, AIAA-82-0284, AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, January 11-14, 1982
1295. (270) "Particle Trajectory Computer Program for Icing Analysis". W. Frost, H. P. Chang and K. R. Kimble, NASA Lewis Research Center Final Report Contract NAS3 22448 by FWG Associates Incorporated, April 1982

1296. (1182) "'Scaling' Analysis of the Ice Accretion Process on Aircraft Surfaces". E. G. Keshock, A. H. Tabrizi and J. R. Missimer, Tennessee University, Knoxville, Tennessee, ASME Paper 82-WA/HT-39, American Society of Mechanical Engineers, Winter Annual Meeting, Phoenix, Arizona, November 14-19, 1982
1297. (128) "A Similarity Analysis of the Droplet Trajectory Equation". Michael B. Bragg, The Ohio State University, Columbus, Ohio. AIAA Journal Vol.20, No.12, pp.1681-1686, December 1982
1298. (98) "Ice Accretion on Airfoils in Two-Dimensional Compressible Flow - A Theoretical Model". T. Cansdale and R. Gent, RAE TR 82128, January 1983
1299. (107) "An Analytical Evaluation of the Icing Properties of Several Low and Medium Speed Airfoils". M. B. Bragg and G. M. Gregorek, The Ohio State University, Columbus, Ohio, AIAA-83-0109, AIAA 21st. Aerospace Sciences Meeting, Reno, Nevada, January 10-13, 1983
1300. (448) "A Steady-State Thermal Model for Analysis of Incipient Icing on an Airfoil Leading Edge". J. L. Fergus Jr., Sverdrup Technology Incorporated, July 1983
1301. (99) "Calculation of Water Droplet Trajectories About an Aerofoil in Steady Two-Dimensional, Compressible Flow". R. Gent, RAE TR 84060, June 1984
1302. (1315) "Aircraft Flow Effects on Cloud Droplet Images and Concentrations". A. M. Drummond, National Aeronautical Establishment, NRC, Ottawa, Canada, June 1984
1303. (2) "Droplet Impingement Analysis of Two Propeller Spinners". M. B. Bragg, The Ohio State University, Columbus, Ohio, AARL TR 8403, August 1984
1304. (1103) "Rotor Icing Research at RAE Farnborough". R. W. Gent, Royal Aircraft Establishment, Farnborough, Hampshire, 1985
1305. (1178) "An Efficient Numerical Computation Scheme for Stiff Equations of Droplet Trajectories". J. J. Kim and R. Elangovan, Boeing Military Airplane Company, Wichita, Kansas, AIAA Paper 86-0407, AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986
1306. (193) "Predicting Rime Ice Accretion on Airfoils". Michael B. Bragg, The Ohio State University, Columbus, Ohio. AIAA Journal, Vol.23, No.3, pp.381-387, March 1985

1307. (Experimental Ice Shapes for Validation of a Theoretical Ice Accretion Prediction Program". R. W. Gent and A. R. Beauchamp, Royal Aircraft Establishment, Farnborough, Hampshire, Report TR86025, May 1986
1308. (56) "Navier Stokes Solution of the Flowfield Over Ice Accretion Shapes". J. N. Scott, W. L. Hankey, W. L. Giessler and T. P. Gielda, Dayton University, Ohio, AIAA Paper 87-0099, 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987
1309. (1011) "A Mathematical Investigation of Water Droplet Trajectories". Army Air, Air Material, Wright Field, AAF Technical Report 5418
1310. (17) "The Development of Mathematical Modelling Techniques for Helicopter Rotor Icing". R. W. Gent and J. T. Cansdale, RAE TM MAT/STR 1054, Procurement Executive, Ministry of Defence, Farnborough, Hampshire, March 1985, Also AIAA-85-0336
1311. (1313) "Experimental Water Droplet Impingement Data on Two-Dimensional Aerofoils, Axisymmetric Inlet and Boeing 737-300 Engine Inlet". M. Papadakis et al., AIAA-87-0097, AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987
1312. (930) "An Empirically Derived Basis for Calculating the Area, Rate, and Distribution of Water-Drop Impingement on Airfoils". Norman R. Bergrun, Report 1107
1313. (1145) "Correlation of Airfoil Icing Relationships with Two-Dimensional Model and Full Scale Rotorcraft Icing Test Data". R. J. Flemming and D. A. Lednicer, United Technologies Corporation, Stratford, Connecticut, AIAA-85-0337
1314. (1183) "The Determination of Ice Deposition on Slender Wings, An Experimental Technique and Simplified Theory". J. W. Flower, Bristol University, Bristol, NASA IAA Conference Paper Issue 21

Also references : 112,211,854,1145 1152

3.9.1.1 Three-Dimensional Particle Trajectory

1315. (1157) "Calculation of Water Drop Trajectories to and About Arbitrary Three-Dimensional Bodies in Potential Airflow. Final Report". Hillyer G. Norment, Atmospheric Science Associates, Bedford, Massachusetts, NASA Washington, NAS3-22199, August 1980

1316. (93) "Three Dimensional Partical Trajectory Calculation". Hillyer G. Norment, NASA Lewis Research Center, The Second Icing Analysis, February 8, 1983
1317. (1164) "Computational Particle Trajectory Analysis, on a Three-Dimensional Engine Inlet". J. J. Kim, Boeing Military Airplane Company, Wichita, Kansas, AIAA-85-0411, 1985
1318. (1165) "Three-Dimensional Airflow and Hydrometeor Trajectory Calculation with Applications". H. G. Norment, Atmospheric Science Associates, Bedford, Massachusetts, AIAA-85-0412, 23rd Meeting of the Aerospace Sciences, Reno, Nevada, January 14-17, 1985
1319. (1040) "Numerical Simulation of an Aircraft Icing". D. Takahashi and K. Kuwahara, National Aerospace Laboratory, Tokyo, Japan, Proceedings of the Third NAL Symposium on Aircraft Computational Aerodynamics, pp.1-6
1320. (1153) "Calculation of Water Drop Trajectories to and About Arbitrary Three-Dimensional Lifting and Non-Lifting Bodies in Potential Airflow / Final Report". H. G. Norment, Atmospheric Science Associates, Bedford, Massachusetts, NASA-CR-3935
1321. (1179) "Particle Trajectory Calculation on a Three-Dimensional Engine Inlet / Final Report". J. J. Kim, Wichita State University, Kansas, NASA-CR-175023

3.9.2 Heat Transfer

1322. (1328) "The Effects of Surface Roughness on the Heat Transfer from a Circular Cylinder to the Crossflow of Air". E. Achenbach, International Journal of Heat and Mass Transfer, Vol.20, pp.359-369, 1977
1323. (1299) "Aircraft De-Icing Performance Analysis by an Adapted Temperature Field Analyser Program". U. G. Hingst, Dornier System GmbH, Friedrichshafen, West Germany, SAE Paper 831141, AIAA, SAE, ASME, AIChE, and ASMA, 13th Intersociety Conference on Environmental Systems, San Francisco, California, July 11-13, 1983
1324. (1329) "Heat Transfer Distributions Around Nominal Ice Accretion Shapes Formed on a Cylinder in the NASA Lewis Icing Research Tunnel". G. J. V. Fossen, R. J. Simoneous et al, Paper AIAA-84-0017, Presented at the 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984

Also References : 18 167 408 439 521 524 544 696
767 853 935 1111 1145 1152 1168
1319 1328 1329 1330

3.9.3 Two-Dimensional Ice Accretion

1325. (1186) "Computer Modelling of Time-Dependent Rime Icing in the Atmosphere". Edward P. Lozowski and Myron M. Oleskiw, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, CRREL-83-2, January 1983
1326. (1327) "Ice Accretion on Aerofoils in Two-Dimensional Compressible Flow - A Theoretical Model". J. T. Cansdale and R. W. Gent, Royal Aircraft Establishment, Farnborough, Hampshire, RAE Technical Report 82128, 1983
1327. (1152) "Potential Flow Analysis of Glaze Ice Accretions on an Airfoil. Final Report". Ronald J. Zaguli, Department of Aeronautical and Astronautical Engineering, Ohio State University, Columbus, Ohio, NASA-CR-168282, January 1984
1328. (1308) "Particle Trajectory Computation on a Three-Dimensional Engine Inlet". John J. Kim, Wichita State University, Wichita, Kansas, Prepared for NASA Lewis Research Center, January 1986
1329. (1318) "Computation of Rime Ice Accretion on Airfoils". Staffan Meijer, Aeronautical Research Institute of Sweden, Stockholm, Aerodynamics Department, FFA-TU-1987-08, Sponsored by National Swedish Board for Technical Development, May, 1987
1330. (1181) "Numerical Simulation of Airfoil Ice Accretion". C. D. Macarthur, Dayton University, Dayton, Ohio

3.9.3.1 Three-Dimensional Ice Accretion

1331. (1160) "Spray Impaction, Retention and Adhesion: An Introduction to Basic Characteristics". J. J. Spillman, College of Aeronautics, Cranfield Institute of Technology, Cranfield, Bedford, England, Report No.8215, November 1982
1332. (1184) "User Guide to a Particle Growth and Trajectory Model (Using One-Dimensional and Three-Dimensional Wind Fields)". J. L. Parrish and A. J. Heymsfield, National Center for Atmospheric Research, Boulder, Colorado, NCAR/TN-259+IA, October 1985

3.9.4 General

1333. (409) "A Numerical Analysis of Frost Formation Under Forced Convection". H. C. Parish, CVI Corp, and C. F. Sepsy, Department of Mechanical Engineering, Ohio State University, Columbus, Ohio, ASHRAE 2231 Presented at ASHRAE Semi-Annual Meeting, New Orleans, Louisiana, January 23-27, 1972
1334. (410) "Equation of the Growth Rate of Frost Forming on Cooled Surfaces". H. W. Schneider. International Journal of Heat and Mass Transfer, Vol.21, pp.1019-1024, 1978
1335. (324) "A Frost Formation Model and Its Validation Under Various Experimental Conditions". Mark A. Dietenberger, University of Dayton, Dayton, Ohio, NASA Contractor Report 3595, Contract NAS8-33369, 1982
1336. (105) "A Model for Nocturnal Frost Formation on a Wing Section". Mark A. Dietenberger, University of Dayton Research Institute, Dayton, Ohio, NASA Contractor Report 3733, Contract NAS8-33369, 1983
1337. (1170) "Experimental Evaluation of Existing Icing Scaling Laws". W. A. Olsen Jr. and J. E. Newton, NASA Lewis Research Center, Cleveland, Ohio, AIAA-85-0470, 1985
1338. (1171) "Towards Modelling Thermochemical Ice Penetration". F. E. Fendell, TRW Space and Technology Group, Redondo Beach, California, and W. B. Bush, King, Buck and Associates, San Diego, California, AIAA-85-0455, 1985

4 APPENDIX

Appendix

5 ACRONYMS AND ABBREVIATIONS

A&AEE	Aeroplane and Armament Experimental Establishment, Boscombe Down, England
AAF	Army Air Force
AARL	Aeronautical and Astronautical Research Laboratory
AASL	Army Atmospheric Sciences
ACS	American Chemical Society
AEC	Atomic Energy Commission
AEL	Aeronautical Engineering Laboratory
AFB	Air Force Base
AFDL	Air Force Flight Dynamics Laboratory
AFGL	Air Force Geographical Laboratory
AGARD	Advisory Group for Aerospace research and Development
AH	Advanced Helicopter
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
AMS	American Meteorological Society
ARC	Aeronautical Research Center
ARDC	Air Research and Development Command
ARL	Aviation Research Laboratory
ARR	Aeronautical Research Report
ASEE	American Society for Engineering Education
ASME	American Society of Mechanical Engineers
ASRE	American Society of Refrigeration Engineers
ATC	Air traffic Control
BAC	British Aircraft Corporation
BAe	British Aerospace
BHTI	Bell Helicopter Textron Incorporated
BTR	British Tyres and Rubber
CAA	Civil Aviation Authority
CIT	Cranfield Institute of Technology
Co	Company
CoA	College of Aeronautics
Corp	Corporation
CRREL	Cold Regions Research and Engineering Laboratory
CSIRO	Commonwealth Scientific and Industrial Research
CSME	Canadian Society of Mechanical Engineers
C-46	Canadair 46
D.C.	District Capital
Dept	department
Dev	Development
DOT	Department of Transport
DR	Dowty Rotol Limited
DRMAT	Dowty Rotol Materials Laboratory
EH	European Helicopter
Eng	Engineering
Est	Establishment
FAA	Federal Aviation Authority
FAR	Federal Air Requirements
GE	General Electric
IAS	Institute of Aerospace Sciences

ICAS	International Council of the Aeronautical Sciences
IGV	Inlet guide vane
Inc	Incorporated
Ind	Industries
Inst	Institute
IRB	International Research Bureau
ISA	International Standard Atmosphere
Jr	Junior
Lab	Laboratory
l.e.	leading edge
LR	Laboratory Report
Ltd	Limited
LWC	Liquid Water Content
M.I.T.	Massachusetts Institute of Technology
Mk	Mark
MoD	Ministry of Defense
MVD	Median Volume Diameter
NACA	National Advisory Committee for Aeronautics
NAE	National Aeronautical Establishment
NAEC	National Aeronautical Establishment of Canada
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NGTE	National Gas Turbine Establishment
No	Number
NPL	National Physical Laboratory
NRC	National Research Council (Canada)
NRL	Naval Research Laboratory
OAT	Outside Air Temperature
pp	page
Pt	Part
RAA	Ross Aviation Associates
RAE	Royal Aircraft Establishment (Farnborough)
RAeS	Royal Aeronautical Society
RB	Research Bulletin
R&D	Research and Development
Ref	Reference
Res	Research
RM	Reports and Memorandum
RMR	Research Memorandum Report
RR	Rolls Royce
SAE	Society of Automotive Engineers
Sch	School
Sci	Science
SERC	Science and Engineering Research Council
SIPRE	Snow Ice and Permafrost Research Establishment
SME	Society of Manufacturing Engineers
SST	Supersonic Transport
Std	Standard
Tech	Technical
Temp	Temperature
TM	Technical Memorandum
TP	Test Proposal

TR	Technical Report
TN	Technical Note
UDF	Unducted Fan
UK	United Kingdom
UNO	United Nations Organisation
US	United States (of America)
USA	United States of America
USSR	United States Soviet Republic
UV	Ultra violet
vel	velocity
WADC	Wright Air Development Center
WHL	Westland Helicopters Limited
WMO	World Meteorological Organisation
WR	War-time Report
WR-A	War-time Report - Aeronautical
2-D	Two-Dimensional
3-D	Three-Dimensional

5.1 AUTHOR INDEX

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 Balcer, Ryszard 6(1076)
 Baldauf, G. H. 3.2.3(362)
 Baliga, G. 4.4.1(167)
 Ballard, O. R. 6(779)
 Banks, Bruce A. 4.13(1148)
 Barber, D. J. 7.1(3)
 Barchet, Richard 6(1075)
 Barnes, P. 1.2.5.2(460)
 Barnes, William Howard 1.9(562)

Barrett, E. W.	5.1.2(1339), 5.1.3(365)
Barsotti, M. F.	3.2.3(1131)
Bartlett, P. M.	2.5(493), (846), 2.6(800), 4.4.2(766)
Bascom, W. D.	1.4(319)
Bass, R. M.	3.1(196)
Bassett, D. C.	4.8(119)
Bastow, S. H.	1.12(356)
Battersby, M. G.	2.6(1102)
Baumgardner, Darrel	5.1.3(576), 5.1.4(124), (129), (346)
Baxter, D. C.	5.1.4(486), 5.1.5(381)
Beard	4.4.6(712), (714)
Bell, J. E.	4.4.2(702)
Belte, D.	2.6(1087), 3.3.2(1147)
Benguier, J. L.	5.1.3(350)
Benson, G. W.	4.6(837)
Berger, J.	3.3.4(326)
Berghausen, P. E.	3.2.3(359), (360)
Bergrun, Norman R.	4.4.4(435), (1110), 9.1(930), (79), (222)
Bernhart, W. D.	4.8(47)
Best, A. C.	6(813)
Bevan, D.	8(142)
Bezos, G. M.	3.2.3(1129)
Biehl, Keith	3.5(1155)
Bigg, E. K.	1.6(537)
Bigg, F. J.	2.3.2(827), 5.1.4(479), 5.1.6(797), (798), (799)
Biguria	1.1(400)
Bilman, A. J.	3.2.3(1128)
Blackman, Calvin C.	3.4(88)
Blade, R. J.	2.11(863)
Blaha, Bernard J.	4.5(166), 7.1(33), (118), 8(1139)
Blatz, Robert E.	4.2.2(963), 4.13.4(717)
Blayle	6(658)
Bleeker, W.	2.7(76)
Block, Patricia J. W.	7.1(1), (22)
Blodgett, Katherine B.	9.1(30), (1334)
Bober, L. J.	7.1(116)
Bocci, A. J.	7.2(179)
Boeke, F. L.	4.4.4(15)
Boelter, L. M. K.	2.7(276), 2.10(1037), 4.4.6(768)
Boetter	2.7(697)
Bonis, K.	6(1064)
Booker, J. D.	8(888)
Bouilloud, H.	8(889)
Bowden, Dean T.	3.1.3(69), 4.2.4(225), 4.4.5(853), 8(43)
Bowden, I. P.	1.12(356), 4.1.3.2(236)
Bowers, R. D.	3.2.3(79), 8(482)
Bowler, E. H.	4.13.4(149), (793)
Boyd, Bemrose	1.9(451)
Bradley, J.	4.2.3(904), 4.12(912)

Bradley, S.	5.1.3(363)
Bragg, Michael B.	2.3.2(25), (101), (112), 2.4(94), 2.10(213), 3.2(86), (92), (576), (1086), 3.2.1(28), (104), (215), 3.2.2(87), 148), (259) 3.4(62), 9.1(2), (27), (107), (128), (193), (210)
Bragg, W. H.	1.9(563)
Braham, R. R. Jr.	5.1.4(510)
Braveman, T. S.	4.5(1204)
Breer, M. D.	2.10(575)
Brewer, Larry. K.	2.3.4(971)
Brian, P. L. Thibaut	1.5(399), 2.11(404)
Brill, Rudolf	1.5(297), 1.9(615), 1.12(361)
Brock, G. W.	5.1.6(378), 6(653)
Brooks, D. B.	6(1337)
Brown, C. D.	2.4(1012), 4.1.2(981), 8(804)
Brown, E.	1.2(298)
Brown, Edward N.	5.1.4(366), (508), (511)
Brown, R. W.	4.3(1202), (1203)
Bright, Loren G.	3.1(26)
Brun	2.3(1295), (1296)
Brun, Edmond A.	2.7(74), 2.11(864)
Brun, J. J.	5.1.3(154)
Brun, Rinaldo J.	2.2(60), (61), 2.2.1(495), (496), 2.3.1 (48), (136), (137), (138), (139), (223), (1323), 5.1.4(477), (1322), 5.3(475), 9.1(226)
Brunet, L.	8(593)
Burgrun, N. R.	6(765)
Burnage, H.	5.1.4(1156)
Burpo, F.	4.13.3(387)
Bush, W. B.	5.1.8(1172)
Bryant, G. W.	1.5.1(296)
Bullard, A. F.	4.13.1(469)
Butkovich, T. R.	1.2.2(299), (525), 1.2.6(526), 1.2.7, (300), 1.5(301)

C

Callaghan, E. E.	4.4.2(1120), 9.1(1105), (1112)
Camp, Paul R.	1.5(297)
Campbell, R. G.	4.1.1(39), 4.5(1236)
Cannon, Theodore W.	5.1.4(347), 5.2(548)
Cansdale, J. T.	2.6(6), 4.2.3(156), 8(999), 9.3(1327) 9.1(17), (98)
Carroll, Thomas	2.7(249), (250)
Carte, A. E.	1.12(185)
Cassady, Patrick L.	8(329)
Cassaing, J.	8(593)
Cerni, Todd A.	5.1.4(130), 6(348)
Chalmers, B.	1.9(392)

Chamagne, G.	4.3(1208)
Chambers, H. W.	2.6(1144)
Chandler, H. C. Jr.	8(413)
Chang, H. P.	9.1(270)
Chang, K. J.	1.12(175)
Chao, David Fu-Kuo,	4.4.1(413)
Chappell, M.S.	8(707)
Charpin, F.	8(214)
Cheverton, B. T.	2.3(1041), 8(818)
Chilman, J. A.	4.2.1(1274)
Chivers, K.	5.1.6(899)
Chu, M. L.	1.2.3(597)
Cipolloni, Alfred D.	4.4.6(1092)
Clareus, U.	2.11(1294)
Clark, J. E.	2.6(238), 4.2.2(20), 5.1.6(1056)
Clarke, T.	4.4.2(703)
Clay, William C	4.1.1(417), 4.13.1(257)
Clifford, J. M.	4.13(803)
Clothier	2.11(622)
Clousing, Lawrence A.	4.1.3.1(271), (272), (273), (457), 8(202)
Cochrane, J. H. M.	2.10(885)
Coirer, W. J.	3.2(576), 3.2.2(259)
Colclough, W. J.	7.1(13)
Coles, W. D.	2.3.1(823)
Colliver, H. G.	2.5(843), 5.1.8(676)
Collyer, M. R.	7.2(32), 9.1(1314), (1316)
Condom, Pierre	7.1(82)
Cook, Nick	7.1(82)
Cooke, D. D.	5.1.3(546)
Coonly, P. E.	4.3(1268)
Cooper, William A.	3.4(87), 6(1070)
Cornell, C. C.	3.2.2(51), (81), 3.3.4(114)
Corson, Blake W. Jr.	3.1.2(219), 3.1.3(37), 4.1.1(36)
Coste, J. H.	1.7(388)
Cottingham, R. L.	1.4(319)
Cowdrey, C. L.	2.5(687)
Cowlin, C. J.	2.10(1024), 5.1.6(1344)
Crease	4.1.3.1(677)
Cremers, C. J.	9.5(403)
Cresap, W.	4.2.3(994)
Crick, R. D.	4.2.3(383)
Cross, E. J. Jr.	3.2.2(51), (81), 3.3.4(52), (114), (151)
Cunningham, R. M.	5.1.8(480)
Curtis, Ray	4.2.3(926)
Cwilong, B.	5.1.3(1338)
Czekalski Loni	8(1138), (1161)
Czyz, Jerzy	6(1076)

D

Dadone, L. U.	2.6(1015), 3.1.1(5), (220), 3.3(16), 3.3.1(261), 3.3.2(50), 3.4(263)
Dale, F. A.	5.11(778)
Dailey, G. J.	5.11(778)
Darsow, J. F.	4.1.1(38)
Davidson, R. E.	4.1.1(64)
Davidson, W. L.	1.9(565)
Davies, C. N.	2.2(500)
Davies, J. M.	4.7(1245)
Davis, D. G. M.	7.1(108)
Day, D. J.	2.5(840) 6(538), (812)
Deacon, W.	4.4.2(691), (709)
Deepak, A.	5.3(568)
de la Rue, A. M.	4.3(1279), (1283)
Delgado, Emil	6(1065)
Dennison, D. M.	1.9(561)
de Quervain, M. R.	2.2(1074)
DeWitt, Kenneth J.	4.4.1(167), 4.2.4(1093), 5.1.8(1319)
Dickey, F. M.	5.3(1162)
Dickey, Thomas A.	2.5(493), 2.12(237), 4.4.2(766)
Dietenberger, Mark A.	2.3.2(322), 2.11(1121), 3.4(89), 9.5(105), (324)
Dietz, R. O.	4.1.2(705)
Diggins, I.	4.8(936)
Dillon, Howard B.	1.2.5(302)
Dingle, A. N.	6(1067)
Diron	6(658)
Ditton Laboratory Staff	4.1.3.1(408)
Dixon, M.	5.1.5(1159)
Dobson, G. M. B.	5.1.3(1338)
Dodson, E. D.	2.10(170)
Dorsch, Robert G.	1.8(558), 1.9(451), 2.1(42), 2.2.1 (495), (496), 6(227), 2.10(1025), 2.11(1295), (1296), 9.1(226)
Dotson, J. P.	1.4.1(335)
Dotson, J. V.	4.13.1(320)
Downs, S. J.	3.5(1312)
Draney, J. J.	4.1(648)
Drell, H.	9.1(498)
Droege, W. C.	5.1.8(664), (729)
Druez, J.	1.4.1(600)
Drummond, A. M.	9.1(1315)
Ducret, A. M.	4.4.3(1207), (1209)
Dufour, L.	1.12(389)
Duncan, L. D.	5.1.3(351)
Dunford, Philip J.	4.2.3(931), 4.13.3(1091)
Dunham, Dana Morris	5.1.5(197)
Dunham, R. E. Jr.	3.2.3(1129)
Dunmore, F. W.	5.1.3(1340)

Dye, James E. 5.1.4(124), (129)
 Dyments, J. L. 5.3(711), (718)

E

Egorov, M. S. 4.4.3(379)
 Ehresman, C. M. 5.1.4(1158)
 Elangovan, R. 2.10(575), 9.1(1178)
 Eldridge, Ralph G. 5.1.4(487)
 Elliot, A. G. 2.5(668), (669), (670), (845), 4.3
 (1284)
 Elliot, H. W. 5.1.4(23)
 Ellis, D. R. 4.8(119)
 Ely, R. S. 4.3(1267)
 Engel, O. G. 2.11(512)
 Englar, K. G. 2.10(260)
 Ensink, H. J. 4.7(1210)
 Eskin, S. G. 1.4(333)
 Evanich, Peggy L. 4.5(166), 8(7)
 Exner, F. M. 6(1336)

F

Fasso, G. 8(214)
 Faure, A. 4.4.3(1207)
 Federou, N. E. 4.2.2(1028)
 Felin, B. 1.4.1(602)
 Fendell, F. E. 9.5(1171)
 Fergus J. L. Jr. 9.1(448)
 Fidlan, F. S. 4.13.4(1272)
 Finch, R. 4.2.3(931)
 Findeisen, W. 6(75), (624), (693)
 Fink, C. 4.13(1148)
 Finlayson, John N. 1.2.3(506)
 Flack, D. C. 4.2.4(969)
 Flemming 4.1.2(698)
 Flemming, Robert J. 2.6(54), (150), (1083), 9.1(1145)
 Fletcher, N. H. 1.5.1(294), 9.1(1183)
 Flower, J. W. 2.3.2(821)
 Fontaine, W. E. 1.4(333), 1.4.1(335)
 Forbes, J. D. 1.5(281)
 Ford, C. J. 4.3(1213), (1280)
 Ford, T. F. 1.2.3(290)
 Forney 6(658)
 Forrester David A. 6(1062), (1150)
 Foskett, L. W. 5.1.3(1342)
 Fossen, G. J. V. 9.2(1329)
 Foster, N. B. 5.1.3(1342)
 Fraser, Don 2.10(869), 4.2.4(870), 4.13.4(149),
 (473), 5.1.6(380), (381), (1345),
 5.2(858), (859)
 Frei, R. W. 2.10(592)

Freire, E. 2.2(1074)
 Freund, G. A. Jr. 2.10(575), 5.3(1162)
 Frick, Charles W. Jr. 4.1.3.1(521)
 Friedberg, R. A. 4.8(572)
 Friendlander, Martin 3.4(1175)
 Frischhertz 4.4.2(719), 4.13.1(723)
 Friswold, Frank A. 5.1.2(192)
 Frost, W. 9.1(270)
 Fuchs 6(623)
 Fuertes, F. A. 6(539)
 Fukuta, N. 1.9(1082)

G

Gaiser, K. 4.2.4(1277)
 Gallagher, Helen M. 2.2(60), 2.3.1(48), (137), (138),
 (1323)
 Galvin, Herman B. 2.11(456)
 Gardner, Tracey B. 2.3.1(522)
 Garner, T. L. 4.13.1(723)
 Garrod, M. P. 5.1.4(513)
 Garvey, D. M. 5.1.3(351)
 Gates, Edward M. 5.1.4(1185)
 Gattingen 5.1.1(629)
 Gaviola, E. 6(539)
 Gay, M. 6(1073)
 Gayet, J. F. 2.7(1325)
 Geer, William C. 3.4(1042), 4.13.1(255)
 Gelder, Thomas F. 2.3.1(72), (1111), 2.3.3(439),
 2.10(244), 4.13.1(868)
 Gensemer, A. E. 8(43)
 Gent, Roger W. 2.3.2(1084), 2.6(932), 4.2.3
 (156), 9.1(17), (98), (99), (1103)
 9.3(1327)
 Gentry, G. L. Jr. 3.2.3(1129)
 Georg, J. C. 2.10(340)
 Gerber, J. F. 2.10(340)
 Gerhart, P. M. 3.2(577)
 Gibbard, G. A. 4.2.3(190)
 Gibbings, David 2.6(1143)
 Gielda, T. P. 9.1(56)
 Giessler, W. L. 9.1(56)
 Gillespie, C. A. 5.1.4(516)
 Gilliland, E. R. 1.5(524)
 Gilow, E. W. 4.2.4(811)
 Glahn 4.13.4(717)
 Glauert, Muriel 9.1(85)
 Glawe, G. E. 5.1.1(153)
 Glen, J. W. 1.2.5(461), 1.2.5.2(552), (277), 1.2.6
 (551), 1.5(606), 1.12(553)
 Gold, L. W. 1.2.5(554), 1.2.5.1(303), 1.12(176)
 Golding, D. E. 4.6(895)

Goldschmidt, Rudolf	4.8(162)
Goldshlak, L.	1.9(283)
Gollings, D. H.	6(40)
Goltizine, N.	2.10(426), 5.1.4(514)
Good, R. J.	3.2.3(359), (360)
Goodman, D. J.	1.5(184)
Gotz, D.	4.2.4(1277)
Gould, D. G.	3.4(871)
Graham, R.	4.1.3.1(677), 4.13.1(1047)
Gray, B. H.	4.4.5(853)
Gray, Vernon H.	3.2(63), (67), (68), (70), (71), (1108), (1113), 4.1.1(39), 4.1.3.2(236), 4.4.5(708), 4.13.1(767)
Gray, W. H.	4.1.1(64), 4.13.1(853)
Green	4.13.2(681)
Greene, H. E.	4.5(1242)
Greenfield, J. R.	5.1.3(547)
Gleenly, K. H.	4.2.5(619)
Gregg	4.13(626)
Gregg, D.	4.5(1262)
Gregorek, G. M.	2.3.2(27), (112), 2.4(94), 3.2, (86), (1086), 3.2.1(28), 3.2.2(87), (148), 3.4(62), 7.1(29), 9.1(107)
Gregory, N.	3.2.2(345)
Griffith, Warren E.	3.3.4(971)
Grimshaw, E. M.	4.2.3(991)
Grocott, D. A.	4.13.1(890)
Grotewold, Walter W.	5.1.4(347)
Guffond, D. P.	2.6(462), (595), 8(593)
Guibert, A. G.	2.10(1037), 4.4(672), 9.1(203)
Gulick, Beverly G.	3.2.2(421)
Gullberg, H. H. Son	4.6(1264)
Gunn, Ross	2.7(667) 5.1.4(80)
Gurney, W. A.	4.3(1270)
Guttman, N. B.	6(1149)

H

Haas, E. G.	1.4.3(10), 4.7(1239)
Hackenberger, G. I.	4.2.3(910)
Hacker, Paul T.	1.8(558), 4.13.4(866), (867), 5.1.3(441), 6(227), (865)
Haines, A. B.	3.1.3(95)
Halbrook, T. R.	1.5(555)
Hales, K. C.	4.1.3.1(406)
Hall, Albert W.	3.4(160)
Hallett, J.	1.8(1045), 1.9(390), (540), 2.11(533)
Handsworth, R. J.	5.1.3(132), (364)
Hankley, W. L.	9.1(56)
Hanks, Marvin L.	3.3.4(971)

Hansman, R. J.	5.1.8(1168)
Hansman, R. John Jr.	2.9(14), 5.1.6(590), (1126), 3.2.3 (1131), 4.9(1303)
Harding, D. D.	6(1067)
Hardy, J. K.	2.4(1012), 2.5(979), 9.1(1098), 3.3.4(326), 4.1.3.1 (243), (764), 4.4.2(689), 4.4.4(678), 4.6(242), 4.13.1(518), (1107), (1116), 4.13.4(657), 5.1.3(407), 9.1 (1106)
Harper, T. C.	4.5(1241), (1244), 4.13.1(1036)
Harris, Maxwell	4.1.3.1(434)
Hastings, Earl C. Jr.	2.3(1125), 3.2.3(1130), (1132)
Haugher, H. H.	2.10(260), (580), 4.4.5(852)
Hauser, H.	4.2.4(1277)
Hawkes, Ivor	1.2.5(205)
Hawthorne	4.4.2(715)
Hay, J. A.	4.2.4(945)
Haynes, B. C.	4.13.4(1293)
Hearty, P. F.	2.2(212)
Hebner, E.	3.4(252)
Heines, J. M. H.	2.5(976)
Henderson, M. R.	6(1149)
Henderson, R. A.	4.8(1301)
Henschke, George E.	4.13.3(1091)
Hensley	3.5(720)
Hermes, H.	4.13.3(907)
Hesford, H. W.	4.3(1281)
Hess, J. C.	4.5(1250)
Heston, E. E.	4.5(1231), (1235), (1238)
Heuvel, Van der	1.5.1(296)
Heymsfield, A. J.	9.3.1(1184)
Higashi, A.	1.2.5.2(304), (463), (527)
Hill, Eugene G.	3.1.3(1301)
Hillendahl, Wesley H.	4.1.4(455), 4.13.1(415)
Himphreys, W. J.	6(248)
Hingst, U. G.	9.2(1299)
Hitch, Robert D.	1.2.4(305)
Hobbs, Peter V.	1.5(125), 5.3(568)
Hodge, B. K.	3.2(218)
Hodkinson, J. R.	5.1.3(547)
Hoecker, Walter H. Jr.	6(489)
Hoeflich, N. J.	5.1.3(1341)
Holdaway, George H.	4.1.3.1(437)
Honick, K. R.	4.2.5(795), (796)
Horeth, J. M.	1.2.4(315)
Hosler, C. L.	1.9(283)
Houghton, H. G.	4.13.1(320), 5.1.4(481)
Hovenac, Edward A.	5.1.4(1317)
Howell, W. E.	6(1333)
Howlett, H. P.	5.1.6(376)
Hubscher, J. J.	4.8(1266)

Hudson, J. G.	5.1.4(1088)
Huffman, P. J.	2.11(1121)
Hughes, R. R.	1.5(524)
Hunsaker, J. C.	4.13.1(320)
Hunter, W. H.	4.5(1228), (1229), (1233), 4.6(1230), 4.12(1234)

I

Ide, Robert F.	3.4(1151), 5.1.8(1169), (1172)
Ingleman-Surdberg, M.	3.4(1043), (1044)
Irvine, W. M.	1.9(341)
Itagaki, Kazuhiko	1.4.2(240), 1.10(464), 4.12(603), 8(607)
Ivaniko, A.	3.4(126), (1043)
Ives, P. J.	4.12(898)

J

Jackson, E. T.	2.7(582)
Jackson, K. A.	1.9(392)
Jackson, Richard	4.1.3.1(414), (427), (444)
Jacobs, E. N.	7.2(24)
Janssen, E.	9.1(203)
Jarman, M.	4.8(936)
Jeck, Richard K.	5.1.4(494), 6(134), (1140), (1149)
Jellinek, H. H. G.	1.2.5.2(58), (528), 1.4(146), (286) (287), (288), (289), 1.4.1(285) 1.5.1(206), (292), 1.9(173), 1.12 (177), (357), (361)
Jenkins	5.1.8(676)
Jenkins, H. F. L.	4.2.4(1269)
Jennings, G. C.	4.5(1259)
Jensen, D. C.	1.3(284), 1.9(283)
Jeracki, R. J.	7.1(118)
Jiusto, James E.	5.1.4(1080)
Joe, P. I.	2.2(1074)
Johnson, C. A.	4.13.1(320)
Johnson, John C.	5.1.4(487)
Johnson, Ruth Cholod	4.4.6(1092)
Johnstone, A. P.	5.3(785)
Jones, Alun R.	3.4.1(424), 4.1.3.1(241), (425), (428) (429), (431), (433), (442), 4.4.6(454) 5.1.8(483), 6(416), 8(647)
Jones, B. F.	4.3(1268), 4.5(1247)
Jones, B. W.	2.11(402)
Jones, J.	4.4.6(682)
Jones, R. F.	6(1095)
Jones, S. J.	1.2.5(461), 1.7(278), (279)
Jordan, Jerry L.	3.4(1151)
Judkins, H. D.	2.10(1063)
Jukoff, David	4.4.4(435), (1110)

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Kadow, C. F.	2.1(42)
Kantrowitz, Arthur	2.7(200)
Katz, R. E.	5.1.8(480)
Katzenberger	4.13.3(722), 3.4.2.3(1347)
Keeler, Charles M.	1.11(438)
Kees, Harold L.	4.1.3.1(446)
Kegeorge, P. W.	4.5(1251)
Keith, Theo G. Jr.	4.2.4(1093)
Keller, John L.	9.1(57)
Kelly, J. J.	5.1.3(377)
Keshock, E. G.	5.3(1330), 9.1(1182)
Ketcham, I. M.	4.3(1267)
Keyes, F. G.	4.13.1(320)
Khomichevskaya, I. S.	1.2.2(307)
Kim, John J.	2.10(575), 9.1(1178), 9.1.1(1179) 9.2(1164), 9.3(1308)
Kim, N. S.	6(897)
Kimball, L. B.	2.10(630)
Kimble, K. R.	9.1(270)
King, R. B.	4.13.4(817), (849)
King, W. D.	5.1.3(132), (363), (364)
Kingery, W. D.	1.2.5(531), 1.11(291), 1.12(553)
Kinloch, A. J.	1.12(181)
Kinzer, Guilbert D.	5.1.4(80)
Kirby, Mark S.	5.1.6(590), (1126), 5.1.8(1168)
Kirkball, L. B.	2.10(634)
Kishi, J. B.	8(911)
Kislovskii, L. D.	1.9(343)
Kitchens, P. F.	4.2.3(901)
Kitson, F. G.	4.6(837)
Klein, Andrew C.	1.9(1307)
Klein, J. S.	9.1(497)
Kleinknecht, Kenneth S.	5.1.4(485)
Klett, J. D.	6(49)
Kline, Dwight B.	6(470), (488), (490)
Kline, R. O.	4.5(1265)
Knight, M.	4.7(256)
Knight, Tom C.	4.2.3(1090)
Knollenberg, R. G.	5.1.3(155), 5.1.4(367), (368), 5.1.8 (349), 5.3(568)
Knowles, P. A.	2.6(1102)
Koegeboehn, L. P.	8(165)
Koflanouts, K.	6(1064)
Kohler, Arthur C.	5.1.6(1057)
Kohlman, D. L.	4.6(168)
Koinuma, S.	1.2.5.2(463), 1.2.6(504)
Kopp, W.	3.4(251)
Korkan, K. D.	1.2.2(308), 3.1.1(5), (90), (220), 3.2.2(51), (81), 3.3(16), 3.3.1(261),

	3.3.2(50), 3.3.4(52), (114), (151), 3.4(263)
Korzhavin, K. N.	1.2.1(306)
Koutz	3.5(720)
Kozitsokii, I. E.	1.2.3(605)
Kraft, E.	4.2.4(1277)
Krastanov, L.	1.7(1079)
Kraus, F.	9(359), (360)
Krebs, R. P.	4.1.2(705)
Kreis, R.	4.13.4(1180)
Krotiuk, J.	1.9(1307)
Krukowski, J.	4.12(913)
Kry, P. R.	2.2(1074)
Kuhring, M. B.	2.5(839)
Kullin, M. G.	5.1.6(1320)
Kumar, Prem	2.3.2(322)
Kurn, A. G.	2.5(844)
Kuroiwa, D.	1.11(293)
Kushnick, Jerome L.	4.1.4(453)
Kuts, M.	4.5(1249)
Kuwahara, K.	9.1.1(1040)
Kyle, Thomas G.	5.1.3(1096)

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Laforte, J. L.	1.4.1(600), (602)
Lala, G. Garland	5.1.4(1080)
Lambert, Art	4.2.4(947)
Landauer, J. K.	1.9(608)
Langham, E. J.	1.6(541)
Langmuir, Irving	6(391), 9.1(30)
Langston, P. A. S.	2.7(338)
La Rue, A. M.	4.12(1243)
Lavrov, V. V.	1.2.1(309)
Lazelle, B. D.	4.2.3(1027)
Le Clair, C. C. S.	4.6(1188)
Leclere, G.	8(214)
Lednicer, David A.	2.6(54), (150), (1083), 9.1(1145)
Lee, J. D.	2.3.2(112), 2.6(262), 3.2(1086), 3.3(53), 3.3.4(326)
Leffel, Kevin L.	4.2.4(1093)
Lemieux, G. E.	8(607)
Lenbarr, F. E.	9.1(1010)
Lenherr, F. E.	9.1(501)
Lesieutre, Daniel J.	7.1(198)
Lesins, G.	2.2(1074)
Le Sueur, H. E.	4.13.1(819), 4.13.4(810)
Levin, I. A.	4.2.2(1028), 4.8(585), (586)
Levine, Joseph	1.8(559), 2.10(1025), 5.1.4(485)
Levkov, L.	1.7(1079)
Levy, G. G.	2.5(836)
Levy, H. H.	1.9(611), 2.3.1(632)

Lewis, G. J.	4.8(573), (587)
Lewis, James P.	2.1(591), 2.3.1(1111), 2.3.3(439), 2.11(863), 4.2.1(420), (447) 4.2.4(225)
Lewis, Ralph D.	5.1.2(192), 5.1.8(66)
Lewis, William	5.1.3(154), 5.1.8(483), 5.3(475), 6(258), (416), (470), (489), (662), (765), (978)
Lindenmeyer, C. S.	1.9(392)
List, C. G.	2.2(1074)
List, Roland	2.2(1074), 9.1(1039)
Ljungstroem, Bjorn	3.4(147)
Lock, R. C.	9.1(1314)
Lockington, N. A.	1.3(172), 1.4.2(161)
Lofgren, Gary	1.9(596)
Look, Bonne C.	4.4.3(432)
Loughborough, D. L.	1.1(393), 1.4.3(10), 4.5(599), 4.6(1189), 4.7(1240), 4.13.2(681)
Lozowski, Edward P.	2.2(212), (328), (1074), 9.1(31) 9.3(1181)
Ludlam, F. H.	1.1(542), 1.9(396), 2.2(331)
Luers, James K.	2.3.2(322), 3.2.3(1127), (1133), (1134), 9.1(57)
Lundstrom, Goran	5.2(127)
Lunn, Kenneth	4.2.3(926), 4.13.3(1091), (1099)

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MacArthur, Charles D.	2.3.2(57), 9.3(1181)
Macauley	2.5(666)
MacCready, P. B. Jr.	5.1.4(509)
Maciag, E. T.	5.1.6(1320)
Macklin, W. C.	1.1(217), (542), 1.9(394), (395)
MacNeil, J. N.	2.10(592)
Mae, S.	1.2.5.2(463), 1.2.6(504)
Maeno, N.	1.5(186)
Magenheim, B.	5.1.6(103), (169)
Majid, H. A.	1.4.3(161)
Mann, G.	2.11(1098), 4.1.3.1(406)
Mansianx, A.	1.4(601)
Mantis, H. T.	1.5(310)
Manuel, G. S.	3.2.3(1130)
Mapp, A. G.	4.2.1(1274)
Marchant, F. C.	4.4.2(702)
Markiewicz, R. H.	3.2.1(914)
Marlow, B. P.	2.7(891)
Marsh, George	2.6(117)
Marshall, D. R.	4.8(939)
Marshall, J. S.	6(1324)
Martin, E. H. E.	4.5(1258), (1260)
Martin, Ruth M.	1.4.1(602), 7.1(1)
Martinelli, R. C.	2.10(1037)

Marvin, C. F.	5.1.2(268)
Masin, I. P.	2.7(617)
Masiulaniec, K. Cyril	4.2.4(1093)
Mason, B. J.	1.5.1(296), 1.6(541), 1.8(1045), 1.9(390), (397), (398), (609), 6(445), (1097)
Mason, D.	2.11(772)
Mason, J. H.	2.6(896)
Masters, Charles O.	6(59), (1141)
Matthews, R.	4.4.2(706)
Matsumoto, A.	1.5.1(282)
Maughmer, Mark D.	2.10(213)
Mauser, W. G.	2.10(213), (375)
May, K. R.	2.2(571), 5.1.4(515)
Maybank, J.	1.9(398)
Maynard, Julian D.	3.1.2(219), 3.1.3(37), 4.1.1(36)
McAvoy, William H.	8(202)
McBain	2.4(725)
McBrien, R. L.	2.7(625)
McCarthy, R.	7.1(194)
McClean	4.2.4(1278)
McComber, P.	1.4(601)
McConnell, D.	1.9(342)
McCullough, George B.	4.1.3.1(521)
McCullough, Stuart	5.1.4(478), 5.1.8(66)
McDonald, L. S.	8(887)
McKenzie, K. T.	2.6(1014), 3.3.2(1050), 8(893)
McKnight, Robert C.	3.4(180), (1085), (1151)
McLarren, R.	2.7(675)
McNaughton, I. I.	6(538), (788)
McTaggart-Cowan, J. D.	2.2(1074)
Meijer, Staffan	9.3(1318)
Meikle, K. M.	8(887)
Melcher, H.	4.13.3(902)
Meline, H. R.	4.1.4(880)
Mellor, Malcolm	1.2(529), 1.2.5(205), 1.2.6(311), (312), (313)
Melson, W. E. Jr.	3.2.3(1129)
Merceret, F. J.	5.1.3(352)
Mergler, Harry W.	2.2(61), 5.1.4(1322)
Merril, R. K.	2.6(906)
Messimer, J. R.	9.1(1182)
Messinger, Bernard L.	4.2.5(96)
Messner, H. P.	3.2.3(362)
Meszaros, A.	6(1064)
Methven, J. J.	5.1.4(787)
Metzger, F. B.	7.1(115)
Middleton, W. E. K.	6(1335)
Mikkelsen, D. C.	7.1(33), (118)
Mikkelsen, Kevin L.	3.4(180), (1085), (1151)
Millar, D. A. J.	9.1(877)
Millenson, Morton B.	5.1.5(199)

Miller, Christopher J. 7.1(195)
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 Milsum, J. H. 4.2.4(806), (822), 6(782), (783), (784)
 Milton, Kerker 5.1.3(546)
 Minervin, V. E. 5.1.3(543)
 Minshall, R. J. 4.5(1261)
 Mitchell, G. A. 7.1(33), (116)
 Mixon, John S. 8(443)
 Morrell 4.4.2(719), 4.13.1(723)
 Morrin, E. H. 2.10(1037)
 Morris 5.1.8(676)
 Moshos, George J. 2.3.1(223)
 Mountain, D. S. 4.13.4(1272)
 Mueller, A. A. 4.8(9), (119)
 Mueller, M. D. 6(1149)
 Mulholland, Donald R. 2.11(456), 4.1.1(204), (419), (583)
 Muller, Fritz 1.11(438)
 Murphy, S. B. 5.1.4(1158)

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 Narramore, J. C. 3.4(263)
 Nayar, H. J. 1.2.6(465)
 Neale, A. E. T. 4.2.4(1269)
 Neel, Carr B. 4.1.3.1(431), 5.1.3(131), (369), (370),
 4.4.5(881)
 Neel, Carr B. Jr. 3.1(26), 4.1.3.1(449), (450), 4.4.4
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 Neish, W. Edward 5.1.4(368)
 Neumann, H. E. 5.1.5(4)
 Newbiggin, H. 4.13.4(728)
 Newcomb, James 3.5(1155)
 Newman, Richard L. 2.11(1154) 4.6(11)
 Newnham, T. O. 5.1.3(372)
 Newport, H. 4.2.1(1274)
 Newton, Dennis W. 2.7(135), 6(40)
 Newton, E. P. 4.2.1(1282)
 Newton, J. 2.3.2(584)
 Newton, James E. 2.8(574), 5.1.8(1319), 9.5(1170)
 Newton, K. E. 5.1.2(1339)
 Newton, P. H. 4.13.2(707)
 Nguyen, D. D. 1.4.1(600)
 Nichols, O. D. 1.2.3(290)
 Nicol, John W. 4.8(938)
 Nisbet, J. L. 4.3(1280)
 Norbury, D. 4.5(1258)

Norment, Hillyer G. 5.1.3(228), (229), (230), (232),
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O'Keefe, J.
Oleskiw, Myron M. 9.1(31), 9.3(1181)
Oliver, M. J. 4.7(882)
Oliver, R. G. 4.5(1137)
Olsen, William A. 2.3.2(584), 2.8(574), 8(123), (142)
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Olsen, W. A. Jr. 9.5(1170)
O'Reilly, C. L. 3.2.2(345)
Ormsbee, Allen I. 2.10(213), 9.1(210)
Orr, John L. 4.2.1(317), 4.2.4(872), (875), 6(502)
Orrok, G. T. 1.9(392)
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Palmer, W. M. 6(1324)
Papadakis, M. 2.10(575), 9.1(1313)
Paramasivam, T. 4.8(8)
Parish, H. C. 9.5(409)
Parker, J. D. 2.11(402)
Parker, L. 4.8(937)
Parkin, D. A. 5.1.3(132)
Parrish, J. L. 9.3.1(1184)
Paselk, R. A. 4.4.4(15)
Pauling, Linus 1.9(564)
Payne, K. J. 4.2.3(991)
Pearce, G. F. 5.1.3(1173)
Peetz, C. V. 2.2(500)
Peppler, Wilhelm 6(503)
Perez, Richard R. 9.1(828)
Perkins, Porter J. 3.4(180), 4.1.1(204), (419), (538),
5.1.3, (154), 5.1.4(478), 5.1.8(66),
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Perkins, Porter J. Jr. 3.4(1085), 5.1.7(199)
Perreault 4.4.2(721)
Perry, H. W. 2.5(695), 4.1.4(635)
Personne, P. 5.1.3(350)
Peterson, Andrew A. 2.6(1015), 4.4.6(1092), 4.13(1163),
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Peterson, S. W. 1.9(611)
Petrjanoff 6(623)
Pettit, K. G. 4.13.4(149), 5.1.3(966), 5.1.8(484),

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Pflaum, J. C.	1.8(1078)
Phan, C. L.	1.4(601), 1.4.1(600), (602)
Piercy, R.	4.8(983)
Pierre, M.	8(594)
Pingsheng, H. E.	1.12(183)
Pinnick, R. G.	5.1.3(351), (353)
Pinty, J. P.	5.1.3(350)
Pita, G. P.	3.2.3(1135)
Platz, Stewart J.	3.4(1151)
Podolsky, B.	9(359), (360)
Podzimer, J.	1.9(1077)
Poinsatte, E.	5.1.8(1319)
Pointin, Y.	5.1.3(350)
Politovich, Marcia K.	3.4(97)
Pollock, J. C.	1.9(341)
Potapczuk, M. G.	3.2(577)
Potash, H. L.	8(1031)
Powell, Clemans A.	8(443)
Powell, J. F.	4.13.1(723)
Pravada	4.13.4(45)
Preston, Merrit G.	3.4(88)
Prewett, W. C.	5.2(517)
Price, R. D.	1.4(91), 3.3.3(191)
Pring-Rowe, M. F.	4.6(1253)
Pruden, F. W.	2.6(791)
Pruppacher, H. R.	1.8(1078)
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Ramseier, R. O.	1.10(466)
Ranaudo, Richard J.	3.4(180), (1085), (1151)
Randall, J.	5.2(727)
Ranz, W. E.	2.1(221)
Raraty, L. E.	1.4(239)
Ray, G. V.	4.12(912)
Reaser, W. W.	2.10(260)
Reehorst, Andrew L.	3.4(1151), 5.3(1310)
Reid, James. S.	3.3.4(971)
Reid, Robert C.	1.5(399), 2.11(404)
Reinmann, John J.	8(55), (123), (157), (1302)
Richardson, D. A.	4.13(803)
Richter, G. Paul	5.1.8(1172), 5.3(1310), 8(1146)
Rideau, J. R.	4.4.3(1209)
Rigsby, G. P.	1.2.3(556)
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Ritter, James E. 4.2.3(1090)
 Ritz, L. 2.7(77)
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 Robbins, W. M. 9.1(203)
 Robertson, R. O. 2.6(373), 4.2.4(815)
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 Robitzsch, M. 2.7(201)
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 Rogers, M. J. W. 4.2.5(801)
 Rogou, I. A. 4.2.2(1028)
 Rohrbach, Carl 7.1(34), (115)
 Rollin, Vern G. 4.11(456), 3.5(459)
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 Roos, D. v. d. S. 1.9(467)
 Roper, R. A. 4.2.4(1273), 4.2.5(618)
 Rosen, K. M. 4.13.4(908), 8(1031)
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 Ruggeri, R. S. 2.1(591)
 Rupe, Jack H. 5.2(491)
 Rush, C. K. 2.3.1(824), 2.3.2(825), (826), 2.10
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Sax, Robert J.	6(1065)
Scavuzzo, R. J.	1.2.3(597)
Schaefer, Vincent J.	4.4.6(673), 5.2(560)
Schaetzel	4.13.1(724), 5.3(716)
Schaller, R. C.	1.9(1082)
Schecter, R. M.	5.1.4(371)
Schemenauer, Robert S.	5.1.3(133)
Scherrer, Richard	4.2.1(207), (208), 4.4.3(430)
Schinstock, William C.	3.4(1151)
Schlauff, Bernard A.	4.1.3.1(442), (434), (436), 4.4.4 (435), (1110)
Schneider, H. W.	9.5(410)
Schnell, Russel C.	6(1069)
Schrag, R. L.	4.8(46), (589), (1309)
Schricker, T. L.	2.2(571), 5.1.3(352)
Schull, C. G.	1.9(565)
Schultz, R. J.	2.10(492)
Schumacher, P. W. T.	2.10(1013)
Schwartz, Herman	9.1(499)
Schwartz, J.	1.12(175)
Schweikhard, W. G.	4.6(168)
Scott, J. N.	9.1(56)
Scott, Merit	2.3.1(246), 4.13.1(255)
Sears, C. T.	4.5(1216), (1225), (1227)
Seibel, W.	2.10(575)
Selden, R. F.	1.4(412)
Sellers, William L. III	5.1.5(197)
Selna, James	4.11(38), 4.1.3.1(436), (440), (446) (449)
Sepsy, C. F.	9.5(409)
Serafini, John S.	2.2(60), 2.3.1(223), (616), (523), 5.1.3(154), 5.1.4(4), 9.1(1105), (1112)
Sewell, John Harold	4.7(927), (929), (1201), 4.11(19), 4.12(164), 4.13.3(928)
Shafer, Thomas R.	32.3.1(828)
Shah, Yatish T.	2.11(404)
Sharp	2.10(426)
Sharp, P. J.	3.5(1023)
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20	4.2.3	4.4.6	7.1	5.1.4	7.2
	2.3.2	3.1	9.1	3.2.1	7.1
30	9.1	9.1	7.2	7.1	7.1
	4.4.1	4.1.1	3.1.3	4.1.1	4.1.1
40	6	5.1.3	2.1	8	4.6
	4.13.4	4.8	4.8	2.3.1	6
50	3.3.2	3.2.2	3.3.4	3.3	2.6
	8	9.1	9.1	1.2.5.2	6
60	2.2	2.2	3.4	3.2	4.1.1
	2.3.2	5.1.8	3.2	3.2	3.1.3
70	3.2	3.2	2.3.1	6	2.7
	6	2.7	2.7	6	9.1
80	5.1.4	3.2.2	7.1	2.4	2.6
	9.1	3.2	3.2.2	3.4	3.4
90	3.1.1	1.4	3.2	9.1.1	2.4
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	9.5	4.1.3.2	9.1	7.1	8
110	8	3.1	2.3.2	3.2	3.3.4
	7.1	7.1	2.6	7.1	4.8
120	4.8	6	7.1	8	5.1.4
	1.5	3.4	5.2	9.1	5.1.4
130	5.1.4	5.1.3	5.1.3	5.1.3	6
	2.7	2.3.1	2.3.1	2.3.1	2.3.1
140	8	4.13.1	8	4.13.2	7.1
	7.1	1.4	3.4	3.2.2	4.13.4
150	2.6	3.3.4	8	5.1.1	5.1.3
	5.1.3	4.2.3	8	2.6	3.4
160	3.4	1.4.2	4.8	1.4	4.12
	8	4.5	4.4.1	4.6	5.1.6
170	2.10	9.1	1.3	1.9	4.4.3
	1.12	1.12	1.12	1.12	7.2
180	3.4	1.12	1.12	1.12	1.5
	1.12	1.5	3.5	4.2.3	5.1.6
190	4.2.3	3.3.3	5.1.2	9.1	7.1
	7.1	3.1	5.1.5	7.1	5.1.7

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	1.2.5	1.5.1	4.2.1	4.2.1	5.2
210	9.1	2.7	2.2	2.10	8
	3.2.1	7.2	1.1	3.2	3.1.2
220	3.1.1	2.1	9.1	2.3.1	4.1.3.2
	4.2.4	9.1	6	5.1.3	5.1.3
230	5.1.3	5.1.4	5.1.3	5.1.4	5.1.3
	5.1.6	4.1.3.2	2.11	2.6	1.4
240	1.4.2	4.1.3.1	4.6	4.1.3.1	2.10
	2.10	2.3.1	2.7	6	2.7
250	2.7	3.4	3.4	6	2.7
	4.13.1	4.7	4.1.3.1	6	3.2.2
260	2.10	3.3.1	2.6	3.4	5.1.2
	5.1.2	5.1.2	1.6	5.1.2	5.1.8
270	9.1	4.1.3.1	4.1.3.1	4.1.3.1	4.7
	2.10	2.7	1.2.5.2	1.7	1.7
280	1.2.5.2	1.5	1.5.1	1.9	1.3
	1.4.1	1.4	1.4	1.4	1.4
290	1.2.3	1.11	1.5.1	1.11	1.5.1
	1.5.1	1.5.1	1.5	1.2	1.2.2
300	1.2.7	1.5	1.2.5	1.2.5.1	1.2.5.2
	1.2.4	1.2.1	1.2.2	1.2.2	1.2.1
310	1.5	1.2.6	1.2.6	1.2.6	1.7
	1.2.4	1.2.5	4.2.1	2.7	1.4
320	4.13.1	4.13.4	2.3.2	4.1.3.1	9.5
	3.1	3.3.4	2.6	2.2	8
330	6	2.2	3.2.3	1.4	8
	1.4.1	1.7	5.1.4	2.7	3.4
340	2.10	1.9	1.9	1.9	4.13.4
	3.2.2	4.1.4	5.1.4	6	5.1.8
350	5.1.3	5.1.3	5.1.3	5.1.3	5.1.3
	5.1.3	1.12	1.12	1.5.1	3.2.3
360	3.2.3	1.12	3.2.3	5.1.3	5.1.3
	5.1.3	5.1.4	5.1.4	5.1.4	5.1.3
370	5.1.3	5.1.4	5.1.3	2.6	2.6
	2.10	5.1.6	5.1.3	5.1.6	4.4.3
380	5.1.6	5.1.6	5.1.6	4.2.3	5.1.6
	4.13.3	5.2	4.13.3	1.7	1.12
390	1.9	6	1.9	1.1	1.9
	1.9	1.9	1.9	1.9	1.5
400	1.1	1.9	9.5	2.11	2.11
	4.1.3.1	4.1.3.1	5.1.3	4.1.3.1	9.5
410	9.5	2.2	1.4	8	4.1.3.1
	4.13.1	6	4.1.1	4.6	4.1.1
420	4.2.1	3.2.2	3.4.1	4.1.3.1	3.4.1
	4.1.3.1	2.10	4.1.3.1	4.1.3.1	4.1.3.1

	0 5	1 6	2 7	3 8	4 9
430	4.4.3	4.1.3.1	4.4.3	4.1.3.1	4.1.3.1
	4.4.4	4.1.3.1	4.1.3.1	1.11	2.3.3
440	4.1.3.1	5.1.3	4.1.3.1	8	4.1.3.1
	6	4.1.3.1	4.2.1	9.1	4.1.3.1
450	4.1.3.1	1.9	4.1.3.3	4.1.4	4.4.6
	4.1.4	2.11	4.1.3.1	4.7	3.5
460	1.2.5.2	1.2.5	2.6	1.2.5.2	1.10
	1.2.6	1.10	1.9	4.12	4.13.1
470	6	6	6	4.13.4	4.13.1
	5.3	5.1.8	5.1.4	5.1.4	5.1.4
480	5.1.8	5.1.4	8	5.1.8	5.1.8
	5.1.4	5.1.4	5.1.4	6	6
490	6	5.2	2.10	2.5	5.1.4
	2.2.1	2.2.1	9.1	9.1	9.1
500	2.2	9.1	6	6	1.2.6
	1.2.5	1.2.3	1.5	5.1.4	5.1.4
510	5.1.4	5.1.4	2.11	5.1.4	5.1.4
	5.1.4	5.1.4	5.2	4.13.1	3.2.3
520	4.4.4	4.1.3.1	2.3.1	2.3.1	1.5
	1.2.2	1.2.6	1.2.5.2	1.2.5.2	1.2
530	1.2.5	1.2.5	5.1.3	2.11	5.1.4
	5.1.2	5.1.3	1.6	6	6
540	1.9	1.6	1.1	5.1.3	2.11
	2.11	5.1.3	5.1.3	5.2	5.1.4
550	5.2	1.2.6	1.2.5.2	1.12	1.2.5
	1.5	1.2.3	1.5	1.8	1.8
560	5.2	1.9	1.9	1.9	1.9
	1.9	5.1.4	5.1.3	5.3	6
570	5.1.3	2.2	4.8	4.8	2.8
	2.10	3.2	3.2	2.7	2.11
580	2.10	2.10	2.7	4.1.1	2.3.2
	4.8	4.8	4.8	4.8	4.8
590	5.1.6	2.1	2.10	8	8
	2.6	1.9	1.2.3	1.7	4.5
600	1.4.1	1.4	1.4.1	4.12	1.5
	1.2.3	1.5	8	1.9	1.9
610	1.6	1.9	1.9	1.2.5.2	1.9
	1.9	2.7	2.7	4.2.5	4.2.5
620	4.4.6	4.6	2.11	6	6
	2.7	4.13.1	2.5	2.5	5.1.1
630	2.10	4.13.1	2.3.1	4.13.1	2.10
	4.1.4	4.1.1	4.4.1	4.5	4.1.3.1
640	4.13.1	4.13.4	4.13.4	4.13.4	4.6
	5.1.8	4.13.4	8	4.1.3.1	4.6
650	4.1.4	2.7	4.4.3	6	4.13.1
	5.1.8	4.13.4	4.13.4	6	4.4.2

	0 5	1 6	2 7	3 8	4 9
660	4.13.1	4.1.3.1	6	4.13.1	5.1.8
	3.1.3	2.5	2.7	2.5	2.5
670	2.5	2.5	4.4	4.4.6	4.4.6
	2.7	5.1.8	4.1.3.1	4.4.4	2.5
680	5.1.8	4.13.2	4.4.6	4.4.2	5.1.8
	6	4.4.6	2.5	4.4.3	4.4.2
690	6	4.4.2	4.2.1	6	5.1.8
	2.5	4.4.5	4.4.6	4.1.2	4.4.6
700	3.1.3	4.4.6	4.4.2	4.4.2	2.5
	4.1.2	4.4.2	4.13.2	4.4.5	4.4.2
710	4.4.2	5.3	4.4.6	4.13.4	4.4.6
	4.4.2	5.3	4.13.4	5.3	4.4.2
720	3.5	4.4.2	4.13.3	4.13.1	4.13.1
	3.4	2.11	5.2	4.13.4	5.1.8
730	5.2	4.13.1	4.13.2	5.2	5.2
	5.2	5.2	4.2.5	4.6	4.6
740	4.4.6	4.4.6	4.13.1	4.13.1	5.1.4
	4.13.1	4.13.1	5.2	5.2	6
750	4.13.4	4.13.4	4.6	6	4.4.2
	4.4.2	4.4.3	5.1.8	4.13.4	4.2.3
760	4.6	4.4.2	4.13.4	4.4.2	4.1.3.1
	2.11	6	4.1.3.1	4.4.6	6
770	4.4.2	6	2.11	9.1	4.1.2
	5.3	5.3	5.3	5.1.1	6
780	5.1.4	4.4.6	6	6	2.6
	5.3	5.3	5.1.4	5.1.3	4.13.3
790	9	2.6	4.13.3	4.4.6	5.2
	4.2.5	4.2.5	5.1.6	5.1.6	5.1.6
800	2.6	4.2.5	4.13.1	4.13.1	8
	5.1.6	4.2.5	8	4.13.4	4.13.4
810	4.13.4	4.2.4	6	6	4.13.4
	4.2.4	4.13.1	4.13.4	8	4.13.1
820	4.13.1	2.3.2	4.2.4	2.3.1	2.3.1
	2.3.2	2.3.2	2.3.2	9.1	2.5
830	2.5	2.5	2.5	2.5	2.5
	2.5	2.5	4.6	4.1.2	2.5
840	2.5	4.4.2	4.13.4	2.5	2.5
	2.5	2.5	2.5	2.10	4.13.4
850	5.2	4.2.5	4.4.5	4.13.1	2.11
	6	5.2	4.2.3	5.2	5.2
860	5.2	4.2.5	4.2.5	2.11	2.11
	6	4.13.4	4.13.4	4.13.1	2.10
870	4.2.4	3.4	4.2.4	4.2.5	4.6
	4.2.4	4.2.1	9.1	6	2.11
880	4.1.4	4.4.5	4.7	4.13.2	4.13.3
	2.10	5.1.4	8	8	8

	0 5	1 6	2 7	3 8	4 9
890	4.13.1 4.6	8 2.6		8 4.12	4.13.3 5.1.6
900	4.2.3 4.2.3	4.2.3 2.6	4.13.3 4.13.3	2.10 4.13.4	4.2.3 8
910	4.2.3 3.2.1	8 5.2	4.13.3 4.13.4	4.11 4.2.5	3.2.1 3.3.2
920	4.2.3 8	4.8 4.2.3	8 4.7	8 4.13.3	2.10 4.7
930	9.1 2.3.2	4.2.3 4.8	2.6 4.8	8 4.8	3.3.2 4.8
940	4.8 4.2.4	4.6 4.2.1	4.6 4.2.4	4.6 4.2.2	4.2.1 4.2.4
950	4.2.4 4.2.4	4.2.2 4.2.4	4.2.2 4.2.4	4.2.4 4.2.4	4.2.4 4.2.2
960	4.2.2 4.2.4	4.2.1 4.13.1	4.2.2 4.2.4	4.2.2 4.2.4	4.1.3.2 4.2.4
970	2.3.2 3.3.2	3.3.4 2.5	3.3.2 2.3.1	3.3.2 3.3.2	8 2.5
980	2.5 4.7	4.1.2 4.7	4.1.2 4.2.4	4.8 4.2.5	4.12 4.2.4
990	3.4 4.3	4.2.4 4.3	4.2.4 4.3	4.2.4 4.3	4.2.4 7.2
1000	7.2 7.2	7.2 7.2	7.2 7.2	7.2 7.2	7.2 2.10
1010	9.1 2.6	9.1 2.6	2.4 7.2	2.10 2.6	2.6 2.6
1020	2.6 2.10	3.3.2 4.2.3	2.10 4.2.3	3.5 4.2.2	2.10 7.2
1030	4.2.3 2.10	7.2 4.13.1	4.2.3 2.10	4.2.3 6	4.2.4 9.1
1040	9.1.1 1.8	2.3.1 5.1.8	3.4 4.13.1	3.4 3.4	3.4 7.2
1050	3.3.2 5.1.6	3.4 5.1.6	5.1.3 5.1.6	5.1.3 5.1.6	5.1.6 4.12
1060	4.2.4 6	4.2.4 6	6 6	6 6	6 6
1070	6 6	6 6	6 1.9	6 1.8	2.2 1.7
1080	5.1.4 3.4	5.1.4 3.2	1.9 2.6	2.6 5.1.4	2.3.2 2.10
1090	4.2.3 6	4.13.3 5.1.3	4.4.6 6	4.2.4 9.1	4.13.3 4.13.3
1100	1.5.1 9.1	1.11 9.1	2.6 4.13.1	9.1 3.2	2.6 2.10
1110	4.4.4 8	2.3.1 4.13.1	9.1 4.4.2	3.2 4.4.2	2.7 4.4.2

	0 5	1 6	2 7	3 8	4 9
1120	4.4.2	2.11	5.1.3	5.1.6	4.13.1
	2.3	5.1.6	3.2.3	3.2.3	3.2.3
1130	3.2.3	3.2.3	3.2.3	3.2.3	3.2.3
	3.2.3	3.2	4.5	8	8
1140	6	6	5.2	2.6	2.6
	9.1	8	3.3.2	4.13	6
1150	6	3.4	9.3	9.1.1	2.11
	3.5	5.1.4	9.1	5.1.4	5.1.5
1160	9.1	8	5.3	4.13	9.2
	9.2	3.4.1	8	5.1.8	5.1.8
1170	9.5	9.5	5.1.8	5.1.3	5.1.8
	3.4	2.7	8	9.1	9.1.1
1180	4.13.4	9.3	9.1	9.1	9.3.1
	5.1.4	9.3	2.7	4.6	4.6
1190	4.6	2.7	4.5	4.5	4.5
	4.5	4.5	4.5	4.6	4.6
1200	4.6	4.7	4.3	4.3	4.5
	4.3	4.5	4.4.3	4.4.3	4.4.3
1210	4.7	4.3	4.3	4.3	4.5
	4.5	4.5	4.5	4.5	4.7
1220	4.7	4.5	4.5	4.5	4.5
	4.5	4.5	4.5	4.5	4.5
1230	4.6	4.5	4.3	4.5	4.12
	4.5	4.5	4.5	4.5	4.7
1240	4.7	4.5	4.5	4.12	4.5
	4.7	4.5	4.5	4.5	4.5
1250	4.5	4.5	4.5	4.6	4.12
	4.6	4.5	4.5	4.5	4.5
1260	4.5	4.5	4.5	4.5	4.6
	4.5	4.8	4.3	4.3	4.2.4
1270	4.3	4.3	4.13.4	4.2.4	4.2.1
	4.3	4.3	4.2.4	4.2.4	4.3
1280	4.3	4.3	4.2.1	6	4.3
	4.2.1	4.3	4.3	4.3	4.3
1290	4.7	4.7	4.2.1	4.13.4	2.11
	2.3	2.3	3.2	6	9.2
1300	4.2.5	3.1.3	8	4.9	2.11
	1.5	2.7	1.9	9.3	4.8
1310	5.3	2.11	3.5	9.1	9.1
	9.1	9.1	5.1.4	9.3	5.1.8
1320	5.1.6	6	5.1.4	2.3.1	6
	2.7	6	9.3	9.2	9.2
1330	5.3	6	6	6	9.1
	6	6	6	5.1.3	5.1.2
1340	5.1.3	5.1.3	5.1.3	5.1.3	5.1.6
	5.1.6	4.8	3.4.2.3		

5.3 Table 2"ANALYSED" LITERATURE

A = "Analysed" (bracketed reference numbers)

	0	1	2	3	4	5	6	7	8	9
0		A	A	A	A	A	A	A	A	A
10	A	A	A	A	A	A	.	A	.	A
20	A	.	.	.	.	.	A	A	A	A
30	.	.	.	.	A	A	A	A	A	A
40	A	.	.	.	.	.	A	A	A	.
50	A	A	A	A	A	.	A	A	.	.
60	A	A	A	A	A	.	A	A	A	A
70	A	A	A	A	.	.	A	.	.	A
80	A	A	A	.	A	A	.	.	.	.
90	.	A	.	.	A	A	A	A	.	.
100	A	A	A	A	A	A	A	A	A	A
110	A	.	A	A	A	.	.	A	.	.
120	A	.	A	.	A	.	.	A	A	.
130	A	.	A	A	.	.	A	A	A	A
140	.	.	.	.	.	.	A	.	.	.
150	.	A	A	.	.	A	.	.	A	A
160	A	A	.	A	A	.	.	.	.	.
170	.	.	A	A	.	.	.	.	.	.
180	A	.	.	.	.	.	.	.	A	A
190	A	A	A	A	A	A	.	A	A	A
200	A	A	A	A	.	A	A	A	A	.
210	.	.	.	A	.	.	.	A	.	A
220	A	.	A	.	.	.	A	A	A	.
230	.	.	A	.	A	.	.	.	.	A
240	A	A	.	.	A	.	A	.	A	A
250	A	.	.	A	.	A	.	.	.	A
260	.	.	.	.	.	.	.	.	.	.
270	.	.	A	A	.	A	.	A	A	A
280	.	A	.	.	.	.	.	.	A	.
290	A	.	.	.	A	A	A	.	.	A
300	A	.	A	A	A	A	.	.	.	A
310	.	A	A	A	.	A	.	.	.	A
320	.	.	A	A	A	.	.	.	.	A
330	.	A	.	A	.	A	.	A	.	.
340	.	.	.	A	A	A	A	A	.	.
350	A	A	A	.	A	A	.	.	A	.
360	.	.	.	.	.	.	A	.	A	A
370	.	A	A	.	A	.	.	A	.	.
380	.	A	.	.	.	.	A	.	.	.
390	.	.	A	.	.	A	A	.	A	A
400	.	.	.	.	A	.	.	A	.	A
410	.	.	A	A	.	A	A	.	A	A

[illegible]

