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Commercial Aviation Icing Research Requirements

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16 Abstract A short range and long range icing research program was proposed to NASA Lewis Research Center. A survey was made to various industry and government agencies to obtain their views of needs for commercial aviation ice protection. Through these responses, other additional data, and Douglas Aircraft icing expertise, an assessment of the state-of-the-art of aircraft icing data and ice protection systems was made. The above information was then used to formulate the icing research programs.			
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FOREWORD

This report is in response to NASA contract #NAS3-22361, Commercial Aviation Icing Research Requirements.

Part of this study contract was to survey the commercial aviation industry to gather their views on the needs for icing research. We wish to thank all the airlines, manufacturing companies and regulatory agencies who responded to the survey and shared their expertise. A list of those participating is given in Appendix A of this report.

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SUMMARY

This report includes the results of NASA contract #NAS3-22361, Commercial Aviation Icing Research Requirements. One object of this contract was to survey the commercial aircraft industry on their views of icing research needs. Survey forms were sent to 43 separate airlines, aircraft manufacturers, and regulatory agencies. Seventeen responses were received.

These survey responses along with other available data were reviewed to assess the state-of-the-art of ice protection system design. This assessment is included in the report.

This study resulted in recommended NASA short and long range icing research programs along with the estimated costs of each program.

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INTRODUCTION

Over the last few years there has been an increasing need for advancement in ice protection technology. Fuel costs have risen. This has encouraged aircraft designers to seek ice protection systems which will save weight and fuel and to optimize existing systems. In response to this need, NASA has re-established an icing research effort at the Lewis Research Center to assist industry in solving present day icing problems.

NASA awarded a contract to the Douglas Aircraft Company to canvass the commercial aircraft industry and to use their vast experience in icing technology to inform NASA with regards to the need for further activity in the area of icing technology and research for commercial aircraft. Commercial aircraft is defined in this report as aircraft designed to carry 30 or more passengers and equipped with jet or turbo prop engines. Appendix A includes a copy of the survey forms and a list of those who responded.

This report presents the findings of this effort and summarizes the recommendations of the commercial aircraft industry in terms of proposed short and long range icing research and technology programs along with approximate cost estimates. The report follows the format as outlined in the Statement of Work. An outline of the Statement of Work is included in Appendix B.

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DISCUSSION

COMPONENT ICE PROTECTION SYSTEMS

Commercial aircraft are designed to encounter the most severe icing conditions, as defined in Federal Air Regulations Part 25, Appendix C, and not affect the safety of the aircraft. Because of this, all components on the aircraft that have the potential for collecting ice must be investigated. Table I shows a list of components which are analyzed or tested to determine the amount of ice, if any, that collects on the component and the resultant effect of this ice on the aircraft and other aircraft components. This, in turn, dictates whether an ice protection system is required.

Also in Table I, the methods of ice protection that have been used on each of the components are identified. Some of the methods listed are no longer used for commercial aircraft, such as pneumatic boots.

ICE PROTECTION PENALTIES

There are six major penalty factors which are related to ice protection systems. They are: energy usage, initial cost, maintenance, aerodynamic performance, reliability, and safety (if ice protection system fails). Aircraft component ice protection systems which are most affected by the factors mentioned above are identified in Table II. The components are listed in order of the most energy required, highest initial cost, etc.

Present day commercial aircraft ice protection systems present no major problems with regards to maintainability or reliability. Aircraft safety requirements are imposed on both the aircraft manufacturers and the operator by the Federal Aviation Administration Regulations. This leaves energy requirements, impact on aerodynamic performance, and initial cost as the factors with the greatest potential for payoff from technology advancement. The component ice protection systems which use the most energy and have the highest initial cost are the wing leading edges, the

TABLE I

AIRCRAFT COMPONENTS AND ASSOCIATED ICE PROTECTION SYSTEMS

AIRCRAFT COMPONENTS	TYPES OF ICE PROTECTION SYSTEMS USED
A. Propulsion systems	
1. Nose cowl	Hot air double skin anti-ice Hot air spray tube anti-ice
2. Blow in doors	Exhaust from hot air system None
3. Inlet noise suppression	Exhaust from hot air system None
4. Inlet boundary layer control	None
5. Bullet	Hot air double skin anti-ice Hot air flowing through a leading edge cavity Exhaust from hot air system None
6. Core inlet	None
7. Fan inlet guide vanes	Hot air flowing through a leading edge cavity None
8. Core inlet guide vanes	None
9. Rotors and stators	None
10. External Strakes	None
11. Pylon	None, but causes measurable aerodynamic penalty
12. Ventilation scoops	None
13. Propeller	Pneumatic boots Electrical Ethylene glycol

TABLE I (cont'd)

AIRCRAFT COMPONENTS AND ASSOCIATED ICE PROTECTION SYSTEMS

AIRCRAFT COMPONENTS	TYPES OF ICE PROTECTION SYSTEMS USED
B. Wing	
1. Wing leading edge	Hot air double skin anti-ice Hot air double skin de-ice Hot air spray tube anti-ice Pneumatic boots Ethylene glycol None, but causes measurable aerodynamic penalty
2. Ailerons	None
3. Leading edge slats	Hot air double skin anti-ice Hot air spray tube anti-ice None, but causes measurable aerodynamic penalty
4. Leading edge slots	None
5. Flaps	None
6. Vortex generators	None
7. Laminar flow control	Ethylene glycol
8. Vortilon	None, but causes measurable aerodynamic penalty
9. Fences	None, but causes measurable aerodynamic penalty
10. Winglets	None, but causes measurable aerodynamic penalty
11. Wing tips	None, but causes measurable aerodynamic penalty
12. Leading edge slat joints	Hot air spray tube anti-ice None, but causes measurable aerodynamic penalty

TABLE I (cont'd)

AIRCRAFT COMPONENTS AND ASSOCIATED ICE PROTECTION SYSTEMS

AIRCRAFT COMPONENTS	TYPES OF ICE PROTECTION SYSTEMS USED
13. Ventilation scoops	None
14. Flap hinge fairings	None, but causes measurable aerodynamic penalty
15. Stall strips	None
16. Stall warning devices	Electrical
C. Tail Surfaces	
1. Horizontal	Hot air double skin de-ice Hot air spray tube de-ice Pneumatic boots Electrical None, but causes measurable aerodynamic penalty
2. Elevator	None
3. Vertical	Pneumatic boots None, but causes measurable aerodynamic penalty
4. Rudder	None
5. Ventilation scoops	Hot air double skin anti-ice None
D. Fuselage	
1. Windshield	Hot air double skin anti-ice Hot air jet blast Electrical Ethylene glycol
2. Wing fuselage juncture	None, but causes measurable aerodynamic penalty

TABLE I (cont'd)
AIRCRAFT COMPONENTS AND ASSOCIATED ICE PROTECTION SYSTEMS

AIRCRAFT COMPONENTS	TYPES OF ICE PROTECTION SYSTEMS USED
3. Cooling air inlet scoops	Hot air double skin anti-ice None
4. Ventilation scoops	None
5. Antennae	Hot air flowing through a leading edge cavity None
6. Radome	Hot air thru passages in surface layer None, But causes measurable aerodynamic penalty
7. Landing gear	None, but causes measurable aerodynamic penalty
8. Lights protruding from fuselage	None
9. Strakes	Hot air double skin anti-ice
10. APU inlet	Hot air double skin anti-ice None
11. Flight compartment windows	Electrical None
E. Aircraft Instrumentation	
1. Pitot static tubes	Hot air flowing through a leading edge cavity Electrical
2. Static ports	Electrical None
3. Angle of attack transducer	Electrical
4. Ice detector	Electrical
5. Total air temperature probe	Electrical
F. Other	
1. Drop out generator	None
2. Waste water drains	Electrical

TABLE II
 Penalties Associated With Presently Used Ice Protection Systems

Aircraft Component	Ice Protected	Penalties Relative Ranking: 1 = Component which causes most severe penalty to aircraft 2 = Less severe etc.	ENERGY	INITIAL COST	AERODYNAMIC	RELIABILITY	MAINTENANCE	SAFETY (IF FAILED)
Engine inlet nose cowling			2	2	3	3	2	5
Engine inlet bullet and inlet guide vanes			4	4	4	8	4	4
Wing leading edge/slats			1	1	1	2	1	1
Windshield			3	7	6	1	3	3
Horizontal tail leading edge			6	3	2	6	5	2
Cooling air inlet scoop			7	6	6	5	6	9
Fuselage strake			5	5	5	4	6	7
Antenna			10	8	6	9	6	9
Pitot Tube			8	9	6	11	6	6
Static Port			9	13	7	13	6	11
Angle of Attack Transducer			12	11	6	7	6	8
Ice detector			13	12	6	10	6	9
Total air temperature probe			11	10	6	12	6	10

horizontal stabilizer leading edges, and the leading edge of the engine cowls. Aerodynamic performance degradation in the protected areas is mainly a result of the ice which is allowed to accumulate due to time between de-ice cycles for a de-icing system or water which runs back from an anti-icing system onto areas where no ice protection is provided. Where leading edge ice protection is not provided, aerodynamic performance is influenced by the shape and extent of the ice shape.

In order to reduce initial cost of an ice protection system, it becomes necessary to design a system which is less complex than previously used. This then points to the fact that research should be directed toward developing new, less complex ice protection systems.

Energy requirements both to remove ice and to overcome extra weight and drag due to the ice or weight of the ice protection system can be reduced by optimizing present ice protection systems, or by developing new concepts with lower requirements. Since most ice protection systems have been optimized over the years, research should be directed toward developing new systems which require less energy.

The impact on the aerodynamic performance can be an important factor during design of an aircraft, for establishing those areas in need of ice protection. Research should be directed toward defining ice shapes and sizes, the effect of the ice shape on aerodynamic performance, the effect of ice shedding and the need for the 45 minute hold requirement as specified by the FAA.

The 45 minute hold in a 20 mile continuous icing cloud is the condition that provides more ice buildup than any other single icing condition. It is also the most severe for amount of runback which can occur with a running-wet ice protection system.

Another factor which affects the size of the ice is the FAR25 requirements of size of flight envelope (altitude and temperature) and the droplet size and liquid water content within that envelope. There have been many comments throughout the

industry indicating that the requirements are overly conservative. A review of these requirements may lead to a recommendation to the FAA to relax the requirement.

Table III shows components and rates them as to the effect that accumulated ice on an unprotected surface has on the aerodynamic performance of the aircraft. Further research could provide a better understanding of this effect.

DATA BASE FOR ICING TECHNOLOGY

Droplet collection efficiencies have been computed and documented in various NACA reports with a compilation of data reported in ADS-4. Most of these data were computed using a differential analyzer method. Some were confirmed with icing tunnel tests, but the cloud parameters in the tunnel were measured by the multi-cylinder method which is also based on the differential analyzer computing technique. Therefore, the analytical method and the instrumentation method are based on the same theoretical technology.

The accuracy of the differential analyzer method is largely dependent on the accuracy of the aerodynamic flow field which is computed for the component in question. Therefore, if the flow field can be computed with high confidence, then the droplet collection efficiencies would be computed with the same confidence.

Some test data has been gathered using a dye tracer technique in a wind tunnel. This technique uses a blotter attached to the leading edge. Water, with dye in it, is sprayed as in an icing tunnel. The blotter is examined to determine droplet size and impingement distribution. This method has been used to substantiate the analytical predictions.

The rate of ice accretion on unprotected surfaces is a function of the droplet collection efficiency. This in turn, is a function of the shape of the surface as a function of time, the time in the icing encounter, the LWC (liquid water content),

TABLE III

Aircraft Components and the Relative Effect of Ice Accumulation on
Aerodynamic Performance

Component (no ice protection)	Relative Effect of Ice Accumulation on Aerodynamic Performance
Wing Leading Edge/Slats	1
Horizontal Stabilizer	2
Winglets	3
Wing Tips	4
Engine Inlet Cowl External Surfaces	5
Vertical Stabilizer	6
Fences/Strakes	7
Vortilon	8
Flap Hinge Fairings	9
Wing-fuselage Junction	10
Radome	11
Pylon	12
Landing Gear (extended)	13

NOTE: Ice accumulation on the internal surfaces of the inlet cowl, inlet guide vanes, bullet, fan blades and rotor blades has essentially no effect on aerodynamic performance. This ice buildup does have a large effect on engine performance and the damage due to ice shedding into the engines can cause considerable damage leading to engine shutdown.

and the droplet size and distribution. All relationships except the shape of the ice are known and calculable. At present the determination of the shape of the ice is empirical since the flow field around an odd shaped ice accretion is not easily determined.

The surface roughness and shape of the ice accretion is dependent upon the ram air temperature. Flight test and icing tunnel data have shown that ice which builds up at cold temperatures (below 10°F) forms "rime" ice. Rime ice forms as a result of the freezing of droplets on impact and is milky white in color. The shape is somewhat regular and does not significantly alter the droplet collection efficiency of the component. The shape can therefore be determined directly from the droplet impingement distribution. Glaze ice accumulates at temperatures above 15°F and is formed by the droplets impinging and flowing a certain distance. This ice is clear and forms a horn on each side of the stagnation line due to the runback water. The ice cap drastically changes the shape of the leading edge and in turn the droplet collection efficiency. This ice cap size and shape cannot be easily determined. Unfortunately, this shape of ice cap has a greater effect on aerodynamic performance than that of the rime ice.

Much information is available on the heat required to shed ice. Very little testing has been done on the trajectory of shed ice pieces and the effect of their impact. The following are areas that may require investigation.

- o Engine damage from injected ice
- o Damage due to ice shed from turbo props.
- o Effect of non-symmetrical shedding of ice from fan blades and turbo props.
- o Trajectory of ice shed from components forward of engines.

Methods have been developed to determine the effect of ice accretion on the performance of the aircraft. These methods are used to compute the increased drag and more importantly, the reduction in maximum lift coefficient. More data on the

effect of ice accretion on aerodynamic performance are needed to expand the data base of these experimental correlations.

Areas of Improvement

The following is a list of possible areas where the data base for icing technology could be improved:

- 1) Methods of computing droplet collection efficiencies are adequate. There is room for improvements in the collection efficiency methods for rotating machinery such as turbo props, fan blades, etc..
- 2) Effort should be made in developing improved methods for predicting the size and shape of "glaze" ice.
- 3) Very little is known about the trajectory of shed ice and the size of shed ice pieces. Studies should be made in this area to determine what further investigations would realize the most benefits. The greatest payoff would probably be realized from an investigation into the effect of ice ingestion on the rotating elements of an engine, the effect of impact on the aircraft from ice shed from rotating machinery, and the trajectory of ice shed from components forward of the engine.
- 4) Additional test data on the effect of ice on aerodynamic performance would be helpful in providing a higher degree of confidence in the use of the aerodynamic performance prediction methods.

ACCURACY OF ICING TEST METHODS

Full Scale Icing Wind Tunnel:

Icing wind tunnels which permit the use of a full scale model are an accurate method of producing ice accretion data. The advantage of this type of testing is that the liquid water content, droplet size and velocity can be closely

controlled. Real time measurement of liquid water content and droplet size would increase the accuracy of the test data. The disadvantages are that the tunnels are limited in (1) size, (2) altitude, (3) velocity and (4) the ability of the spray system to provide the required liquid water content and droplet size. Use of the well known scaling factor, K_0 , may be used to increase the capabilities of the tunnel. This factor is a function of droplet size, velocity, air temperature, altitude and model size. For models having the same shape and the conditions providing an equal K_0 , the collection efficiency for both models is equal.

Availability of icing wind tunnels is generally within six (6) months to a year of application for testing. With good planning this should not be a detriment. Cost of this type of testing is high but acceptable.

Subscale Icing Wind Tunnel:

Testing of subscale models in an icing tunnel has the same advantages and disadvantages as full scale testing but to different degrees, though the subscale method is usually less expensive, it is also less accurate. The higher degree of scaling the less accurate the data. Some scaling may be necessary due to the limited size and performance of available icing tunnels. Scaling should be kept to a minimum even though the scaling parameter K_0 can be applied.

In-Flight Spray Rig/Tanker:

This can be used to determine the effect of ice accretion on a component of an aircraft during actual flying conditions. It is inexpensive for general aviation manufacturers who have developed their own tankers.

This test method lacks control of the droplet size and liquid water content at the component due in a large part to evaporation. Also, only a portion of a commercial aircraft can be covered by the limited size of available spray rigs. Because of the inaccuracies and inability to produce conditions equivalent to natural icing, spray rigs/tankers have not been acceptable for FAA certification in the past.

Ground Spray Systems:

Ground spray systems have been used effectively in the past for testing of engines and helicopters in the hover mode. With this method the liquid water content and droplet size can be closely controlled by measuring conditions at the component being tested. Because of the dependence on weather conditions this method of testing presents the risk that needed conditions will not develop at the test site.

Natural Icing:

The best icing data can be obtained from natural icing flights, if good instrumentation is used and is operating satisfactorily. If flight conditions which produce glaze ice at hold speeds are encountered, natural icing conditions produce representative ice shapes for all components. Natural icing tests are also needed to evaluate flying characteristics with ice on all unprotected surfaces and are deemed mandatory by the FAA for certification of new aircraft.

The main drawback for natural icing flights is the difficulty in finding the right condition and the cost of flying the aircraft over a wide area in search of a severe encounter. The encounter must be of sufficient severity to gather data needed to confirm satisfactory flight characteristics as well as performance of the systems.

Analytical Techniques & Computer Programs

Most of the major commercial aircraft manufacturers have analytical techniques and computer programs available to accurately compute water collection rates and ice protection system performance. These analyses have been proven by matching test data from clear air, natural icing and icing wind tunnel tests with analytical predictions. This method has a relatively low cost. One observation is that these techniques have been developed at considerable expense and are proprietary and not available to the minor and infrequent commercial aircraft manufacturers.

IMPROVEMENTS IN TESTING

Scope of Data:

The data which has been acquired seems to have been adequate for designing ice protection systems for aircraft of 25 years ago. In order to satisfy today's needs, which include new technology aircraft components and greater fuel efficiency; the following additional information is required:

- 0 Ice accretion data on new types of airfoils, such as supercritical airfoils and the effect on aerodynamic performance.
- 0 Ice accretion data on airfoils with high lift devices deployed.
- 0 Effect of engine mass flow ratio on nose cowl water collection.
- 0 Methods of predicting ice cap shapes and sizes on all components.
- 0 The definition of shadow zones and high concentration zones in the near vicinity of large bodies.
- 0 Droplet impingement data on new shapes of high speed turbo-props for commercial applications.

Testing Techniques:

As stated above most icing tunnels are limited in capability as to velocity, altitude, liquid water content and droplet size. These variables can be simulated for ice accretion testing. To test a heated leading edge ice protection system in the tunnel, the heat transfer external to the test specimen must also be controlled. There are no generally accepted methods available for these simulations. One should be developed.

There are no generally accepted test procedures for certifying aircraft in natural icing and in clear air. It would be helpful if test procedures were standardized along with acceptable liquid water contents and flight duration. A review of previous certification tests could lead to a composite standard test. This test plan could be recommended to the FAA for approval.

Instrumentation:

There are several methods of measuring parameters of icing clouds in nature and of those artificially produced. The manufacturers make claims as to the accuracy and capability of the instruments. These instruments should be tested against a standard to determine which are viable and which are not. From this study a standard measuring device providing real time output could be recommended for approval by the FAA. The instruments could then be used during all types of testing with no question as to the acceptability of these data.

Analytical Methods:

Analytical techniques which seem to be universally lacking throughout the industry are as follows:

- o Water droplet trajectory analysis for three dimensional bodies (swept wings, etc.).
- o Ice accretion modeling.
- o Prediction of shed ice trajectories.

Another helpful aid for designing ice protection systems for aircraft would be a new handbook of icing technology which would include state-of-the-art technology and areas overlooked in previous handbooks. Items that should be included are:

- o Ice accretion data on new type airfoils with and without high lift devices (super critical airfoils, etc.).
- o Effect of ice formation on unprotected areas, including runback ice from protected areas.
- o Effect of engine mass flow on nose cowl water collection.
- o Ice shape prediction methods.
- o Shadow zones and high concentration zones near fuselage.
- o Updated statistical data on icing conditions.

Operating Parameters of Experimental Facilities:

The following are a list of parameters which are required of experimental icing facilities by the commercial aviation industry:

- o Altitudes up to 30,000 feet
- o Velocities up to 400 knots true air speed
- o Liquid water contents and droplet sizes covering the range of FAR 25 in Appendix C.
- o Real time measurement of liquid water content and droplet size.
- o Data recording instruments for model and tunnel temperatures and pressures.
- o Instrumentation to measure change in aerodynamic performance degradation due to ice accretion.
- o Automatic control of icing tunnel parameters such as; temperature, velocity, liquid water content, droplet size, etc.

EFFECT OF ICE ON AERODYNAMIC PERFORMANCE

If the effect of ice on aerodynamic performance were known, ice protection systems might not be required on some components now protected. The degree of ice protection might also be reduced.

The effects of ice accretion on the overall flight characteristics of modern turbojet-powered aircraft can be more significant than the resulting drag increase. Therefore, in addition to a drag analysis, an estimate is made of the effects of such accretions on the wing and tail maximum lift coefficients. This is done utilizing a method based on an empirical correlation of the effects of wing surface disturbances. One such correlation, developed by Douglas Aircraft and shown in Figure 1 for a high lift device retracted configuration, is based on wind tunnel and flight test data for wing leading edge surface disturbances ranging from small frost-like roughness elements to large horned icing accretions. For icing accretions that do not substantially alter the basic airfoil shape, such as light to moderate rime icing, the loss in maximum lift coefficient (C_{lmax}) can be

FIGURE 1 ESTIMATED EFFECT OF ROUGHNESS ON MAXIMUM LIFT COEFFICIENT

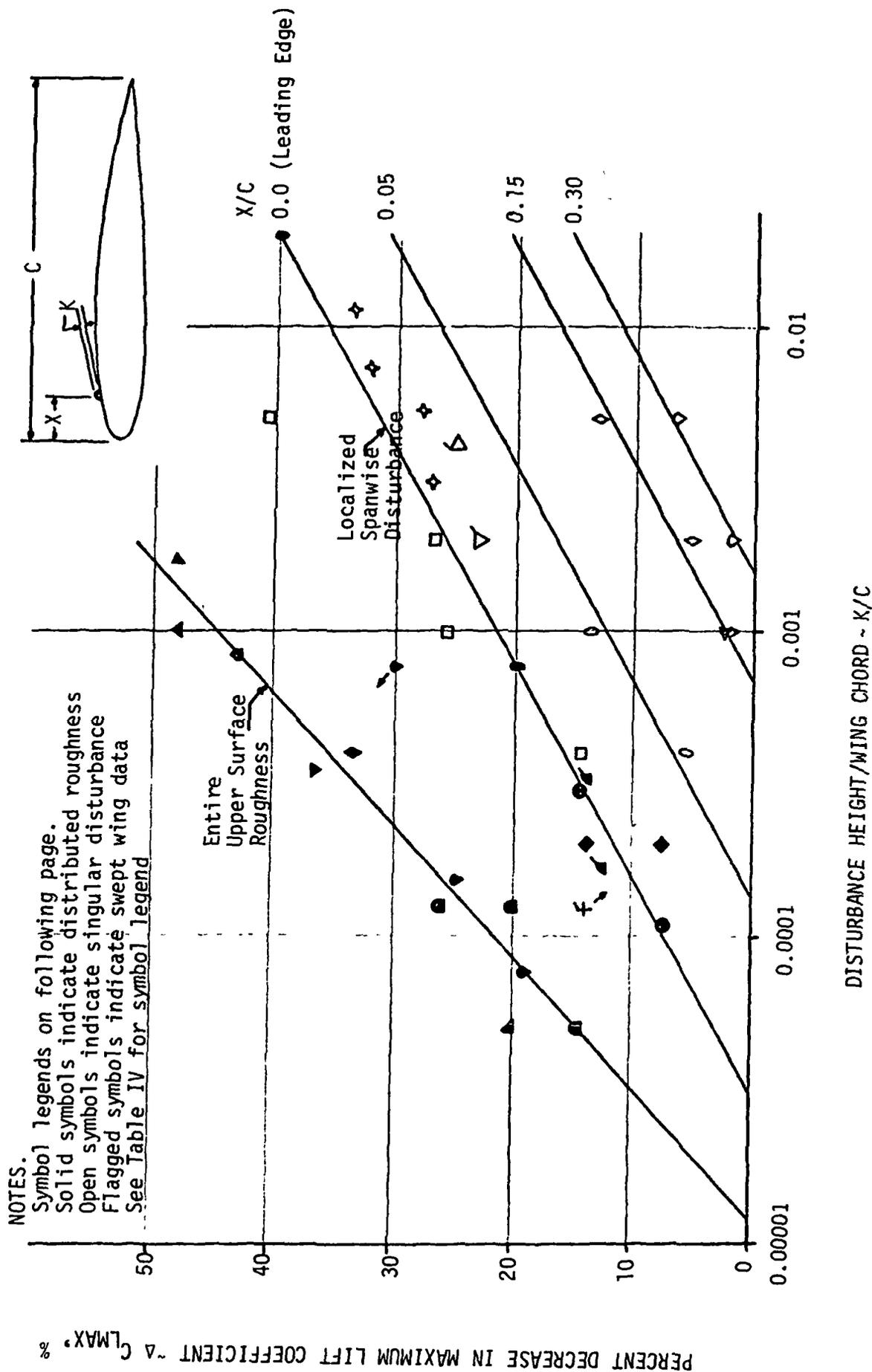


TABLE IV. FIGURE 1 SYMBOL LEGEND

<u>SYM</u>	<u>REYNOLDS NO.</u>	<u>TYPE OF ROUGHNESS</u>	<u>REFERENCE</u>
●	26×10^6	Sand Grain Band	"Theory of Wing Sections" (Abbot)
□	3.1×10^6	Protruding Strip	NACA TR 446
◆	" "	Multiple Grooves	NACA TN 457
▲	" "	Carborundum Grit	" "
▴	5×10^6	Sand Grains	"Aerodynamische Profile" (RiegeIs)
▾	6.3×10^5	Wire Mesh on Surface	NACA TM 375
▽	3.1×10^6	Fwd Facing Step	NACA TN 457
◇	" "	Protruding Strip	NACA TR 446
◊	" "	" "	" "
○	" "	" "	" "
●	3.6×10^6	Carborundum Grit	NACA TN 457
▼	----	Frost (in icing tunnel)	NACA TN 2962
↙	24×10^6	Insect Contamination	Flight Training Incident (DC-9)
↘	4.5×10^6	Simulated Tailplane Ice	(DC-9)
↗	5.5×10^6	Simulated Tailplane Ice	(DC-10)
↖	7.8×10^6	Simulated Deicer Boot	(C-133)
↕	7.0×10^6	Carborundum Grit	R&M 1708
f	24×10^6	Chipped Paint on L.E.	(DC-9)
◆	29×10^6	Ballotini	NPL AR 1308
▾	24×10^6	Burred Rivets on L.E.	(DC-9)
◆	3.2×10^6	Simulated Frost	FFA RPT AU-902
◇	1.8×10^6	Simulated Wing Ice	FFA RPT AU-995
●	----	Simulated Ice Roughness	ICAO BUL. Oct 77

estimated by entering Figure 1 at a K/C value corresponding to the height of the ice "bumps". For large accretions, such as a horned ice catch, an equivalent roughness height is estimated as shown in Figure 2.

The results are utilized to either define the spanwise extent of ice-protection required, or to guide the design of components to compensate for the effects of ice accretion. The validity of the results are normally verified during subsequent developmental wind tunnel testing, using simulated ice shapes, and confirmed during flight testing with either simulated or natural ice accretions.

NEW ICE PROTECTION SYSTEMS

Icephobics

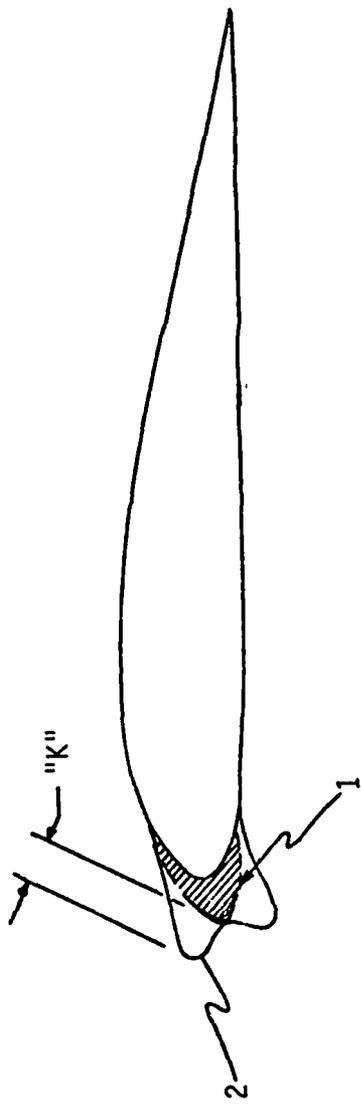
In the past many icephobic coatings and materials have been tested in the icing tunnels and laboratories. To date, none have proved successful in shedding ice with only aerodynamic forces applied to the ice cap.

An icephobic coating would have a high payoff if one could be developed which would satisfactorily release the ice. The probability is high that it will be impossible to develop a candidate material. The real payoff for icephobics may lie in the area of use in conjunction with another type of ice protection system. The icephobic may allow the reduction in weight or energy required to provide adequate protection. The system may perform better in conjunction with an icephobic by providing a cleaner airfoil.

Probably the best method of appraisal will be to test new candidate materials as they are developed. Most of the testing could be done in the laboratory and then promising material evaluated in an icing wind tunnel alone or in conjunction with other ice protection systems.

Should an icephobic substance be deemed capable of causing ice to shed from an aircraft component, then data should be taken at a variety of icing conditions in

FIGURE 2 EQUIVALENT ROUGHNESS HEIGHT



For use in estimating the reduction in maximum lift coefficient, the icing accretion is assumed to be composed of two parts, as shown above.

1. A smoothly faired approximation of a chord extension to the point of minimum ice thickness
2. An equivalent roughness element of height "K"

the tunnel. After successful testing, the icephobic substance should be applied on an in-service aircraft to determine its durability and compatibility with commercial aircraft operation. It should also be tested in natural icing conditions. This system would work well with any component which incorporates either a metallic or a smooth non-metallic leading edge.

Electro-impulse

The electro-impulse de-icing system has been developed by the Russians and has been licensed to various manufacturers around the world. This system consists of a series of coils spaced along the leading edge of an airfoil. The coils are mounted in close proximity to the inside surface of the leading edge. A capacitor in series with the coil is charged. Discharging of the capacitor through the coil sets up a magnetic field. This magnetic field induces an eddy current in the leading edge skin which in turn sets up an opposing magnetic field in the skin. The resultant pulse causes sufficient movement of the metal that the ice adhering to the outer surface shatters and is carried away by the airstream.

This system is simple, and according to Russian information is about 400 pounds lighter and requires 1/40 the energy of that required for a large commercial aircraft, hot air wing anti-ice system.

This system has been tested by the Russians and the French. Development work is continuing by both groups. To our knowledge, the system has not been installed on any production aircraft, other than the Russian produced IL-86, wide-bodied commercial aircraft.

To develop this system for use by manufacturers in the United States would require further development testing. This testing should address the following questions:

- o Size of coils and capacitors
- o Required spacing along the leading edge
- o Determination of ideal chordwise location of coils for best effectivity
- o Evaluation of the effect on fatigue life of the structure

- 0 Design of a reliable control system for systematically discharging the capacitors.
- 0 Determine the compatibility of the system with the aircraft electrical system.

All the above factors must be determined as a function of the size of the component being de-iced and the location of ribs and spars in the leading edge.

The above should be sufficient for design data. The certification would need to be accomplished on the production component or full scale model thereof.

This system would require additional considerations for use with a non-metallic leading edge because of the need to produce eddy currents in the material.

Microwave Ice Protection System

This system consists of a microwave generator which sends the microwave energy through a wave guide. The wave guide forms the leading edge of the component to be ice protected. The wave guide is made of a material with a dielectric constant approximately equal to that of ice. When ice forms on the wave guide, the ice also forms a portion of the now thicker wave guide. The microwaves then activate the water molecules, heat the ice to melting and in the process de-ice the component.

The microwave system has not been tested in an icing tunnel according to available documentation. This must be tested in an icing tunnel to determine the following information:

- 0 Energy required to de-ice/anti-ice.
- 0 Effectiveness of system in melting ice
- 0 Erosion resistance of wave guide
- 0 Effect of microwaves on other aircraft systems, such as; electrical, communications, etc.

For certification, the actual component would need to be installed on an aircraft and flown in natural ice. The material to which the wave guide is attached should have a dielectric constant considerably different from that of the wave guide so as not to affect the transmission of the microwaves.

Ice Tolerant Aerodynamic Shapes

The designing of ice tolerant aerodynamic shapes for airfoils and other components depends on the capability of determining the effect of ice on the aerodynamic characteristics of the component. This method was described earlier in this report.

Therefore, any testing that provides data for ice cap shape and size and its effect on aerodynamic properties of the component would be a part of the data base for designing ice tolerant components. The ice tolerance of a component depends heavily on the aerodynamic requirements of the aircraft. Cost and performance studies must be made to determine if the penalty is more severe with an ice tolerant component or an ice protection system.

It is expected that both a smooth composite or metal leading edge would have the same ice tolerant aerodynamic shape.

Certification of an ice tolerant shape would involve flying the component on the aircraft with a simulated ice cap installed.

AIRCRAFT OPERATION IN ICING CONDITIONS

One method to save fuel or save initial cost and weight is to design a system which will ice protect the aircraft in only a portion of the FAR 25 icing envelope.

It would appear that it is not practical to design an anti-icing system for commercial aircraft which will provide ice free surfaces only when the icing encounter is less than the most severe continuous icing condition. This statement is based upon the fact that commercial aircraft must fly a specified route at a

specified time. Also, the severity of the icing encounter is frequently not known upon entering clouds, and, even if it is known, it may be impossible to avoid the severe icing conditions and still maintain an acceptable schedule. Based on these facts, it is desirable to design the anti-icing and de-icing systems for commercial aircraft to meet the most severe continuous icing conditions. On the other hand, there may be an advantage in this for general aviation and helicopters.

In order to use a system with lower performance capabilities, the crew must be aware of the severity of the icing conditions which are encountered. This requires that an awareness exists regarding the rate that water is encountered by the aircraft, the total air temperature, and the ambient pressure; if an anti-icing system is used. If a de-icing system is used, the total air temperature and the amount of water encountered in a certain amount of time must be known. The severity of an icing encounter for which proper protection can be provided will generally not be the same for anti-icing and de-icing system. It will also vary for different aircraft.

Several types of commercial aircraft have different descent schedules for descent in clear air than descent in ice. For an airplane with thermal anti-icing, the descent in clear air is at a lower engine thrust setting and therefore more fuel efficient. The descent into icing conditions is at a higher thrust setting and less fuel efficient. An even less fuel efficient operation occurs when a descent is planned through non-icing conditions and then ice is encountered. Now, to maintain the descent schedule, the power increase for ice protection must be offset by an equivalent drag increase. More reliable forecasting of icing conditions prior to initiating descent would help save fuel.

Aircraft that have collected ice while on the ground need to be de-iced prior to takeoff. This is usually done with a hot glycol solution sprayed over the aircraft surfaces. Often in inclement weather the aircraft will ice up again prior to takeoff. An end of runway installation that the aircraft would taxi through and be sprayed with de-icing fluid would be a money saver and increase safety.

ICING INSTRUMENTATION

Uses

Commercial aircraft can benefit from an ice detector which advises the crew that the aircraft is actually in an icing encounter. This will enable the crew to turn on the ice protection system only when ice is encountered and to turn it off when the encounter is past. With this approach the energy required for ice protection is expended only when needed and the fuel usage is minimized.

Another use of icing instrumentation is during icing tests. There is a need for accurate measurement of liquid water content and droplet size for analytical correlation and for FAA certification. It would be desirable to have standardized equipment that could be used in icing tunnels, ground spray systems, and onboard aircraft for tanker tests and natural icing flight tests.

There have been discussions in the past regarding the benefits of an ice detector located in the engine inlet versus one on the fuselage of the aircraft. The engine location would detect ice while the aircraft is stationary with engines running and there are some conditions where icing may occur in the engine inlet while the rest of the aircraft is above freezing. The advantage of a fuselage location is a more favorable environment for the detector and close proximity to the cockpit which reduces installation weight and cost (shorter wiring).

The airlines, through the survey, have expressed a desire to have an ice detector which would indicate residual ice on the aircraft prior to takeoff. This ice may have accumulated through freezing rain or by snow melting and re-freezing. This indication would inform the crew of the need to deice the entire aircraft prior to takeoff.

Detector Types

Several different types of ice detectors have been developed for commercial use.

They are as follows:

- ° A rod located so it will collect ice and is visible from the flight compartment and can be illuminated for night operation. It has a heater to de-ice it subsequent to ice detection, so the pilot can determine when the aircraft is no longer in the icing cloud.
- ° An ultrasonic system which consists of an axially vibrating rod mounted in the airstream where it can collect ice. The frequency of the rod is matched to a stable reference frequency generated electronically. When ice builds up on the rod it changes the frequency so that the two frequencies no longer match. This mismatch causes a light to illuminate in the cockpit and a heater to de-ice the rod. A device of this sort can also be used as an icing rate meter by monitoring the rate of change of frequency or the frequency of the probe de-icing cycle.
- ° A hot wire system which has two heated sensors. Both sensors are exposed to the air stream. One is located in an impingement area and the other in a shadow zone (an area where impingement will not occur). The system attempts to maintain both sensors at the same temperature level. A difference in power required to each sensor indicates the presence of free moisture. The differential is indicative of the liquid water content. A ram air temperature below 32^oF in conjunction with the power differential, indicates that an icing condition has been encountered.
- ° A radioisotope system consists of a radioactive beta particle source and a Geiger-Muller counter. As the ice builds up on the area between the two, the beta particles are attenuated below the value normally read by the counter. This illuminates an advisory light in the cockpit to inform the flight crew of the icing condition and de-ices the area between the source and counter. The time between de-ice cycles is a function of the icing rate.

- ° An infrared system which operates similar to the radioisotope system but has an infrared emitter and detector in place of the beta particle source and the counter.
- ° A pressure differential sensor which compares the dynamic pressure sensed at one large hole in the leading edge of a probe with that sensed by a number of smaller holes also located in the leading edge. A small hole at the tip of the probe senses a low pressure in a region not susceptible to icing. This hole communicates with the same passage that senses the pressure at the small holes in the leading edge. When ice blocks the small dynamic pressure sensing holes, the sensed pressure drops to that existing at the tip hole. This causes sufficient pressure differential to develop between that sensed at the big hole and that sensed at the small holes so that a differential pressure switch actuates. This switch outputs an icing encounter signal and applies power to a heater element to de-ice the probe. Time between cycles is a function of the icing rate.
- ° A rotating cylinder and cutter where the torque required to shave the ice from the cylinder activates a display in the aircraft cockpit to inform the crew of icing conditions.

Cloud Property Determination

- ° The rotating multicylinder method measures the median droplet size, liquid water content and droplet size distribution. This method was developed several years ago. Its calibration is based on calculation of droplet trajectories using the differential analyzer method.
- ° Size and distribution of water droplets plus the liquid water content can be measured using laser holography. This technique consists of measuring the interference bands associated with half a beam passing through a water droplet and the other half undisturbed. This interference is related to the droplet size.

0 An oil coated slide momentarily exposed to an icing cloud can be used to visually measure the droplet size, distribution and liquid water content. A 35 mm slide frame coated with gelatine can be used in the same manner. Quite often these methods do not record accurately the smaller droplet because of the low collection efficiency of the slides.

Recommendations

A Douglas Aircraft, in-house review of the available ice detectors has shown that the ice detector with the simplest installation and best reliability in combination with reliable indication is the ultrasonic system.

None of the candidates for measuring droplet size and liquid water content stands out over the rest. Further studies and tests should be made of available instrumentation. The results should dictate which measuring devices should be developed to be used onboard aircraft, in icing tunnels, and with ground spray rigs.

RECOMMENDATIONS

Icing Research Tunnel

Following is a list of features that could be incorporated to make the NASA Lewis Icing Research Tunnel (IRT) more capable of meeting future needs of icing research:

- o More accurate methods of setting the liquid water content and droplet size.
- o An automated control system which would assist in faster stabilization of tunnel conditions to save time and energy.
- o Instrumentation to measure droplet size and liquid water content during testing.
- o A direct method of measuring increased drag and also reduction in maximum lift coefficient due to ice accretion (e.g. force-balance system).
- o Recalibrate the tunnel for liquid water content and droplet size if no real time measurement is available.
- o Periodically check uniformity of icing cloud and adjust as needed.

Altitude Wind Tunnel

A majority of the responses to the commercial aircraft icing survey have indicated a need for a facility such as the Altitude Wind Tunnel (AWT) at NASA Lewis to be converted to an icing tunnel. Features in addition to the above listed for the IRT that should be included in the AWT are:

- o Altitudes up to 30,000 feet
- o Speeds in the range compatible with commercial aircraft hold speeds (up to 400 knots true air speed).
- o Liquid water content values in the range of continuous and intermittent icing as defined in FAR 25, Appendix C.

Test Techniques Needed for Icing Research

The normal design condition for commercial aircraft ice protection is a 45 minute hold in a 20 mile continuous icing cloud. This is also the design condition for

maximum ice cap size in an unheated area. Most icing tunnels, including the IRT, do not have the capability of producing the needed liquid water content at the needed mean droplet diameter as specified in FAR 25, Appendix C. Many of the tunnels including the IRT, do not have altitude capability. Impingement and the internal and external heat transfer coefficients on the model are a function of altitude.

Simulation testing techniques should be developed to overcome the tunnel limitations and enable the model to be tested at altitude design conditions. Some successful attempts by Douglas Aircraft Company have been made at developing these techniques, but none have been documented.

Methods of measuring resultant ice caps and/or runback off the heated surfaces should be improved. If the ice is scraped, often part of the ice blows down the tunnel before it can be captured. If the icing surface is heated to melt the bondline, some of the ice melts and runs off.

Instrumentation is needed for icing research for measuring liquid water content and droplet size during icing tunnel, ground spray rig, tanker and/or natural icing tests. This instrumentation should be approved by the FAA and the military and standardized so all testing can have the same basis for icing cloud parameters. A good candidate for this is laser holography.

The only other facilities that could be used in conjunction with NASA Lewis Icing Tunnels are wind tunnels where drag and lift coefficients could be measured on airfoils with simulated ice accretion shapes affixed to them. The ice accretion shapes would have been determined in the IRT or, in the future, the AWT.

An effort should be made to coordinate between the various icing tunnels throughout the country/world so that testing accomplished at one icing facility could be duplicated at other facilities. Part of this effort would be methods of measuring the icing cloud parameters, the air temperature, and the air velocity during the tests.

CONCLUSIONS

GREATEST PAYOFF AREAS

The greatest payoff area for commercial aircraft would be in developing new ice protection systems or optimizing presently used systems. The areas where benefits would be realized are: weight savings, fuel savings, high reliability, lower manufacturing costs, and low maintenance.

Optimization of present ice protection systems could be used to improve commercial aircraft. This improvement is small compared to that which could be realized by new systems.

One of the new systems which has a decided advantage in weight and fuel savings is the electro-impulse de-ice system. The weight savings for a commercial jet aircraft can be as much as 400 pounds and the fuel usage as low as one-fortieth of conventional systems.

There are some unanswered questions. What effect do the impulses have on structural integrity, namely, riveted attachments? Does the aerodynamic performance of the wing or other surface allow for ice buildup between de-ice cycles and how clean need the surface be after the de-ice cycle? Any one of these points could make the system unusable.

Another system which has a high payoff possibility is ice phobics. Development of a material or solution that could be applied to the leading edge which would allow ice to shed due to aerodynamic forces would be a tremendous advancement in ice protection. The drawback is that there may never be a material that will accomplish this. It may be more of an advantage to determine the gains realized by using the ice phobics in conjunction with other systems to reduce the overall fuel costs and weight of the primary ice protection system.

Another system which requires more research is the microwave system. If this system is proven to be viable, it could be used as an anti-ice or de-ice system for areas that can not be easily adaptable to other ice protection methods. This system could replace electrically heated systems which are normally not damage tolerant.

There are several instruments that have been developed for measuring icing parameters within an icing cloud. These various instruments should be tested to determine their accuracy and consistency. They should all be tested in identical environments. The outcome of this should be acceptance by the military and the FAA of approved icing instrumentation to be used for certification testing of ice protection systems.

Some of this same instrumentation can and is being used as ice detectors. Those and other ice detectors should be tested in identical environments to determine sensitivity to ice and to evaluate the sensor characteristics.

There is some controversy whether it is necessary to install the detector in the engine inlet or on the fuselage. In-service tests of dual locations would help determine the optimum location for an ice detector.

NASA SHORT RANGE ICING RESEARCH PROGRAM

The following is a list of proposed goals for a short range NASA icing research program that would benefit the commercial aircraft industry. These goals are short range and should be started within a year and accomplished by the end of two years. The order in which the goals are listed is a recommended priority. The costs included are estimates based on the job being done by a commercial aircraft company rather than a college or university. The costs are also based on 1980 dollars.

- 0 Develop and test the electro impulse de-ice system that is low in cost and has fuel saving qualities. The system should be tested in the lab prior

to constructing full scale models for tunnel testing. If the lab tests give encouraging results, then icing tunnel testing should follow to gather design data. The information which should be provided by these tests are feasibility of the system including ice protection effectiveness, effect on structure, reliability and a minimum amount of design data to allow a system to be designed for an aircraft. Total cost of system development, lab tests, model fabrication and tunnel testing is approximately \$500K.

- 0 Using a super critical airfoil, run a series of ice accretion tests in the tunnel and measure the effect of ice accretion on drag and lift coefficients. Compare the results of ice accretion and its effect on drag and lift to a conventional airfoil of the same basic size and shape. Evaluate the difference in ice accretion and also the difference in the effect on drag and lift. Cost estimate \$500K.

- 0 Obtain one of each of the various types of available devices for measuring cloud properties. Test these either simultaneously or in identical environments in the IRT. Based on the results of these tests, recommend acceptable types to the military and the FAA for their approval. These instruments could possibly then be used in the tunnel, with ground spray rigs, or on board the aircraft to measure icing cloud parameters during icing certification tests provided the velocity differences did not limit their use. Estimated cost of program, including tunnel costs, \$150K.

- 0 Develop computer programs for ice protection analysis. The order of importance is as follows:
 - I. Ice accretion modeling on airfoils, inlets, rotors, etc.
 - II. Prediction of aerodynamic penalties due to ice accretion
 - III Prediction of shed ice trajectories
 - IV Water droplet trajectories for 3-D lifting and non-lifting bodies

Each computer program would cost approximately \$100K. This would not include tests to gather data to validate the programs.

NASA LONG RANGE ICING RESEARCH PROGRAM

The following is a list of proposed goals for a long range NASA icing research program that would benefit the commercial aircraft industry. These goals are long range and could be accomplished over a number of years. The order in which the goals are listed is a recommended priority.

The cost estimates are based on 1980 dollars and assume the effort would be accomplished by industry rather than a university.

- o Initiate a program to evaluate new materials with ice phobic properties that have not been tested previously. These tests may be accomplished in the lab to measure the adhesion forces between the ice and the ice phobic. If the adhesion forces are found to be low enough, the ice phobic should be affixed to the leading edge of an airfoil model or a propeller and tested in an icing tunnel. This would be an ongoing program dependent upon the availability of untested ice phobics. Cost could be as much as \$25K per ice phobic for lab tests. Tunnel testing would be approximately \$75K per ice phobic. As stated previously, the payoff would be great but the risk is also great.

- o An off shoot of the ice phobic program would be to test the best candidate ice phobic in conjunction with an anti-ice or de-ice system such as hot air or electro-thermal. It may also be tested in conjunction with new ice protection systems such as microwave or electro-impluse. The estimated cost of an icing tunnel test to determine the advantages of an ice phobic used in conjunction with another ice protection system would be approximately \$200K if a basic model were available and \$300K if a model were not available.

- o Initiate a program to determine water catch rates and impingement limits for advanced turboprops. This could be used for design of ice protection for the advanced engines which are being proposed for commercial aircraft. This program would include several different shapes of propellers at an array of icing conditions within the FAR-25 envelopes. The test would be a stationary test in the IRT with simulated airflow around the turbo prop. Cost estimate \$400K. A test using rotating machinery could provide more accurate results, but the cost would be much higher. The IRT probably does not have the capability and the AWT is not functional at this time.

- o Develop and test a microwave ice protection system which is low in cost and has fuel saving qualities. The system should be tested in the lab prior to constructing a full scale model for tunnel testing. If the lab test gives encouraging results, then icing tunnel testing should follow to gather design data. The information which should be provided by these tests are feasibility of the system and a minimum amount of design data to allow a system to be designed for an aircraft. Total cost of system development, lab tests, model fabrication and tunnel testing is approximately \$500K.

- o Determine feasibility of predicting ice prior to descent so that the most fuel efficient descent may be programmed based on icing conditions that would be penetrated or possibly avoided. This would involve review of icing statistics and study of present icing forecasting capability such as satellite data. Approximate cost \$30K.

- o Review natural icing and clear air tests that have been performed for certification of all commercial jet aircraft ice protection systems. From this review, propose a test plan and associated analysis necessary to obtain FAA certification. Propose this to the FAA so all aircraft may then be certified on the same basis which would save time, money, and be equitable for all manufacturers. Estimated cost \$75K.

- 0 Update or develop new handbook of icing technology to include advances in the state of the art and include areas that were previously overlooked. Cost estimate \$100K.
- 0 The FAA requires the hold design icing condition for commercial aircraft to be 45 minutes in a 20 mile continuous icing cloud. Due to the versatility of commercial aircraft and the inconsistency of icing clouds, this is a very conservative requirement. Through studies of service experience and contact with airlines, establish a more realistic design hold condition for icing. This would then be proposed to the FAA for approval. Estimated cost \$50K.
- 0 Initiate a program to develop a sensing system to indicate to the flight crew that excess quantities of snow or ice have accumulated on the aircraft prior to takeoff. This would allow the crew to take the precaution to clear ice from the aircraft. Adaption of an existing ice detector would probably be required. Cost estimate \$100K.
- 0 Working with airlines and airport facilities, develop an end of runway ground de-icing facility which will clear aircraft of ice which collected while the aircraft was on the ground. This would also provide protection from ice buildup from the time the aircraft is de-iced until liftoff. Cost unknown.
- 0 Review natural icing conditions previously measured and initiate program to collect additional data on natural icing conditions. Based on this data, propose a revision to FAR-25 Appendix C, icing envelopes to make them more representative of actual conditions encountered. Cost unknown.

NASA CONTRIBUTION

NASA could make the greatest contribution to commercial aircraft icing research by working with the airframe manufacturers, engine manufacturers, airlines and others to promote the aforesated goals. Also, NASA could provide leadership and funding to support the goals. One further area for NASA is to provide the facilities necessary to perform the tests required to support these goals. This would include continuing to improve the IRT and also to convert the AWT into an icing tunnel with capabilities up to 400 knots, altitude up to 30,000 feet and liquid water contents and drop sizes necessary to simulate the entire icing envelopes as defined in FAR part 25, Appendix C.

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APPENDIX A

Icing Survey Information

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APPENDIX A

Icing Survey Information

The icing survey questionnaire which is included on the following pages was sent to 43 separate airlines, aircraft manufacturers and regulatory agencies. The results of this survey were used to assess the present state-of-the-art of ice protection system design. The survey was also useful in defining the proposed short and long range icing research programs for NASA.

Following is a list of those companies/agencies which responded to the survey. Their cooperation is appreciated.

- o Air Canada
- o Boeing Commercial Airplane Company
- o CP Air
- o The deHavilland Aircraft of Canada, Limited
- o Department of Transportation, Federal Aviation Association, Northwest Region and Western Region
- o Fairchild Republic Company
- o General Dynamics
- o Hamilton Standard
- o Lockheed-Georgia Company
- o McDonnell Aircraft Company
- o Messerschmitt-Bolkow-Blohm
- o Pratt & Whitney Aircraft Group
- o Rockwell International
- o Rolls-Royce Limited, Aero Division
- o Scandinavian Airlines System
- o Swissair



National Aeronautics and
Space Administration

Washington, D C
20546 .

Reply to Attn of

Dear

NASA has recently started a new program in aircraft icing research at the Lewis Research Center, Cleveland, Ohio. The program will include in-house research, university grants, and industry contracts. Since you are a member of the large transport aircraft industry (manufacturer or operator), your recommendations for our icing program are important.

Therefore, we have included with this letter a QUESTIONNAIRE on aircraft icing. Your responses to this QUESTIONNAIRE will help NASA determine what advances in aircraft ice protection technology will most benefit your industry. We hope you will consider this an opportunity to voice your concerns about aircraft icing, and to influence future NASA research.

Rather than send this QUESTIONNAIRE directly to the person responsible for ice protection in your organization, we are sending it to you to insure that the responses represent corporate technical policy. Since the QUESTIONNAIRE is rather long, please respond only to those questions that your organization regards as important.

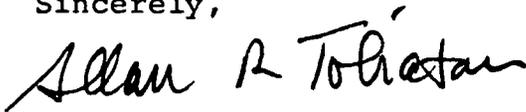
Please understand that the enclosed QUESTIONNAIRE is intended to aid you in communicating your thoughts to NASA. It should be considered as a guide. Please feel free to omit answers to questions or address your concerns in letter form if you deem it appropriate to do so. NASA is interested in your ideas, not the form in which they may be submitted. You are under no obligation to respond to this request, but all replies will be given careful consideration.

If you choose to respond, please do so within two weeks of the date of this letter. Please send your replies and address any inquiries to:

Mr. Larry Koegeboehn
Douglas Aircraft Company
Mail Code 36-47
3855 Lakewood Boulevard
Long Beach, CA 90846

Telephone: (213) 593-6094

Sincerely,



- Allan R. Tobiason
Manager, Aviation Safety Technology

Enclosure

P.S. The two weeks mentioned above for your response may not be compatible with your schedule, therefore we would appreciate receiving your comments at any time in the near future.

INTRODUCTION

The NASA Lewis Research Center, Cleveland, Ohio, has contracted with the Douglas Aircraft Company to conduct a study for commercial aviation icing research requirements. The objectives of the study are to define for NASA both a long-term and a short-term icing research and technology program that is responsive to the needs and desires of members of the commercial aviation industry.

For the purposes of the study and this survey, commercial aircraft is defined as fixed wing aircraft with a capacity of over 30 passengers. Aircraft with the following types of engines are being considered: jet and turboprop engines.

OBJECTIVES OF THE QUESTIONNAIRE

The objectives of this survey are to solicit from commercial aircraft manufacturers, government agencies, and others technical data, where available, but more importantly, their views, comments, and recommendations concerning icing research subjects. This should be considered by the respondents as an opportunity to voice their concerns relating to icing and icing protection, and to influence the direction of future NASA research. Your inputs will allow the reflection of the broader view of the commercial aviation industry in the recommendations given to NASA for short-term and long-term research plans.

QUESTIONNAIRE/SURVEY QUESTIONS

The questions in this survey have been grouped into six basic sections dealing with: (1) ice protection systems, (2) ice protection penalties, (3) propulsion system icing, (4) airframe icing, (5) testing techniques, (6) calculational techniques, (7) weather data, (8) final recommendations.

I. ICE PROTECTION SYSTEMS

1. Established ice protection systems include (1) hot air from compressor bleed, (2) electrothermal, (3) pneumatic boots, (4) engine waste heat,

and (5) anti-freeze fluids. The USSR has developed an electromagnetic impulse ice protection system for which they are offering licensing agreements. What additional development, research data, design data, or performance data are required for the systems mentioned above?

2. Icephobics (materials that reduce ice adhesion) development is a high risk, high payoff venture. What priority should NASA place on developing an ice phobic?
3. What are the most important features that any new ice protection system should provide?
4. If new ice protection systems could be developed or existing ones improved, which ones would provide the greatest payoff?

II. ICE PROTECTION PENALTIES

Information is needed on penalties to the aircraft or to individual components due to the effects of icing. It is requested that Table I be filled out for the various aircraft or components manufactured or tested by your company for which icing penalties are available. Note that penalties may be given as actual values, if known, or relative rankings of the penalties involved.

In addition, penalties on aircraft due to the use of ice protection systems are also needed. It is requested that Table II be filled out for the various aircraft, engines, or components manufactured or tested by your company. Again penalties may be given as actual values or in the form of relative rankings. If the penalties can be broken down for each component, please do so.

III. PROPULSION SYSTEM ICING

1. What icing research is required in support of the following propulsion components?

TABLE I
 PENALTIES OF ICING EFFECTS ON AIRCRAFT OR COMPONENTS
 o List Component or Aircraft and Associated Actual or Relative Penalties Due To Icing

AIRCRAFT OR COMPONENT	PENALTIES DUE TO ICING						
	WEIGHT	Δ MAX SPEED	Δ LIFT	Δ DRAG	Δ STALL SPEED	Δ RANGE	SAFETY (If Inoperative)

TABLE II
PENALTY ASSESSMENT OF THE PROTECTION SYSTEMS

- o List Aircraft and Check Components Protected From Icing
- o Note actual or Relative Penalties of Individual Components or for Total Aircraft

AIRCRAFT TYPE, NAME, OR MODEL	CHECK COMPONENTS THAT ARE ANTI-ICED/DEICED									ANTI-ICING SYSTEM PENALTIES OF INDIVIDUAL COMPONENTS FOR TOTAL AIRCRAFT							
	WINDSHIELD	WING LEADING EDGE	TAIL LEADING EDGE	PROPELLER	ENGINE INLET	NACELLE	PITOT	ICE DETECTOR	BALANCE HORN	OTHER	POWER REQD BY SYSTEM	INITIAL COST	WEIGHT	RANGE REDUC-TION IMPACT	CRUISE SPEED IMPACT	MAX SPEED IMPACT	RELIABILITY IMPACT

Use Actual Values or Relative Ranking: 1=Severe Penalty to Aircraft; 2=Moderate; 3=Small

- 0 Propellers
- 0 Inlet guide vanes (fixed and variable)
- 0 Core inlets
- 0 Engine or fan inlets
- 0 Fan blades
- 0 Stator blades

2. What analytical and experimental research is required on shed ice control and transient heat transfer for engine de-ice systems?
3. What research is required to make ice protection systems compatible with engine components made of composite materials?

IV. AIRFRAME ICING

1. Airfoil lift, drag, pitch moment, and stall speed increments due to ice accretion have been obtained in the past in the NASA Lewis Icing Research Tunnel (IRT). Do you want such icing sensitivity data from the IRT for the following:

YES	NO	
___	___	Airfoils on your current aircraft
___	___	Your future airfoils
___	___	New computer designed airfoils (Low Speed, Laminar Flow, Supercritical)

2. Do you want NASA IRT data on airfoil ice shapes from which artificial ice shapes could be made for use in dry wind tunnel and flight testing?
3. Are there any aircraft components, especially vulnerable to icing, for which the airframe designers needs special design guidelines.
4. What research needs to be done to make ice protection systems compatible with airframe components made of composite materials?

5. In Table I please identify the ice sensitive components which require additional research, and list, in order of importance, the required research in the area of (1) ice accretion or water collection efficiency, (2) ice shedding, (3) ice protection system, (4) performance penalties.

V. TESTING TECHNIQUES

1. The methods listed below are used for determining (1) the nature and extent of icing of a component, (2) ice protection system performance, and (3) aircraft performance penalties due to either ice accretion or ice protection system operation. Based on your experience, please comment on such factors as the accuracy, practicalness, availability, and costs of these methods.

- 0 Full-scale icing wind tunnel tests
- 0 Sub-scale icing wind tunnel tests
- 0 In-flight tanker spray cloud tests
- 0 Ground spray cloud tests
- 0 Flight tests in natural clouds
- 0 Analytical techniques and computer codes
- 0 Other

2. What improvements should NASA make to their icing facilities? Please discuss such improvements as test section size, air speed, range of icing parameters, instrumentation (e.g., force balance, cloud parameters).
3. Should the NASA Lewis Altitude Wind Tunnel be rehabilitated to provide expanded icing facilities which include a 20-ft diameter high speed test section (up to $M=1$) and a low speed 45-ft diameter test section with speeds to 200 knots?

- YES. Would be willing to use on a cost basis.
- YES. But do not foresee any immediate application for us.
- NO. Our facilities or test procedures are adequate.
- NO. No need.
- OTHER: _____

4. Should spray systems be standardized for the existing icing spray tankers, and should instruments for measuring the spray cloud properties be standardized?

VI. CALCULATIONAL TECHNIQUES

1. There are a number of handbooks available which provide technical icing data. Which of the following do you use?

- FAA ADS-4, Engineering Summary of Airframe Icing Technical Data
- FAA RD-77-76, Engineering Summary of Powerplant Icing Technical Data
- OTHER: _____

2. Are the design procedures and icing data in ADS-4 sufficient enough to be worked up into computer codes for preliminary design trade-off studies and for inputs to mission analyses?

3. What new ice protection problem areas do you feel need to be addressed by these or new technical handbooks?

4. Which existing areas covered by these handbooks most need improvement?

5. Please list and briefly explain any computer codes you use to design ice protection systems and to determine icing penalties. Indicate whether they are proprietary or available in the open literature.

6. Listed below are several computer codes that NASA is either procuring or planning to procure.

0 Water droplet trajectories for water catch rates and impingement limits on:

- 2-D lifting bodies (wings, tails)
- 3-D lifting bodies (wings, tails, fuselage)
- 3-D non-lifting bodies (fuselages)
- Axisymmetric engine inlets at angle of attack.

0 Steady-state heat transfer for anti-icing analysis.

0 Ice accretion modeling on wings, inlets, and rotors.

0 Prediction of aerodynamic penalties due to ice accretion.

0 Transient heat transfer codes for de-icer analysis.

0 Prediction of shed ice trajectories.

Will these computer codes be of use to you in addressing your icing requirements?

_____ *YES. Would supplement or replace codes currently used

_____ *YES. Currently do not use computer codes

_____ NO. Would not use any computer codes

_____ OTHER: _____

*What additional codes or special features would you want in these codes?

7. Since these codes will require extensive in-house expertise in programming and analysis, some companies may prefer to buy such services. When these codes become operational should NASA create an Ice Protection Analysis Center similar to the Airfoil Design Analysis Center created by NASA at Ohio State University?

VII. WEATHER DATA

1. What improvements in weather forecasting would most directly help icing forecasts.

2. Are you satisfied with the present method of categorizing the icing condition (e.g., trace, light, moderate, severe)? Please explain.
3. Is there a need for a better flight test instrument that measures cloud properties to be used in conjunction with natural icing flight tests for certification.

VIII. GENERAL

1. Do you think a pilot training movie should be made that addresses the problems of flight into icing conditions - how to avoid it, how it affects aircraft performance, how to cope with it, and how to get out of it?

IX. FINAL RECOMMENDATIONS

1. What aspects of the icing problem most need attention? In the short term? In the long term?
2. In what areas of the icing problem could NASA make the greatest contribution? In the short term? In the long term?

APPENDIX B

Outline of Statement of Work

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Outline of Statement of Work

- TASK I. Identify aircraft components considered for ice protection and survey the commercial aviation industry to obtain their views on their needs with respect to ice protection.
- TASK II. Identify existing ice protection systems.
- TASK III. Assess ice protection system penalties.
- TASK IV. Assess the experimental data base for ice protection systems and recommend improvements.
- TASK V. Assess accuracy of icing test methods and analytical techniques and recommend improvements.
- TASK VI. Propose new and/or advanced ice protection systems and discuss relative merits.
- TASK VII. Assess aircraft operation in icing conditions and discuss existing icing instrumentation.
- TASK VIII. Recommend improvements to be made to the NASA Lewis Icing Research Tunnel and the Lewis Altitude Wind Tunnel.
- TASK IX. Propose NASA short and long range icing research programs.
- TASK X. Report results of contract.