AIAA 97-0302
A Hybrid Anti-icing Ice Protection System

K. Al-Khalil, T. Ferguson, and D. Phillips
Cox & Company, Inc.
New York, NY

35th Aerospace Sciences
Meeting & Exhibit
January 6-7, 1997 / Reno, NV

A HYBRID ANTI-ICING ICE PROTECTION SYSTEM

Kamel M. Al-Khalil*, Thomas W. Ferguson†, Dennis M. Phillips‡

Cox & Company, Inc.
200 Varick Street
New York, NY 10014

ABSTRACT

A hybrid ice protection system has been developed to provide an economical alternative to conventional anti-icing systems on roughness sensitive airfoils where high power is either impractical or unavailable. It consists of a thermal subsystem operating in a running-wet mode that partially or fully covers the impingement zone at the leading edge, and a low power de-icing subsystem just downstream. The thermal system maintains a clean leading edge in the roughness sensitive zone by preventing the impinging supercooled water droplets from freezing. This requires minimal power because the surface temperature is held just above freezing. The heated water then runs back and freezes downstream where the low power de-icing system removes the ice contamination periodically. The total power consumption of the hybrid system is a fraction of that required to achieve total evaporation. Tests conducted in the NASA Lewis Icing Research Tunnel on a truncated horizontal stabilizer section of a light business jet proved the hybrid system to be a viable alternative to conventional anti-icing systems that require substantial power.

I. Introduction

AIRCRAFT manufacturers continue to seek ways to improve aerodynamic performance, even by a very small percentage. This has led to the development of efficient but sensitive airfoils which loose their maximum lifting capabilities when leading edge (LE) roughness is present. Roughness affects the aerodynamic performance by altering the boundary layer development. It can also induce early separation resulting in a significant loss of lift. Ice accretion on the LE surface of an aircraft, or ice that remains on the surface (residual) after activating a de-icing system, leaves the surface covered with a rough texture of ice.

The initial ice formation on unprotected LE's generates distributed roughness elements on the surface. The nominal heights of these elements have been investigated during several icing tunnel tests. Most recently noted are those conducted by Shin at the Icing Research Tunnel (IRT) of *NASA Lewis Research Center*.[1] Inadvertent icing encounters can lead to such an initial roughness.

*Engineering Scientist, Member AIAA
†VP Engineering, Member AIAA
‡VP Marketing, Member AIAA

Aerodynamic degradation due to LE roughness was investigated at the Low-Turbulence Pressure Tunnel (LTPT), *NASA Langley Research Center*, and in the ONERA F-1 facility, France.[2,3]

The result of these tests showed that the resulting decrease in the maximum lift coefficient ranged from 20% to 33% for the smallest to highest roughness heights, respectively. The reduction in angle of attack (AOA) margin to stall as shown in Fig. 1, varied from 3 to 8 degrees for the smallest to the highest roughness height, respectively, with the 3-D results being more adverse at the larger roughness heights.

There have been documented effects of this performance reduction on aircraft. A number of incidents has been attributed to Ice Contaminated Tailplane Stall (ICTS). Ice formation on the tail LE surface, whether distributed roughness or added irregular bulk shape, leads to a large reduction in the AOA margin to stall and maximum lift coefficient. During approach, flaps are extended and the effective AOA of the tail dramatically increases as a result of the downwash produced by the high lift coefficient of the wings. This can lead to a sudden flow breakdown on the lower surface of the horizontal stabilizer; provoking a nose pitch down which sets the airplane in a diving path.

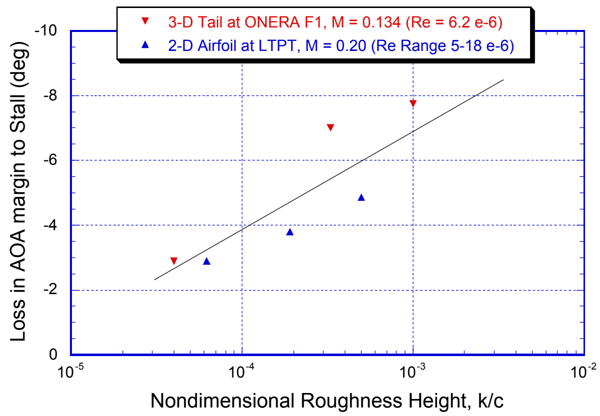

Figure 1: Effect of LE roughness on the AOA margin-to-stall[3]

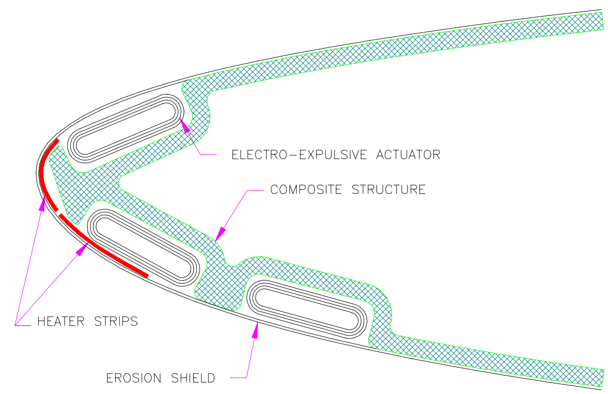

Figure 2 Schematic of Hybrid System Tested

Recent experimental tailplane icing studies were conducted on a full-scale 3-D horizontal tail assembly.[4,5] A 1-inch grit strip was attached at different locations near the LE to simulate the surface roughness of an initially accreted thin layer of ice. The resulting maximum lift coefficients were 1.30, 0.87, 1.07, and 1.21 for the clean LE, a strip located at 0%, at 5%, and at 10% of the chord, respectively. The corresponding AOA margins to stall were 21.0, 14.5, 17.5, and 19.5, respectively. The detrimental effects were most pronounced when distributed roughness was near the LE where the pressure gradients are high.

Clearly, aircraft with roughness sensitive wings or horizontal stabilizers require an effective solution for safe flight into known icing conditions. So far, this solution has been provided in the form of a thermal evaporative system which requires substantial electrical power or bleed air. In this paper, an alternative and more economical solution is presented. It will be referred to as the hybrid system and is described in the following section.

II. The Hybrid System Concept

The objective of this system was to develop an alternative to existing high power anti-icing systems, to improve on currently used thermal/mechanical de-icing systems, and to provide an effective anti-icing system to aircraft that require a smooth LE surface but lack the power budget.

Figure 2 represents the hybrid system concept. A running-wet anti-icer--either electro-thermal or hot gas--is located at a portion of the LE to keep it free of ice contamination. The runback water freezes downstream of the heated zone where any thermal system would be inefficient as a result of the low

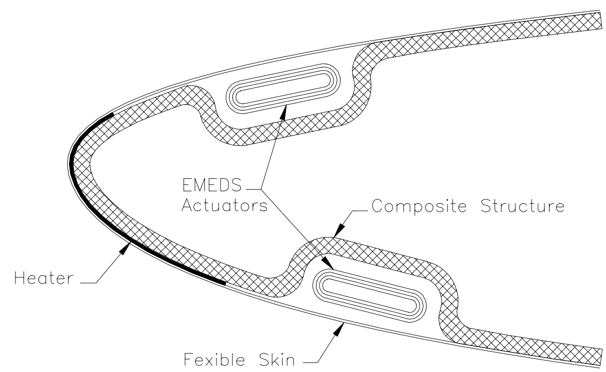

Figure 3 Current Hybrid System Layout

surface wetness factor associated with the runback rivulet flow structure. In this hybrid system, a mechanical de-icing system is used at those locations to deflect the airfoil's semi-rigid skin and periodically remove the ice accumulation which results from frozen runback and/or direct water droplet impingement. The de-icer selected was of the Low Power De-Icing (LPDI) system type which works on the principle of opposing electro-magnetic fields resulting from opposing current flow in adjacent conductors. Unlike systems using the "parting strip" concept, the current LPDI does not require the thermal system at the LE to function. The combined sub-systems deliver an efficient and effective ice protection system. Typical constructions are shown in Figs. 2 and 3, and will be discussed later.

One of the earliest LPDI systems was based on electro-impulse technology. The history goes back to the year 1939 when a patent was granted to Goldschmidt.[6] The first general documentation on Electro-Impulse De-Icing (EIDI) systems technology was reported by Levin.[7,8]

In the early 1980's the technology attracted interest of the US government and industry which led to the development of several variations in LPDI systems.[9] The LPDI used in these tests is Electro-Magnetic Expulsion De-icing System (EMEDS) which was developed by Innovative Dynamics, Inc. under NASA SBIR and ARPA sponsorship. Cox & Company, Inc. has exclusive worldwide manufacturing and marketing rights to this system.

Regardless of the LPDI system used, it was demonstrated that there exist minimum levels of ice thickness accumulation before a particular system can fully clean the surface during a de-icing cycle.[10] The minimum "critical ice thickness" varies among the different systems and depends on the type of ice on the surface (rime or glaze) and the location of ice (LE or downstream). The use of any of these systems requires an assessment of the level of residual ice that can be tolerated on the surface. Aircraft with sensitive airfoils require that no ice be allowed to accumulate on the LE. A combination of a heater and a LPDI can meet this requirement.

Typical LPDI systems are capable of removing ice buildup as thin as 0.05" and as thick as 2 inches. Thus, the ice thickness can be controlled and maintained within certain acceptable levels by varying the de-icing cycle time of the LPDI sub-system or other means. This information along with aerodynamic data of airfoil sensitivity to roughness should be used to determine the extent of the heated region on the LE.

The system is non-intrusive to the flow since it is mounted internally. Consequently, the airflow is not disturbed as is the case with externally mounted systems, and the problems associated with roughness near the stagnation region are eliminated.

The currently used system consists of a De-icing Control Unit (DCU), an Energy Storage Bank (ESB) which contains capacitors, and the electro-mechanical actuators. The unique element of the EMEDS system is the actuator that imparts a large force on the inside surface of the airfoil skin in a very short duration when current is discharged through it from the capacitors. The force deflects the skin which shatters the ice buildup. The DCU controls the firing sequence of actuators and de-ice cycle timing. In production units, the DCU also controls the heater power output.

Spanwise actuators are mounted in a composite material housing that constitutes a substantial part of the LE edge structure. There were initially three actuator rows located chordwise as shown in Fig. 2. Tests have shown that it was possible to reduce the number on actuator rows to two without jeopardizing performance. A typical system design would be as illustrated in Fig. 3.

III. Icing Tunnel Test Article

A hybrid system was fabricated as described above and tested at the NASA Lewis *Icing Research Tunnel* (IRT) in March 1996. The objective was to provide proof of concept and insure that the system was in fact a feasible means of providing a contamination free LE with low power requirements as part of the NASA SBIR Phase I program.

The test article was a truncated model of a full scale horizontal stabilizer of a new business jet. The model had a tapered and swept 3-D geometry of about six foot span. It included an electro-thermal anti-icing heater at the LE, mounted on the outboard half of the model, from mid-span to tip.

The heater was bonded to the internal surface of a 0.015" thick stainless steel LE abrasion shield. The heater was made of wire conductors embedded in an elastomeric insulating material and consisted of two separate bands, each of which was individually controllable. A 0.45 inch wide heater band was mounted within the airfoil stagnation zone, and another 0.65 inch heater band was mounted directly downstream on the lower surface. Those heater strips were 15 inches long in the spanwise direction, and were mounted on the outboard section of the horizontal stabilizer. Aerodynamic sensitivity data at various roughness levels and chordwise locations were unavailable during the testing period. Consequently, the heater width was selected based on estimates of impingement limits. The heater was designed to be within those limits. This relates directly to the region of maximum sensitivity of the specific airfoil to LE roughness.

The system is generally designed to yield a surface temperature that is a few degrees above freezing to operate in a running-wet mode irrespective of meteorological conditions. The stagnation heater band was designed to deliver a maximum power rating of the order of 20 W/in^2 and the downstream band had a nominal power density of 8 W/in^2. Surface temperature was measured and monitored using fine gage type-T thermocouples mounted on the stainless skin. Power was manually controlled with variacs to yield a surface temperature in the range of 35 to 40 ºF.

An LPDI system was placed immediately downstream of the electrically heated zone. The arrangement tested in the March 1996 tunnel entry is shown in Fig. 2. The front actuator row on the lower surface was deactivated where the aft heater was located at outboard section of the horizontal stabilizer.

A wide range of conditions was considered. An abbreviated version of the test matrix is shown in Table 1. Basically, two airspeeds were considered with a selection of temperatures and Liquid Water Contents (LWC).

Table 1: IRT Test Matrix (AOA = 0)

Run #	T_{total} (°F)	T_{static} (°F)	V (mph)	MVD (μm)	LWC (g/m^3)
1	2.5	-4	190	20	0.45
2	0	-4	133	20	0.55
3	2.5	-4	190	20	0.70
6	18	14	133	20	0.53
7	18	14	133	20	0.60
8	29.5	23	190	20	0.53
11	27	23	133	20	0.53
12	27	23	133	20	1.00
16	2.5	-4	190	20	0.70
19	-16	-22	190	20	0.42

IV. Test Results and Discussion

The performance objective of the hybrid system was achieved. Two key points must be understood when evaluating and comparing power consumption between the hybrid and other systems:

! Power consumption in totally evaporative systems is highly dependent on the water loading of the model (i.e., the product of the freestream velocity, the cloud liquid water content, and the droplet collection efficiency). Due to the high value of the water latent heat of vaporization, the power requirement of evaporative systems tends to be very high.

! Power consumption in running-wet systems depends mostly on the ambient temperature. This fact was demonstrated in many of the runs where the effects of temperature and LWC were independently investigated. The power requirements increased with increase in temperature differential between the surface and the ambient.

Figure 4 Horizontal stabilizer in the NASA Lewis IRT during a severe condition (Run #19)

The system performance met the smooth LE requirements with some residual ice on downstream regions where the EMEDS was used to shed the frozen runback and accreted ice. The maximum height of the bumps on the remaining roughness did not exceed 0.05" for most cases. The heater managed to keep the thermally protected surfaces clean. Occasionally, a lump of about 0.045" thick, 1" span, and 0.1" long chordwise remained on the surface of the downstream heater. This was observed on the aluminum tape used to hold the thermocouple to the external surface. The surface was maintained at 35 to 40 °F. However, due to the drop in temperature across the tape adhesive, the actual surface temperature on the aluminum surface may have been very close to freezing in the warm conditions, and below freezing in the cold conditions.

A qualitative assessment of the system's performance is shown in Fig. 4. The outboard half of the LE is seen to be essentially clear of residual ice

Figure 5: Impingement Limits Study (Run #1)

as compared with the inboard half. Recall that the outboard half of the LE is heated, and the inboard half is de-iced using the LPDI only. This photograph is part of the data record for Run 19 as shown in Table 1.

Figure 5 shows the results of a run to determine the impingement limits prior to the activation of the hybrid anti-icing system. The Mean Volume Droplet diameter (MVD) for all runs was 20 microns. This photograph also shows the aluminum tape that was applied over the control thermocouple. This was Run 1, for which the airspeed was 190 mph, the LWC was 0.45, and the temperature was -4 ºF. Run 2 also consisted of impingement limit studies at the lower airspeed of 133 mph.

Figure 6 is a close-up of the heated LE taken after the impingement limit determination runs. The run record number is Run 3. The static temperature was -4 ºF, the airspeed was 190 mph, and the LWC was 0.7 g/m^3. This was one of the first attempts to clear the ice using electro-thermal heat, and the initial power estimates were less than what was required. In fact, this run produced a capping of ice on the LE where the static temperature was -4 ºF. This was due to three reasons:

! Capping initiated at two locations: (1) over the aluminum tape near the center of the heated area as a result of the increase in thermal resistance caused by the adhesive, and, consequently, a false surface temperature feedback from the thermocouples; and, (2) at the outboard location near the tip where the ice cap bridged over from the unprotected wing tip and was held in place by surface adhesion forces despite being debonded from the skin in the heated area (large amounts of runback were observed to flow out of those regions).

Figure 6: The Effect of under-estimating power requirements (Run #3)

! The Angle of Attack (AOA) was zero. Therefore natural shedding due to aerodynamic forces could not be attained once ice started to form. However, the actuators were able to shed the ice cap with help from the heaters.

! The heater was powered when the cloud was initiated, and was controlled based on the incorrect surface temperature feedback.

The power density was 10.8 W/in^2 for the stagnation heater, and 5.4 W/in^2 for the downstream heater. As this run progressed, ice formed over the heated zone, and would not release. An attachment region for the ice between the protected zone and the far outboard tip--which was not protected--would enhance the cap-over effect, making release of ice over the heater that much more difficult. However, as the EMEDS actuators would fire, the de-icing action eventually resulted in complete clearing of the LE . Once the initial bridging and capover difficulties were resolved, the system functioned satisfactorily.

The test conditions for Fig. 7 were the same as for Fig. 6, but adjusted power densities were used:

Figure 7: Clean leading edge with a properly controlled heater (Run #16)

17 and 6.6 W/in^2 for the stagnation and the downstream heater, respectively. It is seen that the LE is clean, and that the system is functioning as desired.

A comparison of power consumption between the hybrid system and an evaporative heating system is provided in Table 2. An analysis of the power required in running-wet and evaporative systems is presented in Reference [11] where a breakdown of the various heat transfer components are illustrated (evaporative, convective, sensible, and kinetic). Results shown in Table 2 are in agreement with the analysis results discussed in Reference [11].

This illustrates that the evaporative power requirement was at least 570% more than that used by the hybrid system for this particular condition (even though Run 6 was exaggerated since it was at a colder temperature than in Run 11). Furthermore, evaporative power would have been even higher when it is considered that heaters would have had to cover up to the impingement limits, at least. It should also be noted that the power required to run the LPDI sub-system is negligible when compared to the heater powered ice protection system (running-wet or evaporative). The hybrid system power consumption can be made lower by reducing the

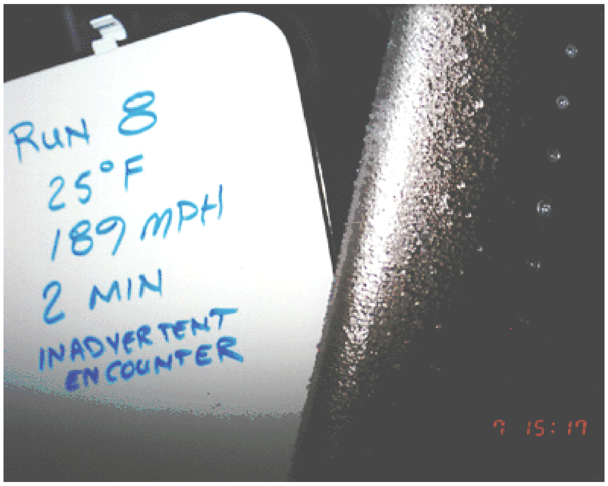

Figure 8: Inadvertent icing encounter in glaze condition (warm)

chordwise coverage of the downstream heater to a point at which the remaining roughness and maximum ice thickness can be tolerated by the aircraft.

Table 2: Power Consumption Comparison

Run #	OAT (ºF)	TAS (mph)	LWC (g/m^3)	Tot Power (W/ft span)
6 (hybrid)	14	133	0.53	69
11 (evap)	23	133	0.53	394

Figure 8 shows the ice accumulation that can be expected as the result of an inadvertent encounter in glaze icing conditions. The ambient temperature of this run was 25 ºF, and the airspeed was 189 mph. This ice was accumulated over a period of two minutes. The removal of this type of ice, near stagnation, is a challenge to most LPDI systems. Almost always some undesirable residual ice will remain at those locations and limit the extent of allowable maneuvers. If an airfoil is sensitive to ice contamination near the stagnation region, then heat is the only practicable means available to remove it, other than freeze point depressants. Otherwise, a certain degree of surface roughness will always be present, to more or less extent, depending upon the particular system.

Figure 9 indicates some frozen runback that extended beyond the protected zone of the de-icer during Run 12. This was a warm and high liquid water content condition. The actively protected zone extended up to the screw line shown at about the

13.5 inch mark on the measuring tape that is stretched across the leading edge. The extended runback was observed to form only during the first minute or two of this icing encounter. This was when the model was initially clean, slightly preheated, and the impinging droplets were warm so that the runback water had to flow some distance on the surface before freezing. After the initial few minutes, the residual ice fortunately would act as a barrier that traps the runback water and prevents it from flowing past the protected region.

Figure 9: Typical hybrid system performance (Run #12)

Figure 10: Comparison between heated and unheated sections (Run #6)

Figure 10 is a clear comparison between the different parts of the stabilizer model: unprotected tip, hybrid system along the first 15 inches from the tip, followed by a pure LPDI system that was also 15 inches long, and finally unprotected root. Clearly, the hybrid system yields the cleanest surface. Certainly, the stand-alone LPDI system results in a relatively clean surface that is free of ice thicker than 0.1 inch which is more than sufficient for other aircraft geometries.

In a nutshell, the best indication of the viability of the hybrid system can be seen in Table 2. In assessing the numbers, it should be recalled that while the power required to anti-ice in an evaporative mode is a direct function of water loading, the power required to anti-ice in a running-wet mode is a function of the ambient temperature. Therefore, had the temperatures been the same, the power required of the hybrid system would have been even less, and the evaporative power would have been even more had the heated zone been extended to the impingement limits.

V. Conclusions

A hybrid ice protection system consisting of an electro-thermal heater followed by a Low Power De-Icing System has been shown to be an effective means of eliminating surface roughness on the LE of a horizontal stabilizer of a light jet transport. A clean LE is essential if an airplane with roughness sensitive airfoils is to perform per FAA requirements such as the "zero-g" pushover maneuver.

The power required was a fraction of evaporative systems with little difference in overall performance.

Essentially, all the runback water froze within the area protected by the LPDI system, and, consequently, there was no potential for the formation of an ice ridge downstream.[12] The exposure time was not seen to be critical in the tests conducted. As a result, an airplane equipped with the hybrid system could remain in the icing environment for indefinite periods.

Because the energy draw is reasonably low, it is possible to protect an entire wing or just surfaces upstream of lateral control surfaces to prevent ice ridge formation. Additionally, the system is non-intrusive to the airflow since it is internally mounted to the structure. This makes it suitable to all aerodynamic surfaces, including NLF airfoils, and affordable to many aircraft that rely on pneumatic boots as a result of power limitations.

Frozen runback thickness is maintained at a very low level, and as a result, aerodynamic penalties due to roughness are reduced or eliminated entirely. Furthermore, the size of the ice particles that are shed is small and controllable to a predictable degree. This could make the system viable for protection of engine inlet nacelles. The heat source in this case could be a pre-existing bleed air or electro-thermal. It is worth mentioning that core flow in high bypass turbofan engines is scarce. Consequently, the available bleed air is not sufficient for full aircraft ice protection, especially during low power settings as in approach and descent.

It is possible that the system may also be an effective solution to protection of LE surfaces upstream of control surfaces during encounters with Super Large Droplet (SLD) icing environments. The FAA, NTSB, and international organizations have been seriously considering issues related to those environments.

Acknowledgments

The present work was sponsored by the *NASA Lewis Research Center* under a Phase I SBIR program. This support is gratefully acknowledged as is the continued support under Phase II. We also appreciate the generosity of *Raytheon Aircraft Company* in providing the icing tunnel model for the test series. The success of this program was a result of a team effort by *Cox* engineers including John Smith, Charles Horvath, and the authors. The support provided by *Innovative Dynamics, Inc*. is acknowledged and appreciated.

References

[1]Shin, J., “Characteristics of Surface Roughness Associated With Leading Edge Ice Accretion,” AIAA Paper No. 94-0799.

[2]Morgan, H.L., Ferris, J.C., and McGhee, R.J., “A Study of High-Lift Airfoils at High Reynolds Numbers in the Langley Low-Turbulence Pressure Tunnel,” NASA TM-89125, July 1987.

[3]Valarezo, W.O., and Lynch, F.T., and McGhee, R.J., “Aerodynamic Performance Effects due to small Leading-Edge Ice (Roughness) on Wings and Tails,” Journal of Aircraft, Vol. 30, No. 6, Nov.-Dec., 1993.

[4]Ferguson, S., Mullins, B., Smith, D., and Korkan, K., “Full-Scale Empennage Wind Tunnel Test to Evaluate Effects of Simulated Ice on Aerodynamic Characteristics,” AIAA Paper No. 95-0451.

[5]Mullins, B., Smith, D., and Korkan, K., “Effects of Icing on the Aerodynamics of a Flapped Airfoil,” AIAA Paper No. 95-0449.

[6]British Patent Specification No. 505,433 issued to Rudolf Goldschmidt; May 5, 1939.

[7]Levin, I.A., ‘USSR Electric Impulse De-Icing System Design,’ Aircraft Engineering, p 7, July 1972.

[8]Levin, I.A., et al., ‘Device for Removing Ice from Surfaces of Thin-Walled Structures,’ US Patent 3,809,341, May 1974.

[9]Zumwalt, G.W., Schrag, R.L., Bernhart, W.D., and Friedberg, R.A., “Electro-Impulse De-Icing Testing and Design,” NASA CR-4175, 1988.

[10]Shin, J., and Bond, T., “Surface Roughness Due to Residual Ice in the Use of Low Power Deicing Systems,” AIAA Paper No. 93-0031.

[11]Al-Khalil, K.M., Horvath, C., Miller, D.R., Wright, W.B., “Validation of NASA Thermal Ice Protection Computer Codes, Part 3 - the Validation of ANTICE,” AIAA Paper 97-0051.

[12]Al-Khalil, K.M., “The Formation of an Ice Ridge Beyond Protected Regions,” *Proceeding of the FAA International Conference on Aircraft Inflight Icing*, Volume II, August 1996, pp. 285-295.