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Inflight Icing Educational Objectives for Air Carrier Pilots

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INFLIGHT ICING EDUCATIONAL OBJECTIVES FOR AIR CARRIER PILOTS

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Abstract

During the early development of commercial air transportation, inflight icing was approached with a policy of avoidance. This policy was applied through a body of knowledge gained through experience. Pilots learned where and when to expect icing encounters, and they developed operational strategies to avoid it. However, the quality of forecasting was not sufficient to reliably predict icing encounters. Thus, manufacturers took the approach of equipping aircraft used in scheduled air transportation with ice protection systems. Currently, general aviation pilots still approach icing with a policy of avoidance. However, commercial transport pilots must rationalize a dual approach. While avoidance remains the best approach, the volume of air traffic and the constraints upon routing imposed by hub operations place heavy restrictions on the avoidance option. A study has been made of 120 accidents involving air carrier aircraft in the United States and, to a limited extent, Canada. The data from these accidents has been compiled and used to evaluate the paradigm is use today, and to identify changes necessary to improve the core knowledge possessed by the air carrier pilot.

Introduction

The mathematician Richard Hilson has said, "A genuine education enables one to acquire, for oneself, the skills one happens, at a given stage of one's life, to need. A training, on its own, contributes almost nothing to education and produces distressingly ephemeral advantages." [1]

Accurate situational awareness is dependent on an understanding of nuance that training cannot provide. For much of its history, aviation has instead relied on experience to provide the necessary understanding. Unfortunately, experience itself often falls short: one thousand hours of experience may turn out to be nothing more than one hour a thousand times.

In contemporary times, the terms training and education have become convoluted. The process of training does not inherently lead to questions such as "What do we know?" and "How do we know it?". The process of education is generally built around these questions. In the absence of these questions, experience which has not been correctly interpreted can be memorialized into axioms or premises which strongly, and often detrimentally, influence attempts to understand nuance and therefore maintain situational awareness.

The operational understanding of the effects of ice contamination on the aerodynamics of transport category aircraft is a case in point.

A review of 120 airframe icing accidents involving aircraft commonly used in air carrier service† dating from 1940 to the present day indicates that the average flight experience for the pilot in command was 7356 hours. The median flight experience was 6415 hours. Figure 1 illustrates the distribution. This would suggest that a reliance on experience to understand the nuance of icing degradations is not sufficient.

A review of a much broader database containing 312 synopses of accidents and incidents worldwide‡ yielded 136 cases in which enough information existed to determine both the flight crew awareness

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† The 120 events that were evaluated for this work were drawn from a variety of sources. First, a search was conducted of the NTSB data using the Board's on-line Database Query Tool. This data covers the period 1962 to present. The search was limited to aircraft types in common air carrier usage, and was limited to accidents only. Corporate aircraft and aircraft more typical to general aviation, as well as incidents to all types, were not considered. Second, a similar search was conducted of the digitized reports available from the Department of Transportations's On-Line Special Collections website. This data covers the period 1934 - 1965. Third, some events were drawn from Flight Safety Digest (ref. 16) . Finally, several reports were included from Canada, although these do not represent the results of a structured search as the U.S. reports do

‡ This data was derived from the following sources: NTSB, Transport Canada, the EURICE project, ICAO, the Flight Safety Foundation, and the NASA ASRS program. This data considered both accidents and incidents.

of the icing situation and whether the ice protection system (IPS) had been operated. In 20 of these cases, the flight crew was not aware of ice accretion on the aircraft. In 30 cases, they were aware but elected not to operate the IPS. In the remaining 86 cases, the flight crew had operated the ice protection system, although it is often not possible to determine whether it had been operated correctly. Figure 2 shows this distribution. This makes a strong case that the knowledge of structural icing hazards possessed by flight crews is either not adequate or is not adequately employed.

It is worth examining that knowledge and comparing it to the accidents themselves. To do so on a case by case basis would be exhaustive. To look at this question from an air carrier perspective, there are four separate collections of events which might be useful. These are the DC-3 accidents, the ICTS accidents, the takeoff accidents, and the contemporary accidents. Before doing this, it is essential to examine the core knowledge basis employed in the training of the air carrier pilot with regard to structural icing.

The Paradigm

In 1928, Carrol and MacAvoy of the NACA began flight investigations of structural ice accretion. They immediately identified two distinct types of ice formation, one forming in temperatures near 32F and the other in a temperature range of 10 degrees less than 32F[2]. The former developed a large shape with considerable chordwise extent and occasionally a mushroom shape at the leading edge. The latter was more confined to the leading edge and sharper. Indeed, the authors suggested that some of these latter shapes might actually improve the airfoil's performance.

The following year they continued flight investigations, and in their paper of that year they posited two fundamental concepts regarding the management of ice accretion by the pilot. First, they suggested that avoidance of icing conditions should be relatively easy. They stated that,

> "This avoidance is not difficult since it [clear ice] will not occur except in the presence of moisture in reasonable quantity, which should be clearly evident, visually, whether the moisture be in the form of rain, fog, or clouds."[3]

Second, they concluded that "all deposits of an icy nature are not dangerous", and they argued that an educated discrimination made by the pilot was necessary. In their words,

> "If pilots can be well and thoroughly acquainted with the conditions controlling the formation of ice and particularly if they can learn that every deposit upon the wings or parts of an airplane is not necessarily hazardous, the problem will be in a large measure solved."[3]

In 1932, Samuels[4] laid out more formalized definitions for clear ice and rime ice. He stated that clear ice would usually be smooth and glassy, and rime would build forward into a sharp nosed shape. He also introduced the argument that clear icing which occurred in the presence snow or sleet would produce a rough ice shape, and that slow freezing would produce ridges.

Despite this conclusion regarding the mixing of snow or sleet with clear icing, which is substantiated by his data, Samuels classified 155 flight observations as 108 cases of rime, 43 of clear and 4 cases "where rime and clear ice formed during the same flight". He did not break the clear ice classification into the two distinct cases he had defined.

Samuels drew the conclusion that clear icing has a "more serious effect" than rime based on the percentage of flights terminated due to the icing. In his data, 31% of the terminations were due to 1/4 inch or more of clear ice, 12% due to less than 1/4 inch of clear ice, 4% due to 1/4 inch or more of rime ice, and no terminations due to less than 1/4 inch of rime.[4] This data also strongly related the icing hazard to quantity (thickness). Samuels did not account for the possible bias of the individuals making the decisions to terminate (the pilots). Nor did he qualify these decisions as based on metrics available to the pilot in the cockpit, i.e., airspeed degradations, rate-of-climb degradations, etc., which may not comprehensively reflect the true degradations of each icing encounter.

Later in his paper he points out that

> "one of the chief difficulties in a study of this kind is the frequent impossibility for the pilot or observer to classify correctly the type of ice formation since it is usually melted by the time the airplane reaches the ground...since many of these flights were made before daylight this difficulty was especially pronounced..."[4]

Perhaps the most interesting point stated in Samuels' paper is that a third type of ice, frost, "does not adhere to the airplane very firmly and *is never dangerous* (italics added) as it has very little resistance to the vibration and wind forces encountered in flight."[4]

German work on icing reported in 1935 by Noth and Polte[5] (and translated by the NACA) set forth three types of ice, similar to Samuels' descriptions. They identified two types of warm temperature icing. The first is clear and creates little form change to the aerodynamic surface. The second is rough, granular, and has a "peculiar tendency to spread more toward the sides than the front, thus building up a fairly broad area". They attribute this second type of warm temperature icing as probably due to supercooled water droplets mixed with solid precipitation.

Noth and Polte then defined a cold temperature ice formation creating slight form changes and characterized by a "crystalline, snow-like coat".[5]

Findeisen[6] in 1938 provides a detailed analysis of icing clouds and argues that knowledge of the freezing level is easily predicted and is sufficient for avoidance flight planning. He states that

> "According to the foregoing, the icing hazard can, in most cases, be avoided by correct execution of the flight according to meteorological viewpoints and by meteorologically correct navigation...the zones of icing hazard are usually narrowly defined. Their location can be ascertained with, in most cases, sufficient accuracy before takeoff."

A paper by the French Committee for the Study of Ice Formation[7], published in May 1938, makes fairly similar distinctions. In this case, two distinct ice formations were identified. The glaze formation is similar to those identified in the American and German papers; the other formation, essentially rime, includes a double horned type of shape descriptor. This paper also advocates avoidance by reference to the freezing level:

> "Equipped with such information before taking off, the pilot can adopt some flight tactic, that is to say, modify his itinerary so as to avoid the dangerous zone..."

The regulatory requirements of 1938 which applied to scheduled airline operation reflect the avoidance approach. Civil Aeronautics Regulations 61.7700 states that

> "When an aircraft, not equipped with approved propeller and wing deicing equipment...encounters, or, in the knowledge of the pilot, may encounter any icing condition, the pilot shall immediately so alter the course or altitude of the flight so as to avoid or withdraw from the icing condition."[8]

However, the development and introduction of ice protection equipment allowed a relaxation of this approach. The rule following the aforementioned requirement, CAR 61.7701, addresses the advantages of ice protection:

> "When an aircraft, equipped with wing and propeller deicing equipment...encounters an icing condition, the pilot shall so alter the course and altitude of the flight as to withdraw from the condition, *if, in his opinion, it appears that the icing condition may be of such duration or severity as to otherwise endanger the safety of the flight.*"[8] (Italics added)

This brings us to the material contained within Civil Aeronautics Bulletin No.25 of January 1943.[9] This document, entitled "Meteorology for Pilots", contains thorough descriptions of ice formations. These descriptions are largely based on the preceding ideas, and include the notion that both rime and clear ice, when mixed with snow or sleet, can produce very rough and hazardous shapes. The Bulletin provides a clearly written description of icing in cumuliform clouds, warm and cold fronts, and over mountainous terrain. Within these descriptions is the recommendation to avoid icing, but when that is not possible, to fly in colder air so as to encounter only rime icing instead of clear.

The Bulletin also contains the definitions to be used in reporting icing in flight. These definitions will be familiar to modern pilots:

> Trace of ice - an accumulation of no consequence, which does not affect the performance of the aircraft but should be reported by air carrier pilots for meteorological purposes.
>
> Light Ice - a condition which can be handled safely by normal functioning of the aircraft's deicing equipment. On encountering light ice, it is assumed that the aircraft can be flown indefinitely provided the deicing equipment is used.
>
> Moderate ice - an icing condition which deicing equipment will safely handle but which for practical flight purposes can be considered the signal to the pilot that it is time to alter the flight plan so as to avoid cruising in that condition.
>
> Heavy ice - an icing condition which deicing equipment cannot handle. On encountering heavy ice, the pilot will change altitude or return to a suitable airport and land,

> inasmuch as to continue under this condition of icing would render the aircraft unairworthy. [9]

These definitions, adopted by the Air Transport Association and approved by both the CAA and the U.S. Weather Bureau, reflect both the idea posited early on by Carroll and MacAvoy that "all deposits of an icy nature are not dangerous"[3], and were written in a way to provide further guidance to the pilot in developing the opinion required by CAR 61.7701.

The Bulletin, actually a 244 page book, also discusses the effects of structural icing. These are listed as loss of lift, increase in drag and increase in weight. It points out that the airplane will likely stall at speeds much higher than normal. This discussion also contains warnings against steep turns, turns at low altitude, and describes the phenomona which would become known as ice bridging with regard to a pneumatic boot system. [9]

The state of civil pilot knowledge, as reflected in published material, remains essentially unchanged from this point forward. In the December 1955 edition of C.A.A Technical Manual 104, "Pilots' Weather Handbook"[10], the discussion of icing formations is essentially the same as that of 1943. The section on weather planning points out that the avoidance of icing as a strategy may be oversimplified, "since it is not always possible to select an altitude at which one would completely escape these ice-forming conditions...". However, the emphasis is still that "in most cases, icing hazards can be minimized by full use of meteorological information", a statement that sounds remarkably similar to Findeisen's phraseology.

C.A.A TM 104 introduces a diagram (Figure 3) and concept that had been suggested in much of the previous work but never quite formalized. This is the notion that "the importance of icing is increased by the fact that the effects of icing are cumulative".[10] This concept and diagram were carried forward into the FAA Advisory Circular 00-6A, "Aviation Weather For Pilots and Flight Operations Personnel", the latest revision of which appeared in 1975.[11] This document states that:

> "Icing is a cumulative hazard. It reduces aircraft efficiency by increasing weight, reducing lift, decreasing thrust and increasing drag."

An interesting concept which can be used as a sort of marker in pilot knowledge of icing is that of added weight. This has always been mentioned in educational and training material. However, from the beginning, Carroll and MacAvoy[3] in 1929 pointed out that the added weight of ice is unlikely to exceed the weight of the fuel consumed during the icing encounter, and thus is not particularly critical. All of the following researchers conclude that ice weight is of little or no consequence when considered in the context of the aerodynamic degradations associated with ice. Newton[12] pointed out that a heavy icing encounter might yield at most 7 pounds of ice per foot of span. Yet weight remains a concern expressed in a number of the educational materials produced since that time. Indeed, it perseveres into the 1996 version of AC 91-51A, "Effect Of Icing On Aircraft Control And Airplane Deice And Anti-Ice Systems"[13]:

> "Also, if the extra weight caused by ice accumulation is too great, the aircraft may not be able to become airborne and, if in flight, the aircraft may not be able to maintain altitude."

Noth and Polte[5] in 1935 discounted the effects of weight and instead focused on changes in handling qualities and stability due to icing, stating that:

> "The weight increase is of secondary importance...The effect on airplane stability is altogether different. Nose and tail heaviness have been observed, as well as torsion, about the longitudinal axis. The reason lies perhaps less in the shifted center of gravity than in the changed air flow on the tail, elevators, and their balance."

It turns out that these may have been prophetic words; however, training material in the United States has remained primarily focused on the cumulative effects concept.

Following World War II, a great deal of the research done on icing had to do with two initiatives: 1) characterizing the icing environment for the purpose of designing thermal ice protection systems, and 2) developing methods to use in forecasting inflight icing conditions. The principal issue in the design of a thermal ice protection system is both quantitative and probabilistic: namely, how much heat is required to deal with the quantity of water that the wing will most likely encounter. The answers to these questions lay primarily with cloud liquid water content. It so happened that the tools available for in-situ measurement were optimal for looking at liquid water content. One of the outputs of this work was a more or less linear relationship between liquid water content and icing intensity.

In 1947, Lewis[14] related the following scale in use by the United States Weather Bureau for the measurement of icing intensity:

Trace of ice - 0 to 1.0 grams per square centimeter hour

Light ice -1.0 to 6.0 grams per square centimeter hour

Moderate ice - 6.0 to 12.0 grams per square centimeter hour

Heavy ice - 12.0 and over grams per square centimeter hour

This scale was specifically defined for use with icing reports from mountain stations. Lewis proposed an alternate scale, equating the same terms, trace, light, etc., to cloud liquid water content based on assumed droplet diameter, and demonstrated good agreement between the scales.

Lewis and other authors of the time specifically refer to these scales as measures of icing "intensity", which is not the same word as "severity". The reader will no doubt have noticed the parallel between the definitions used by the CAA for aircraft icing and the weather bureau definitions. The CAA definitions are qualitative, while the Weather Bureau and Lewis definitions are quantitative. Nevertheless, both address intensity. When looked at through the model of McAvoy and Carroll, that "all deposits of an icy nature are not dangerous"[3], and from the perspective of the energy requirements to remove the ice, it would appear that lesser intensities would equate to less hazard. Indeed, this is consistent with Samuels'[4] data on flight terminations. The convolution of the argument was completed in the late 1960s, when the term "heavy" was dropped in favor of the term "severe".

However, nothing in these definitions makes any specific reference to the severity of the aerodynamic effects on an airfoil.

Thus, by the early 1950s, the paradigm was set. The icing hazard was considered to be cumulative, continued exposure could progressively render an airplane "unairworthy", clear ice was more hazardous than rime ice, and small amounts of ice accretion were not generally considered hazardous. The icing hazard could in large part be avoided by competent use of all available meteorological information, and that which could not be avoided by this approach would rarely be of serious consequence.

Review of Accidents

The DC-3 Accidents

During the 1930s, 1940s and 1950s, structural icing contributed to numerous air carrier accidents. The accident reports provide a useful characterization of icing knowledge in the operational community, both from the standpoint of the flight crews involved and from the standpoint of the accident investigators. They also provide some useful factual information with which to examine the paradigm described above.

Probably the two best documented accidents of this era in which icing played a role are those of United 21 and Northwest 5. These accidents took place within 10 months of each other; United 21 crashed at Chicago on December 4, 1940 and Northwest 5 crashed at Fargo, North Dakota on October 30, 1941. Both accidents involved ice protected DC-3 aircraft. Both were approach/landing accidents. Between the two, there was one survivor, the Northwest captain.

United 21 crashed while circling the field following an instrument approach at Chicago. The conditions on the surface at the time were light snow and a temperature of 32F.[15] Freezing drizzle had prevailed until approximately one hour before at the surface. During the five hour period surrounding the time of the crash, there were thirteen landings and eighteen takeoffs involving seven different airlines.

The accident is interesting for a number of reasons. The captain had intentionally held above the clouds until he was cleared for the approach, specifically in order to remain clear of the reported icing conditions. The total time that the report estimates the aircraft was in icing conditions was only 8 minutes. The airplane appeared to be established on final approach when it simply rolled off on the left wing, and, despite the application of power, crashed. The flight crew was aware of the icing.[15]

Because of the high volume of operations at Chicago that afternoon, there were a number of qualified witnesses who flew in these conditions both before and after the accident. They described the icing as anything from light to heavy rime and glaze. In all cases, the pneumatic boots were described as effective. However, in one case the pilot evaluated the ice accretion on his airplane after landing. He found 3/8 of an inch to one inch of clear ice on the leading edges, but also found 1/2 inch of very rough ice extending aft of the boots about 4 and 1/2 inches. A similar formation was found on the empennage. The pilot believed that all of this ice had accumulated during the four minutes between when he shut off his pneumatic boots and his landing.[15]

The accident airplane exhibited 3/8 of an inch of rough, granular ice on the leading edges extending aft about 2 inches and a thin film of clear ice aft of this to the boot seams. No ice was found aft of the boots. In this case it was also believed that the ice had accumulated after the boots had been shut down. This was a standard practice due to the effects of inflated boots during the landing.[15]

Subsequent flight tests several days later encountered 1/4 inch of clear ice on the boot together with a substantial mass of rough ice extending about six inches aft of the boot. A second flight test the same evening encountered 5/8 of an inch of very rough ice over the leading edge.[15]

While the stalling speeds of several flights landing that afternoon were reported as higher than normal (an informational advantage of an era in which full stall landings were the norm), the flight tests revealed only an increase of approximately 6 miles per hour over that of a clean wing. The accident report noted that

> "Although pilots do not agree as to the effects of ice on the DC-3, it may be concluded that the ice does raise the stalling speed to some unpredictable extent and that the effect cannot be stated in terms of the amount of ice alone, but is dependent upon both the amount of accumulation and its location on the wing."[15]

Horn or wedge shapes were not identified in this report. None of the ice shapes were particularly large. They all exhibited roughness of varying degrees.

A very similar accident took place on December 21, 1947 at North Platte, Nebraska. A Seattle Air Charter DC-3 was making an approach in drizzle (probably freezing drizzle, since ice was forming) when it stalled and dropped off on the left wing. In this case, a recovery was made in time for a hard landing which did substantial damage.[16]

The Northwest accident is a different case. In this case, the airplane stalled after leveling at a minimum descent altitude during an approach to Fargo. This accident is interesting because of the viewpoints of the surviving pilot and the investigation itself. The pilot had been very alert for ice, and identified it as soon as it began accreting.[17] He described the first accretion as very light ice, "but not any amount to even be bothered about,". During the approach descent, the ice accretion increased, and the captain described it as rime, "the type that forms in irregular chunks and irregular chips, little extensions out on the windshield,". He still did not consider it unusual.

Five hundred feet lower, the captain stated that "we did start to pick up quite a lot more ice,". The report notes that, "having on previous flights experienced what he considered to be heavier icing, he was still unduly concerned." In this case, upon lowering the landing gear, the captain ordered the first officer to operate the pneumatic boots.[17]

Upon leveling at the minimum descent altitude, the airplane stalled. Although he applied maximum power and retracted the landing gear, the captain was unable to avoid impacting the ground.[17] An aviation mechanic arriving at the scene within minutes of the accident found a coating of rough ice from 1/2 to 2 inches thick along the deicer boot on the outboard right wing. The temperature at the ground was approximately 32F.[17]

Subsequent flight testing revealed that an uncontaminated DC-3 could remain in an aggravated stall with power on, continuously descending until the nose was pushed over and recovery effected.[17]

Propeller strike marks on the ground indicated that the airplane had impacted at an airspeed of 90 miles per hour. The flaps up, power-off stalling speed of the DC-3 is reported to be 80 MPH, and would be lower with power on. The investigation was perplexed about the normal flying characteristics exhibited during the descent: "If the wing had been stalled to the degree...required, it is hard to conceive of the airplane having been kept continuously under control during the descent..."[17]

The investigators considered the effects of ice. They stated that:

> "A careful consideration of the evidence has satisfied us that the partial loss of control was not caused solely by the ice which had been accumulated on the airplane. A collection of ice on the upper surfaces is not an uncommon experience and, while it is to be avoided to the fullest extent possible by the exercise of great caution, in the nature of things it cannot be eliminated entirely. Although the amount of ice which had accumulated on the airplane was substantial, experience has shown that aircraft may safely be flown with a far greater accumulation of ice than that which obtained in this case. The testimony in the record of this accident, as well as general knowledge previously acquired, convincingly shows that the accident was not caused solely by ice. It is equally clear, however, that the amount of ice which had been gathered by the airplane was sufficient to affect materially the flight characteristics of the plane. The effect of ice is to reduce airspeed and increase the stalling speed."[17]

The effects of encountering the non-linearity in the contaminated lift curve could not have been more dramatic. But it is important to consider the Northwest report's analysis, because it succinctly describes the prevailing operational understanding of the effects of structural ice accretion.

On March 2, 1951, Mid-Continent 16 crashed at Sioux City, Iowa while circling for landing. The weather was characterized by a 500 foot ceiling, 1 mile visibility in light snow showers, and a temperature of 29F.[18] Ice was observed by both passengers and rescue personnel. The airplane clearly stalled; however the report does not detail a serious analysis into the effects of icing on the stall characteristics or performance, except to state that :

> "Ice accumulation would not have been critical for normal flight operations, but, under a condition of low air speed in a turn, might have been a factor in causing the aircraft to stall at a slightly higher than normal air speed."[18]

On January 20, 1954, a Zantop Airways DC-3 crashed during an approach at Kansas City. The weather was characterized by a 600 foot overcast ceiling, light freezing drizzle, light snow, and a strong northwest wind.[19] 1/2 inch of clear ice was found on the leading edges of wings and tail; the evidence indicated that the deicing system had been in use. Indeed, the investigation criticized the crew for making a turn during the approach with the boots in operation, as it was well known that pneumatic boots, when inflated, would increase the stall speed.

On March 8, 1964, another DC-3 crashed at Chicago. Although this accident was heavily influenced by an encounter with wake turbulence caused by a Boeing 707, the weather in this case was a 700 foot overcast, light drizzle, surface temperature 34F, and a north wind at 10 knots.[20] The ice accretions found on the right wing an right stabilizer were characterized as "mixed rime and clear which was extremely rough textured", about 3/8 of an inch thick with numerous projections extending about 1 inch from the airfoil leading edge. The flight crew did not operate the pneumatic boots in this case, and the report criticizes them for this action.

Four days later, on March 12, 1964, another DC-3 crashed on approach to Miles City, Montana. The weather was an indefinite ceiling of 500 feet, light snow showers, temperature 32F and wind from the northwest at 20 knots with gusts to 30. No ice accretion was found after the crash, perhaps due to the post-crash fire. Based on propeller slash marks, an indicated airspeed at impact of 134 knots was established; the investigation believed that this precluded ice as a cause because, it said, this airspeed should have been more than sufficient to counteract the effects of severe airframe icing.[21]

None of these accidents involved large quantities of ice accretion. To the extent that a narrative account is available, none of them involved obviously abnormal handling characteristics until a critical angle of attack was reached.

The Ice Contaminated Tailplane Stall (ICTS) Accidents

On April 6, 1958, during an approach to land at Freeland, Michigan, a Capital Airlines Vickers Viscount crashed in a steep nose-down attitude. The aircraft had just rolled wings level onto final approach following a fairly steep turn.[22] The weather in this case was a ceiling of 900 feet variable to 1100 feet, visibility 3 to 4 miles, light snow and freezing drizzle, with winds from the northeast at 18 to 27 knots. No ice was recovered from the crash site, however, the impact was quite violent and a substantial post-crash fire ensued.

Icing conditions had been forecast, and a Constellation which had landed 13 minutes earlier reported one inch of ice at landing. The original investigation focused heavily on a wing stall. The effect of an inoperative stick shaker was explored, and icing was investigated in the wind tunnel. Propeller pitch malfunctions were looked at.[22] But no clear explanation for this accident was forthcoming.

Then, on January 29, 1963, it happened again at Kansas City. This time, a Continental Airlines Viscount crashed following an attempted landing. While the landing was not definitively aborted, it was clear that the airplane was in trouble and that the flight crew was preoccupied with maintaining control as the airplane flew down the full length of the runway. It nosed over steeply and crashed on the far end. The weather in this case was 3000 feet overcast, visibility 12 miles, no precipitation and a temperature of 17F.[23] No ice was found after the crash, but, again, there was a post-crash fire.

During this investigation, the Board discovered that this type of event had taken place before and a successful recovery had been achieved. The most interesting event took place on February 20, 1963 at Colorado Springs.[23] In this case, the Viscount crew effected recovery with both pilots pulling the nose up together. The aircraft returned to a normal behavior, then encountered a second set of pitch excursions with another recovery, and then handled normally to the landing. Examination of the wings found a light rime accretion, but the empennage surfaces exhibited a one inch thick double horn shape of what was described as "rough rime ice". It turned out that, after a ten minute exposure to cloud, the flight crew had visually checked the aircraft and found no ice. Between this inspection and the event, the aircraft was exposed to cloud for only another two minutes.

Another Viscount had survived a similar event at Willow Run in Michigan. In this case, an ice shape was found on the empennage described as a "cove" buildup, presumably alluding to a double horn shape.[23]

The manufacturer was able to duplicate the ice shape in an icing tunnel; however it required 20 minutes exposure to .72 grams per cubic meter of liquid water with an MVD of 20 microns. The Continental flight which crashed at Kansas City was estimated to have been exposed to icing conditions for six to eight minutes. In none of the cases in which the crew survived was the thermal ice protection system operated, because the flight crews did not realize that ice was accreting. In the accident cases, the evidence extracted from the wreckage supported, but did not prove, the idea that the IPS had not been operated.[23]

Of course, a subsequent Viscount accident at Stockholm in 1977 led to further tunnel testing. Trunov and Ingelman-Sundberg were able to show that the double horn shape is not required; a thin roughness will do the job as well. In that accident, it was believed that the crew did operate the IPS, but that descent power resulted in a less than adequate heat supply to the surfaces.[24]

On December 21, 1963, a corporate Convair 580 experienced this phenomona during an approach to Midland, Texas. The weather at the time was 200 feet overcast, visibility less than 2 miles, light snow, and a temperature of 27F. When landing flaps were extended, the aircraft began a series of divergent pitch oscillations, culminating in ground impact. Nine hours later, 1/2 inch of rime ice approximately 2 inches wide was found on the left wing leading edge; the flight crew had not operated the IPS.[16]

On March 10, 1964, the event happened again, this time involving a Slick Airways DC-4 landing at Boston. The weather was, surprisingly, 700 feet overcast, visibility 1 and 1/2 miles in moderate sleet and fog, temperature 32F, wind from the northeast at 22 knots with gusts to 28. Again, due to the high energy ground impact with subsequent fire, no ice accretion was recovered. This DC-4 was not equipped with airfoil ice protection.[25] However, in that sense, it bears perfect resemblance to the Viscounts with ice protection systems not operated by the crew.

The Slick accident report is the first to consider some of the NACA work done in the late 1950s, particularly by Gray and von Glahn.[26] The report points out that "Rotation of an airfoil to angles of attack higher than that at which icing occurred, generally creates an even greater loss of lift than if the airfoil iced when at higher angles of attack.".

The Continental accident report, released on June 17, 1964, included a reasonably good discussion of ice contaminated tailplane stall; the only oddity in the report is a statement that nose up elevator may induce a tailplane stall, which is not consistent with the findings of the NASA Tailplane Icing Project.[27]

On March 15, 1989, a Nihon YS-11 operated by Mid-Pacific Airlines crashed at West Lafayette, Indiana. The available report indicates that the weather in the terminal area was good, with no reported ceiling and a visibility of 8 miles.; however the aircraft's behavior was completely consistent with an ICTS event. Examination of the wreckage revealed 1/2 to 3/4 inch of rime ice accreted on the horizontal stabilizer, with none found anywhere else.[16] The airframe deicing system was not operated. A year later, another Mid-Pacific YS-11 experienced the same type of event on approach to West Lafayette. In this case, the crew recovered. After landing, "substantial" ice, by some reports up to 2 inches, was found accreted on the empennage aft of the protected surfaces; in this case, the flight crew had also not operated the IPS.[28]

Several other aircraft have experienced this phenomona since this time, notably the British Aerospace BaE-3100 Jetstream, the Aerospatiale ATR-42, and the Saab 340 (prior to the manufacturer's modification of the horizontal stabilizer). In January of 1998, a NASA ASRS report was filed which describes an ICTS event involving an MD-80 aircraft. In this case, the IPS was being operated, and the system had been cycled to heat the tail. Nevertheless, when the flaps were extended to 40 degrees, the nose pitched over and 500 feet of altitude was lost prior to recovering.[29] This aircraft had the singular advantage of configuring for landing at a significantly higher altitude than many of the aforementioned cases, which is typical for jet transport aircraft operated in contemporary times.

These accidents are interesting when considered in light of the statements made by Noth and Polte during the 1930s, as cited above. In any event, the effects of an ice contaminated tailplane can hardly be described as cumulative.

The Ground Deicing Accidents

Although the Air Florida 90 accident at Washington, D.C., on January 13, 1982, is perhaps the most well-known accident involving a failure to adequately deice prior to takeoff, this type of accident has been occurring for many years. Two that appear in earlier years are the accidents on January 2, 1949 involving a Seattle Air Charter DC-3 and on January 4, 1951 involving a Monarch Airlines Curtiss C-46. In the DC-3 case, numerous attempts were made to deice the airplane before the pilot was advised to be sure and get "plenty of speed" before lifting off.[30] The Monarch case is more interesting in that the investigation refused to acknowledge a role for icing. The airplane had been deiced inside a hangar with an alcohol solution. Although the first officer reported observing frost on the wings forming prior to takeoff, the investigation concluded that, since other airplanes with frost on the wings had successfully taken off, this should not have been a problem. Rather, the investigation concluded that the captain's election to use a lower than standard takeoff power setting caused the crash.[31] This report makes interesting reading when read side by side with the Air Florida 90 report.

On February 12, 1979, a Mohawk/Frakes 298 version of the Nord 262 crashed during takeoff at Clarksburg, West Virginia. The aircraft had accreted a 1/4 inch layer of wet snow prior to takeoff, and had not been deiced.[32] In this case, the investigation refers to Ralph Brumby's paper, "Wing Surface Roughness: Cause and Effect", published in January 1979. The report states that,

> "According to a recent review of the effects of wing surface roughness, frost, snow or freezing fog adhering to wing surfaces causes a reduction in maximum lift coefficient, a reduction in the angle of attack at which stall occurs, and a rapid post stall increase in drag. The above effects are most pronounced when the roughness is on or near the leading edge of the wing."[32]

In March of 1979, Trunov and Ingelman-Sundberg of the Swedish-Soviet Working Group on Scientific-Technical Cooperation in the Field of Flight Safety published their paper entitled, "Wind Tunnel Investigation of the Hazardous Tail Stall Due to Icing".[24] Although this report is more relevant to the preceding discussion on ICTS, it details their results with distributed roughness on the leading edge of a modified 18 degree swept tailplane model used to investigate the Viscount accident at Stockholm. They concluded that a leading edge roughness of only 1/1300 of the chord resulted in degradations almost as significant as the large ice shapes they had also tested. This conclusion parallels that of Brumby, quoted above by the NTSB, at about the same time.

In the Air Florida case, the Safety Board indicated an awareness of 22 events involving "aircraft pitchup or rolloff immediately after takeoff in weather conditions which were conducive to the formation of ice or frost on the wing leading edges."[33] Boeing had investigated these events and published several Operations Manual Bulletins addressing them. The particular condition had to do with the use of reverse thrust while taxing on slippery surfaces, which resulted in a melt/refreeze cycle of blown snow. Following flight tests with a simulated roughness applied to the leading edge slats, Boeing found that "The stall characteristics with both symmetric and asymmetric leading edge contaminations were characterized by a very apparent pitchup, yaw rate and rolloff." The flight test program concluded that "Wings should be kept clear of ice...and rotation rates should not exceed 3 degrees per second." The NTSB also quoted Boeing as concluding that "additional speed margins were advisable when operating in adverse weather such as snow, sleet, or rain at near freezing temperatures." The subsequent Operations Manual Bulletin emphasized care in controlling pitch rate during rotation and the use of additional flaps, when possible, to increase stall margins. It stated that,

> "If leading edge flap roughness is observed or suspected for any reason, care should be exercised to avoid fast rotation rates in excess of 3 degrees per second and/or over rotation."[33]

On November 15, 1987, Continental 1713 crashed during takeoff at Denver. During the investigation of this accident, the Board quoted McDonnell Douglas as stating that a roughness of only 1/10,000 of the wing chord can "adversely affect the maximum lift coefficient and significantly increase the stall speed."[34] Testimony was also heard during this investigation that "ice contamination may also produce roll oscillations and unexpected pitch-up tendencies during flight." (The pitch up tendency is related to outboard wing stall, resulting in a significant change in the overall pitching moment.)

On March 22, 1992, USAir 405 crashed during takeoff from LaGuardia airport in New York. Once again, a discussion of wing leading edge roughness ensued. In this case, the airplane involved was a Fokker F-28. The report details differences between the conclusions drawn by McDonnell Douglas and Fokker regarding whether or not slatted wings have an advantage. McDonnell Douglas had already concluded that non-slatted wings were more susceptible to roughness effects; Fokker cited Swedish research indicating that there was no difference in the effects of frost between a slatted or non-slatted wing.[35]

Between these cases can be seen some uncertainty as to the full effects of leading edge roughness. Although the Civil Air Regulations had, since 1938, always clearly prohibited air carrier aircraft from being taken off when the wings or tail surfaces have a "coating of ice or snow", regulatory language regarding frost did not appear until 1953.[36] The rules then prohibited takeoff with "frost, snow or ice adhering to the wings, control surfaces, or propellers...". (One may presume that the rules had finally caught up with the decline of fabric covered wings, rendering Samuels' 1932 conclusion about frost obsolete, i.e., frost now *did* adhere to the wing firmly, had considerable resistance to the vibration and wind forces in flight and was, in fact, dangerous.)

This language is identical to the basic language contained in the present Federal Aviation Regulations. Even the present rule, however, allows that "Takeoffs with frost under the wing in the area of the fuel tanks may be authorized by the Administrator. ". [37] This statement gets to the heart of the matter, which is to optimize the ability to tolerate a certain amount of roughness with the ability to eliminate it. The current guidance is quite specific, but the evolution of understanding what can be tolerated, and where, has been quite painful.

On December 27, 1968, Ozark 982 crashed during takeoff from Sioux City, Iowa. The investigation found that the airplane, a non-slatted DC-9-14, had accreted ice during the preceding approach and that this ice had not been removed prior to the takeoff.[38] The report said that "The crew was aware that a 'small' accumulation of ice was present on the aircraft, but the captain did not consider it significant." This is once again illustrative of the fundamental aspect of the paradigm that "every deposit upon the wings or parts of an airplane is not necessarily hazardous, ". Actually, this ice was anywhere from 1/16 to 1/2 inch thick and extended 6 to 8 inches aft of the leading edge. The accident report in this case presents an excellent analysis of why many instances of ice accretion result in unremarkable events or, indeed, go unnoticed. The report states that:

> "The approach and landing at Sioux City were most probably completed without incident because they were flown at near the same angle of attack as the angle of attack at which the ice was accumulated and [had] the benefit of the increased lift as the aircraft descended into ground effect during the landing flare; whereas, during lift-off the aircraft was rotated to an angle of attack most probably 7 to 9 degrees greater than the angle of attack at which the ice was accumulated, coupled with the reduced lift as the aircraft departed ground effect."[38]

The same type of accident had occurred many times before. On February 16, 1950, an Eastern Airlines DC-3 had landed at Lexington, Kentucky. During the approach, ice had accreted on the leading edges of the wings. Additional speed was used on final approach, and a normal landing was made. The ice was not removed, probably by virtue of the same reasoning used by the Ozark crew, and the aircraft crashed on the subsequent departure.[16]

The Ozark report is the second report to refer to the NACA work done by Gray and von Glahn. It is worth noting that this report was adopted on September 2, 1970. The Slick 12 report which also referred to this work was released on November 5, 1964.

On February 17, 1991, Ryan 590, a cargo version of a DC-9-15 (non-slatted), crashed during takeoff at Cleveland. Once again, the aircraft had not been deiced prior to takeoff.[39] It is interesting to note that, although this aircraft had also flown a successful approach through icing conditions, there is no reference to the work of Gray and von Glahn or to the effects of increasing the angle of attack beyond that at which the ice was accreted. In this case, the Board made the assumption that the flight crew had operated the IPS during this approach and that it would have been effective, although the deceased crew and overwritten voice recorder prevented any certainty of this. The investigation posited the idea that the still-hot wing had, after landing, melted some snow accumulation which subsequently refroze as the wing cooled.

The emphasis in this investigation was on the considerable work done by McDonnell Douglas to make flight crews aware of the hazards of small roughnesses. As can be seen in many of the preceding accidents, this is an extremely important aspect. However, unlike the accidents involving Continental 1713 and USAir 405, this aircraft had not been deiced. Consequently, it was not possible to determine when the ice accreted. A comprehensive approach to this accident would have been to posit both types of analysis, that of Continental 1713/USAir 405 and that of Ozark 982.

The absence of an analysis in the report similar to that of Ozark 982 reflects a preference for recent knowledge in isolation from a broader historical perspective. This may lead to bolted-on additions to the paradigm described earlier without seriously investigating the effects of the new knowledge on the whole thing.

The data reviewed indicated that this type of accident continues to occur to aircraft operated from remote facilities without ready access to deicing fluids.

The Contemporary Accidents

The investigation into the accident at Roselawn, Indiana, on October 31, 1994, stands as the most comprehensive work on a single icing accident to date. Simmons 4184, an ATR-72-212, crashed after accreting ice while descending in a holding pattern. For a variety of reasons, the flight crew had extended 15 degrees of flap while holding.[40] Upon retraction of the flaps as the descent was begun, flow separation occurred, probably as a thin-wing type of stall, at the outer wing panel and an aileron became unbalanced. The aileron fully deflected, rolling the airplane completely and leading to a rapid loss of control. The circumstances of this event were surprising to the operating community, and the broad response within that community was that, although "every deposit upon the wings or parts of an airplane is not necessarily hazardous", this one was and the flight crew should have realized it.

Yet within two hours of this accident, another ATR-72 crew experienced a similar ice formation. This aircraft experienced a buffet at 170 to 180 knots; although the leading edges appeared clean, close examination revealed a ridge of ice built up aft of the deicing boots, which had been in operation.[41]

The actual mechanics of the Roselawn accident were not too disimilar from the ICTS mechanics described earlier. The effects of ice in this case were clearly not cumulative; there was little if any drag rise, and the airplane behaved quite normally until the angle of attack was driven up by the flap retraction. The loss of control at a high altitude led to a fairly prolonged struggle during the descent before impact, and the CVR and DFDR provided very detailed information on the entire sequence. The extended length of the accident sequence and the quantity and quality of data available led to an understanding of the event which far surpassed previous icing accidents.

At the same time, the tools available for evaluating the weather conditions had evolved tremendously since the 50s and 60s. It was determined with reasonable certainty that the aircraft had been exposed to large droplet conditions, in particular, freezing drizzle. It became immediately apparent that this environment exceeded that of FAR Part 25, Appendix C, which defined the conditions under which certification had been granted. The effect of freezing drizzle in this case was to accrete a ridge of ice aft of the protected surfaces, which was sufficient to induce a significant change in the aileron hinge moment.

On January 9, 1997, Comair 3272 crashed while being radar vectored for an approach at Detroit. This investigation was also a very comprehensive one, if not as visible as that of the Roselawn accident. In this case, it was discovered that a thin roughness of ice accreted during a 4 to 5 minute period while in descent, perhaps accompanied by a small ridge of ice, may have been sufficient to induce a stall when the airplane was leveled off. The accident report emphasizes the hazards of surface roughnesses to airfoils, and points out that the traditional method of operating a pneumatic deice boot system may lead directly into this type of situation.[42]

While these accidents were both fairly visible, there have been other significant accidents in recent years. Rocky Mountain Airways 217 crashed east of Steamboat Springs on December 4, 1978. The aircraft had departed Steamboat Springs with freezing rain falling and climbed into icing conditions which were described as "heavy" by the same crew upon arrival earlier in the day. While the deicing equipment was able to remove much of the ice, the aircraft encountered a mountain wave condition which yielded severe ice accretion. It was unable to climb to an altitude sufficient to cross the mountains, and the flight crew attempted to return to Steamboat Springs. The airplane settled into the terrain under maximum power. The investigation concluded that the ice accretion combined with downdraft activity to cause the accident.[43]

On February 16, 1980, Redcoat 103, a Bristol Britannia, crashed several minutes after takeoff from Boston. The aircraft was having considerable difficulty climbing after takeoff in icing conditions and significant turbulence. The captain's decision to radically increase the angle of attack in response to repeated low altitude warnings from air traffic control likely resulted in a stall. Ice accreted in flight very probably played a role, and ice accumulation prior to takeoff may also have been involved. Although the aircraft had been deiced, approximately one hour had elapsed and some witnesses thought that some snow had accumulated, although the surviving flight engineer stated that he had specifically examined the wing prior to takeoff and saw no ice.[44]

On March 28, 1989, Air Canada 571, a McDonnell Douglas DC-8-73, experienced a hard landing at Edmonton. The aircraft had flown an approach in weather conditions characterized by a 100 foot ceiling, 1/4 mile visibility in light freezing drizzle, and a temperature of -4C. Rough, jagged ice shapes were found on the airfoils after the landing, ranging from 1/4 inch to 1 inch in thickness. Again, the IPS had not been operated during the approach. The accident was attributed to inadequate control during the landing procedure; an actual stall could not be verified. However, the manufacturer noted that a 25 to 30 percent increase in stall speed would have been likely with the reported ice shapes. In this report, the authorities pointed out that, had a go-around been required, the ice accretion would have seriously compromised performance.[45]

Finally, performance degradations were noted by the Transportation Safety Board of Canada in two contemporary accidents. On March 8, 1996, Canadian 48, a Boeing 767-300, experienced a tail strike while landing at Halifax. The weather conditions at the time were characterized by a 300 foot ceiling, visibility 1 and 1/2 miles in light freezing drizzle, and a temperature of -3.7C.[46] Although ice accretion could not be verified, the IPS was not operated and a performance degradation was noted in the last 400 feet of the approach, The accident was attributed to a visual illusion and a failure to respond to glide path indications from the precision approach path indicator (PAPI). A second event occurred at Fredericton involving Air Canada 646, a

Bombardier CL-600. The flight crew initiated a go-around from an unstabilised, unspooled Category II approach in freezing fog.[47] The aircraft stalled and crashed. It was considered likely that some ice accretion had influenced the aircraft's performance during the late stages of the approach and subsequently, the stall characteristics. The accident was largely caused by the flight crew following the flight director go-around guidance before the engines had spooled up; however, the flight guidance system was also not certificated with any icing effects in mind, and this accident raises the question of what relationship might exist between automated flight guidance and contaminated wings.

Analysis

In order to consider improvements to the knowledge base that is necessary for commercial pilots to have, a spreadsheet was developed containing a variety of data extracted from the previously mentioned 120 accident reports, summaries or synopses. This data includes the following fields:

Flight Designation
Date
Location
Manufacturer
Type
Pilot Flight Time
Co-Pilot Flight Time
Phase of Flight (Accretion)
Phase of Flight (Accident)
Stablised Approach Data
Surface Temperature
Ceiling
Surface Precipitation Intensity
Surface Precipitation Type 1
Surface Precipitation Type 2
Visibility
Wind
Ice Shape Descriptors
Ice Thickness
Chordwise Extent
AoA Change
Ice Accretion in Flight
Exposure Time
IPS Type
IPS operated

The accidents reviewed are not a complete set. Additional accidents have taken place, and the associated reports may not be a part of the databases searched for this paper. However, this set is believed to be reasonably representitive of the complete set.

Exposure, Duration and Severity

The paradigm in use for operations in icing has relied heavily on an understanding of the meteorology conducive to icing in order to minimize the exposure to, if not avoid entirely, those conditions. This is Findeisen's concept of "meteorologically correct navigation". It would be impossible to evaluate this concept comprehensively, since no data is available for the flights which, apparently, made optimum navigational choices to avoid icing, or, for that matter, about what would have happened to them had they not done so.

Of the 120 accidents and incidents evaluated for this research, 82 involved ice accreted while in flight. Within this set, 60 took place during the approach/landing phase (Figure 4a). A further subset of 21 presented reliable evidence that the ice was accreted during the approach phase (Figure 4b).

The approach phase brings with it geographic constraints that are sufficient to reduce the concept of meteorologically correct navigation to its simplest form: one either flies the approach or one doesn't. In this sense, the concept of icing as a cumulative hazard plays an influential role; consider again the language used in the 1938 version of CAR 61.7701:

> "encounters an icing condition, the pilot shall so alter the course and altitude of the flight as to withdraw from the condition, if, in his opinion, it appears that the icing condition may be of such duration or severity as to otherwise endanger the safety of the flight."[8]

The phrase, "icing condition may be of such duration..." strongly suggests that if the exposure can be minimized in time, the hazard can be managed. This is undoubtedly what the captain of United 21 had in mind while holding before the approach at Chicago. He insisted on remaining above the clouds until receiving his approach clearance, a strategy that resulted in exposure to the icing conditions for only 8 minutes. Nonetheless, sufficient ice accreted to result in an unexpected stall during the final stages of the approach.[15]

15 of the 82 events involving inflight accretion presented adequate information to identify an icing exposure time prior to the event. This data is illustrated in Figure 5. Some of the reports provide a range of exposure times, such as "8 to 10 minutes", or "less than 20 minutes". Others are quite specific, for example, "9.5 minutes". In order to provide a weighted perspective on what the minimum exposures might have been, the median of the range cited in the report was used as a minimum exposure for those cases which inferred zero

minutes as the minimum. For example, 10 minutes would be the minimum used for the "less than 20 minutes" case.

It should also be borne in mind that 65 of these inflight events do not provide adequate information to determine exposure times. 2 cases provide data indicating that the exposure was more or less continuous. With this in mind, it is useful to consider the minimum and maximum exposure data.

The average minimum exposure is 10.6 minutes; the median minimum exposure is 8 minutes. The average maximum exposure is 12.8 minutes, with a median maximum exposure of 10 minutes. The range of the maximum data is 2 to 40 minutes. 12 of the15 events took place during the approach/landing phase of flight. This data is significant because a typical exposure time of 8 to10 minutes is overlapped by the nominal time that it takes a transport aircraft to fly an approach.

The above data speaks to the notion that only those aircraft which operate at lower altitudes, and which "spend more time in icing", are at risk. In fact, all aircraft are at risk from the standpoint of exposure. Regardless of whether the flight was one hour long or eight hours long, only a few minutes during the approach is required to build sufficient ice for an event to occur.

The strategy of minimizing exposure during the approach can also significantly impact the execution of a stabilized approach. This was the case in the Northwest Airlink 5719 accident at Hibbing, Minnesaota on December 1, 1993. In this case, the captain also elected to remain above the clouds to minimize exposure to icing during the approach. Unfortunately, he chose to delay his descent until a point which required a very high rate of descent in order to reach the minimum descent altitude prior to arriving over the missed approach point. Although this descent rate was arrested, the airplane was not leveled at the minimum descent altitude (probably because the captain was looking outside for the approach lights) and the airplane crashed short of the runway. The NTSB report is highly critical of this strategy of icing avoidance because of the impact it has on a stabilized approach.[48]

The question then defaults from one of duration to the other conditional provided so many years ago in CAR 61.7701: severity. As has already been discussed, severity is strongly linked in concept with quantity and ice type. Current Part 121 regulatory language requires the pilot to have an opinion regarding icing conditions that "might adversely affect the safety of flight". Again, the concept of icing as a cumulative hazard influences the argument. In conjunction with the icing descriptors of trace, light, moderate and severe (heavy), and with the understanding that rime ice is not as threatening as clear ice, the pilot's opinion is largely reliant on quantity.

In 20 of the 82 in flight events, enough data was present to estimate a thickness of the ice adhering to the aircraft (Figure 6). Many of the ice thicknesses were estimated after the crash. Often some time had passed; some of the reports are careful to point out that local temperatures had remained below freezing during the interval. However, in some cases, fire had resulted, and the effects of this on what ice was found are not known. In no case is anything like the possibility of sublimation discussed. However, the best way to handle data from the reports is to take it as much at face value as possible, since there is no way to estimate any corrections.

In some cases, the reports cited a range of thicknesses. For example, "1/4 to 1 inch of ice" might be stated. Since it is impossible to know what the distribution of thickness was in what was found, a median thickness was taken in these cases. In the aforementioned example, that would be 0.625 inches.

The average thickness was 0.80 inches; the median was 0..5 inches. The smallest average thickness derived from the reports was 0.19 inches; the largest was 2 inches. This highlights the distinction between severity from the standpoint of the energy requirements to remove the ice and severity from the standpoint of the aerodynamic requirements for sustained flight.

It is important to consider these thicknesses with respect to the operation of deicing systems. The procedures published for the operation of most pneumatic and some thermal deicing systems typically include a minimum accretion thickness prior to operation of the system (an "observable" thickness). This has been anywhere from 1/4 inch to 1-1/2 inches. These operating procedures carry with them the implication of safety up to the prescribed thickness. The data from the accidents, as well as considerable research data, suggest to the contrary.

For example, during the IRT tests in support of the investigation of Comair 3272, NASA reported a maximum overall thickness of 1/4 inch of ice, consisting of a "rough, 'sandpaper-like' ice coverage", with small ridges forming along the deicing boot seams.[42] Trunov reported significant degradations when testing the 18 degree swept airfoil used to represent the Viscount tailplane with a roughness height of only 1/1300 of the chord length. [24] Lynch and Khodadoust have provided references and discussion of a wide range of data addressing roughnesses representitive of initial in-flight leading edge ice accretions.[49] Not the least of this data is information from Abbott and von Doenhoff, which has been around for over 50 years.[50]

The reports were also surveyed for descriptors of the ice accretion found after the event. In 71 of the 120 events, no descriptor is available. It must be noted that many of these reports are of the pre-1983 format used by the NTSB, in which narrative text is extremely sparse. In the remainder, various words are used in the reports, such as white, milky, jagged, slushy, and granular. The term "rime" appears 11 times in the reports of in flight events, and only once in reports of ground events. The term "clear" appears 7 times for in flight reports, and also just once for ground events. The term "mixed" appears only once in all of the reports; however, in the aforementioned rime and clear usages, these terms are used together 3 times.

Interestingly, the word "rough" is used on 8 separate occasions to describe the ice found after the event; 5 of these cases were in flight events. Other descriptors of texture include "jagged", "course", and "granular". Not too surprisingly, the reports of ground icing accidents use the term "frost" on 5 occasions and "snow" on 4.

Beginning with Samuels' work, then with the United 21 accident report, and continuing through the accident reports for Jetlink 2733, Simmons 4184 and Comair 3272, the difficulty of seeing and correctly identifying ice formations has been well documented. Yet the paradigm emphasizes an evaluation of the ice shape as a means of estimating risk. The double ram's horn shape exhibited by forms of clear, or glaze, ice has always been described as the most serious threat. But the ice formations described in the accident reports, as well as in flight tests or icing tunnel tests done to support accident investigations, often do not bear much resemblance to the classical training models. In fact, only one accident report actually described the observation of a double horned shape (the Viscount ICTS events at Colorado Springs and Willow Run). On the other hand, a flight test conducted following the crash of United 21 at Chicago produced:

> "a clear glaze ice of approximately 1/4 inch in thickness, extending back 2-1/2 inches on top and bottom of the center line of the leading edge of the de-icer boot, together with a mass of rough ice extending from a point behind the smooth ice over the cap strip and running back onto the wing proper for a distance of about 6 inches."[15]

Thus, while the concept of meteorologically correct navigation can play a significant role in route planning and execution, its applicability to terminal area operations is quite limited. More significantly, the concepts of duration and severity, while logical, are seriously biased by the notion that the ice shape must attain a certain size before becoming a serious threat. Finally, the expectation that a visual assessment of the ice formation can be made accurately predisposes the flight crew to draw quantitative and qualitative conclusions that are simply not possible within the limits of human sensory perception.

But perhaps the most important concept called into question while evaluating these accidents and incidents is that of the "cumulative" threat. Nearly all of these events involve airplanes that were behaving more or less normally up to a point in time, so far as can be inferred from the reports. In 49 of the 120 events , that point in time could be generally correlated with a change in the angle of attack of either the wing or the horizontal stabilizer.

Webster's defines the word "cumulative" as an adjective meaning "increasing with successive additions". The concept of icing as a cumulative threat is consistent with early ideas such as "every deposit upon the wings or parts of an airplane is not necessarily hazardous", right on through the use of progressive descriptors of intensity based on liquid water content. Indeed, relationships have been established between drag and ice formation size which show a relationship between ice shape size and drag change. Accidents such as Rocky Mountains 217 and the General Airways DC-3 at Kerrville, Texas are strongly linked to these types of effects.

But there are other extremely important relationships. For example, while training material nearly always emphasizes the reduction in stall angle or increase in stall speed, there is rarely any discussion about the shape of the lift curve at its peak. The abruptness of the stall may be considerably different from that of the same wing when uncontaminated; conversely, it may be more benign and thus less recognizable. The stall initiation and propagation may be wholly different from the clean wing, resulting in pitch characteristics not previously experienced by the flight crew. The effects of separated flow on control balance may be significant.

Some significant relationships which are supported by the accident history are discussed below.

Aerodynamic Relationships

A very significant relationship that is not part of the traditional model is that between the effects of ice formations, the slope of the lift curve and the shape of the lift curve after the lift peak. The cumulative model suggests that lift loss is progressive, which would appear as a change in the shape and slope of the lift curve. In some cases, this may be true, but not always.

Broeren, et.al.,[51] showed differences in the lift curves for a typical airfoil section, the NACA 23012, when tested at high Reynolds numbers with a variety of intercycle ice shapes and a standard, distributed roughness. Figure 7a shows the results for the intercycle shapes; Figure 7b the results for the sandpaper roughness. Three things are important to the pilot. First, the lift degradation for a given ice shape is very dependent on angle of attack. Second, below a certain ice shape-dependent angle of attack, the contaminated lift curve and the clean lift curve are virtually identical. Third, the behavior of the contaminated lift curve as it crosses C_l max can vary significantly with the ice shape, and it can be quite dramatic.

The roughness results shown by Broeren agree well with the roughness results from Abbott and von Doenhoff. In both cases, the lift curve slopes do not depart significantly from the clean lift curve until within 2 to 3 degrees of the contaminated C_l max, and then the departure is immediate. This characteristic is not too disimilar to the clean stall. The lift curves with the zero degree ice shapes, however, are quite a bit different. While much greater lift loss is evident, the development of the lift loss is more benign. Were this to occur in a symmetrical manner to the entire wing, it might not be recognized in a timely manner; more realistically, one or more lift curves with the associated non-linearities will apply to different wing sections, depending on ice accretion shape. Thus the entire stalled behavior is likely to be different from the crew's nominal experience.

A second very important relationship is that between the angle of attack at which the ice was accreted and the effects of the same ice formation when the angle of attack is increased. Several of the accident reports in the 1960s cited work done by Gray and von Glahn. In this work, the authors stated that:

> "A glaze ice formation on the leading edge section for a simulated approach condition, during which the airfoil attitude is increased from 2 to 8 [degrees] angle of attack, caused a severe increase in drag coefficient of over 285 percent over the bare airfoil drag at 8 [degrees] angle of attack and was accompanied by a shift in the position of the momentum wake that indicated incipient stalling of the airfoil." [26]

The ice shapes tested by Broeren, et.al., in the NASA LTPT were all formed at a zero degree angle of attack in the BF Goodrich icing tunnel.[51] The drag results shown in Figure7 are dramatic. Although these are section drag coefficients, and there are questions regarding scale effects between the 36 inch chord model used in these tests and a full scale wing, the effects of accreting ice at a low angle of attack and then increasing that angle can be seen clearly.

Further, Broeren's results with the sandpaper roughnesses are consistent with the warning found in Trunov and Ingelman-Sundberg:

> "For thin but rough ice layers on the wing leading edge there can be a very large disproportion between its effect on drag in cruise and its effect on the maximum lift in the landing case. An ice layer which has a relatively small effect on cruising speed can have a large effect on the stall speed."[52]

The upshot of this is that there may be little in the way of altered lift characteristics or significant, noticeable drag rises when continuing to operate at the angle of attack at which the ice shape was accreted. However, when the angle of attack is increased, significant degradations can occur rapidly. If the angle of attack is increased due to routine attitude and/or configuration changes, the cliff may be encountered before the magnitude of the degradations can become clear. Consequently, the captain of Northwest 5 experienced normal behavior during his descent only to be surprised at the sudden stall when he leveled off, and the flight crew of Ozark 982 did not perceive any degradation during their approach. This same characteristic has appeared many times, most recently with the Comair 3272 accident.

It follows, then, that the understanding of how angle of attack is controlled is critical to icing operations. Conventional civilian pilot training places nearly all of its emphasis on the control of angle of attack through pitch attitude. Obviously, this is the primary method, but in this simplification, the true nature of more subtle variations in angle of attack is overlooked. Flight crews should first understand that they are constantly flying two wings, and two angles of attack....that of the main wing, and that of the horizontal stabilizer. They need to understand the effects of all primary controls, vertical accelerations, ground effect, propeller slipstream, and, particularly important, of all secondary controls, on the angle of attack at each lifting surface. This point argues for a much broader, more comprehensive education in the function and operation of the airplane's lifting surfaces than that produced by conventional training, and that is what is needed. For example, the understanding of the effects of secondary flight controls is important because these controls are most often motorized and usually preselected and then automatically driven. This results in changes to the angle of attack that are more or less forced. While the scheduling of secondary flight control deployment or retraction can be rescinded, this can rarely be done quickly in response to an undesirable aerodynamic effect. A perfect example of this can be seen in the Simmons 4184 accident at Roselawn, in which the flap retraction forced an increase in angle of attack, leading to flow separation. For that matter, all of the ICTS events fall into this category, as they all occur following flap extension. In consideration of the sensitivity of a contaminated wing to angle of attack changes, knowledge of how each configuration change impacts the angle of attack at both lifting surfaces is crucial.

A corrollary to the control of angle of attack is the understanding of flow separation and stall. All of the icing accidents evaluated involved separated flow and stall of some type. Conventional design promotes a stall propagation which is intended to insure that lateral control remains effective and the general behavior of the wing is benign. The contaminated stall may develop very differently, leading to airplane behavior that is unusual in the experience of the flight crew. The stall may initiate at the leading edge instead of the more typical trailing edge. The stall may also initiate nearer the tip instead of the root, leading to premature problems in lateral control and substantial changes in pitching moment.

The effects of flow separation on lateral and longitudinal stability are another part of this aspect. For example, the loss of longitudinal stability during an instrument approach can lead to a disastrous pilot induced oscillation. A good case in point is the Union Oil Convair 580 accident at Midland, Texas in 1963. In this case, the tail may never have actually stalled, but the flow separation may have led to a substantial reduction in longitudinal stability. Because the ice contaminated airfoil no longer retains the benign characteristics that were intended in the original design, it is imperative that pilots understand how the lifting surfaces may behave and what effect this may have on the overall handling of the airplane. This is a subject that requires considerably more depth than the current discussion of whether or not stall warning systems will function before the stall.

A final aspect of the flow separation discussion is that of flight control balance. Without doubt, the flight crew of Simmons 4184 was not familiar with what could happen if the aileron hinge moment coefficient was altered. The same is likely true for those crews involved in ICTS events. A more comprehensive understanding of how the flight controls are balanced and what aerodynamic considerations can change this balance is required. Because flight control designs vary, care must be taken to avoid inappropriate generalizations.

All of these relationships belie the myth that the effects of icing are cumulative. Instead, they are very much a function of angle of attack, and, consequently, can present shifts and nonlinearities which are sudden and catastrophic.

Ice Formation Descriptors

Beginning with the work done by Carrol and MacAvoy, the primary and virtually sole factor in the operational description of inflight icing has been whether the shape is rime or clear. Around the time of Samuels, the notion of what are today known as "mixed conditions" became known. Mixed conditions are defined as a combination of supercooled liquid precipitation and solid precipitation. Sometime during the intervening period, the definition of mixed conditions appears to have devolved into "mixed icing" which is generally recognized as a combination of rime and clear ice.

However, the accident record suggests that the utility of such terms in actual risk management is questionable. Lynch and Khodadoust have provided what may be a much better organizational hierarchy of icing shape descriptions. They discuss four categories of ice accretions: initial leading edge accretions, runback/ridge accretion, large (glaze) accretions, and ground frost.[49]

If, to this, three additions are made, then a much better structure of descriptors for use in the education of the air carrier pilot will result. First, the terms "intercycle" and "residual" ice must be added for cyclic deice systems. Second, the runback category must also include the ice developed by a thermal system during the period that it runs wet. Finally, the effects of roughness, alone or in combination with any other shape, absolutely must be emphasized. These terms allow the pilot to evaluate the ice encountered with respect to both the characteristics of the particular ice protection system in use and, most importantly, with the aerodynamic aspects of ice shape and location.

Interpretation of Terminal Surface Observations

A final aspect of this analysis must be meteorological. With respect to those events which occurred in close proximity to the surface (low altitude events), the reported surface weather observations were evaluated. For these events, the average surface temperature was -1.76C, with a median of -0.28C (Figure 8). The range was from -9.0C to 2.8C. In the case of the ground icing accidents, these numbers are not too different; the average surface temperature is -3.37C and the median is -2.21C, with a range from -12.2C to 1.1C.

The cloud ceiling for the inflight events averaged 1006 feet, with a median height of 650 feet and a range of 100 feet to 5000 feet. For the ground events, it is hardly different. The average was 1123 feet, the median 450 feet, and the range from 100 to 5500 feet (Figure 9).

Most interesting was the precipitation data (Figure 10) In 27 of 69 inflight events for which adequate data exists, snow was falling at the surface. In 7 of these snow cases, freezing drizzle was also falling concurrently. Freezing drizzle was falling alone in 10 additional cases - thus, freezing drizzle is present in 17 of the 69 inflight events. Freezing rain fell concurrently with snow in 2 cases, and fell alone in 1 case. In 2 other cases, sleet was reported to be falling alone. There was no precipitation reported in 15 cases, and rain or drizzle prevailed in the remaining cases.

With regard to the ground icing accidents, snow was falling in 21 of the 30 cases which presented adequate data. Freezing drizzle was reported in isolation in 2 cases. The remainder involved no reported precipitation.

In 29 of the 47 in flight events which presented enough data the reported precipitation intensity was light; this was also true of 10 out of17 takeoff events. In 2 of the inflight events, moderate precipitation was reported. This was the case with 2 of the 17 takeoff events as well. Due to the format of a number of these reports, however, precipitation intensity was not recorded.

The in flight events yielded an average wind direction of 006 degrees and a median of 360 degrees. The average wind velocity was 12.3 knots, and the median was 11.5 knots.

The inescapable conclusion from this data is that, for air carrier operations, a surface observation of a ceiling below 1000 feet, a temperature of 0C or a couple of degrees less, a north wind of around 10 to 15 knots and light snow or freezing precipitation is a pretty good warning of serious icing potential during the approach and landing. Further, the same conditions pose a serious threat with regard to the ground deicing/takeoff situation.

It is interesting to consider that NACA published research papers and CAA documents of fifty years ago, and FAA documents to this day, describe a sort of "special case" of icing when freezing or frozen precipitation is mixed with liquid precipitation. For example, the current Advisory Circular 91-51a states that, "Ice particles become imbedded in clear ice, building a very rough accumulation."[13] This is remarkably consistent with the frequency of freezing precipitation and/or snow in the above accident and incident reports, and with the weak but noticable prevalence of the term "rough" and similar terms in the icing descriptors used in the reports. Yet like the large droplet environment, the mixed phase environment is not part of FAR 25 Appendix C.

None of this is to say that other conditions are not equally or perhaps more serious. However, this work has shown that the current paradigm in use by transport aircraft pilots is essentially unchanged over the course of 50 or 60 years. In that same time period, presumably due to the influence of that paradigm, these are the conditions in which air carrier aircraft seem to find the right combination of exposure and susceptibility.

Application To Modern Transport Operations

The above relationships may form the core knowledge of icing and its effects. However, the pilot must also understand how to integrate this knowledge into operations.

Aircraft Systems

It is important to first consider several aspects of aircraft systems . These are:

1. Ice Protection System Design
2. Flight Control Design
3. Automated Flight Angle of Attack Guidance

It is important for the flight crew to understand the design of the specific ice protection system they will be using. In the case of pneumatic deicing boot systems, this includes understanding the possible effects of pre-activation ice, intercycle ice and residual ice. It involves understanding the limitations of using the system throughout the landing, including what ice might be accreted after the system is shut down prior to landing. In the case of thermal systems, it includes understanding whether and/or when the system functions as a running wet system and what the effects of runback ice might be. It also includes understanding the power requirements for effective operation of the thermal system, and what changes to configuration might be necessary to maintain adequate power during the descent and approach in icing conditions. Finally, it includes understanding the ramifications of a thermal system which must be cycled, either automatically or manually, between the wings and the tail and what implications that arrangement might have during the approach. For example, Gray and von Glahn found that :

> "the residual runback icing formed during cycles at low angles of attack will determine how closely the drag after an angle-of-attack

change to 8º will approach the bare wing drag at 8º angle of attack following the heat-on period."[26]

It is also important for the flight crew to understand the design of the specific flight controls used on their airplane, i.e., are they reversible or irreversible and, if reversible, how are they balanced? For example, besides aerodynamic balancing, horn balances can respond poorly to ice accretion, and the simple addition of hydraulic boosting does not in itself make a control irreversible.

Finally, and perhaps the most subtle, is the issue of automated flight attitude guidance. This is best seen in the Air Canada CL-600 accident at Fredericton. Flight crews need to understand that stall warning and recognition systems are not always biased for icing situations, and even when they are, they are biased on the basis of the effects of a presumed ice formation. But the Air Canada accident serves to point out that there are other systems that do not recognize the ice condition. Most notably, this applies to automated go-around guidance. The flight crew must consider ice formations when using automated pitch guidance, particularly when that pitch guidance calls for significant increases in the angle of attack.

Operation of the IPS

All of this knowledge must then be integrated into the planning of operations. First and foremost in this planning is the vigilant operation of the airplane's ice protection system. In 55 of the 82 inflight ice accretion events studied, an ice protection system could be identified. In 25 of these cases, the system was not operated. This is consistent with data from the larger database of 312 events worldwide. In this database, 143 events yielded information about the operation of the IPS. In 30 of these cases, the pilot was aware of icing conditions but the IPS was not operated.

In many cases, the IPS probably was not operated because it was a deice system, usually pneumatic boots, and the manufacturer's instructions required delaying operation while an "observable thickness" developed. The discussion above regarding how well transport pilots can see ice formations speaks to the fallacy of this. However, the practice probably originated due to concerns about ice bridging. The FAA Ice Bridging Workshop[53] concluded that this phenomona is very unlikely to occur with a rapid inflation/short duration type of system typical today, and many manufacturers have changed their procedures. It is very important for pilots operating pneumatic boots to understand the relationship between boot cycle times and icing effects. For example, Figure 11 is an extract from Bowden's 1956 work.[54] The sawtooth pattern represents the cycle periods of a pneumatic system; the relationship between cycle period and the delta in aerodynamic coefficients can be seen. The important aspect of this for the pilot is to understand that delaying operation in order to obtain a clean, complete shedding of ice results in a higher percentage of a given period flown with an ice accretion, and the degradations themselves are greater. A continuous cycle period, while perhaps not as effective at achieving a complete shedding of ice, results in a lower percentage of a given period flown with the ice accretion, and the degradations are themselves less significant.

The notion of vigilant operation of the IPS must be integrated with the conclusion that most of the accidents take place during the approach phase. This is a high workload phase, particularly during an approach in icing (read: instrument) conditions. Many airplanes do not have a well automated IPS, or have one equipped with an automation schedule which is may not dovetail well into the approach sequence and workload. This is a situation which may lead to some degree of complacency, particularly in the absence of a reliable negative consequence.

The Takeoff

Enough has been said in many publications about the function of deicing fluids and the procedures to be used with them that little more need be added. However, curiously, nearly all of this emphasis stops at brake release, so to speak. Very little is said in training material regarding ice accretion immediately after takeoff.

It is important, however, for flight crews to consider the icing situation immediately after liftoff. There will be a couple of forced changes in angle of attack. The first change will come with departure from ground effect, and while that should not be an issue if adequate deicing has been accomplished, it is worth being aware of. The next change will come with the first configuration change. This is usually a flap retraction. This has been associated with a couple of the Cessna 208 accidents. Shortly thereafter may come a slat retraction. Both of these substantially change the wing characteristics and the angle of attack. In many cases, they come in close proximity to the minimum altitude for IPS operation. Between the time of liftoff and that minimum altitude, it is possible for sufficient ice to accrete to cause problems. It may be wise to delay reconfiguring the airplane, in certain cases, until the IPS has been operated. It is also important to consider the various angle of attack changes that may come with a climb profile.

The Stabilized Approach

A third aspect of this integration is based on the conclusion from the air carrier data that an icing event rarely results from a stabilized approach. FAA Order 8400.10 states that "Maintaining a stable speed, descent rate, vertical flight paths, and configuration is a procedure commonly referred to as the stabilized approach concept."[55] In 60 of the 82 inflight icing cases evaluated, the event took place during the approach phase. In only 6 of these cases could it be concluded that the approach was truly stabilized. In 33 cases, it was not stabilized; for example, in 9 of the cases, the aircraft was not configured in a timely manner. Typically, this involves the ICTS events in which the flaps are lowered on very short final; this remains a standard procedure for turboprop aircraft. In 10 of the cases, the aircraft was executing some type of circling maneuver. In an additional 8, the aircraft was flying some type of non-precision approach which required intermediate level offs (this set might be arguable as to whether the approach was "stabilized" by conventional definition; however, even a well flown non-precision approach lacks some of the elements of stabilization considered essential, which is one reason why such approaches are not desirable for transport operations). In 3 cases, the aircraft was below the glide slope; in 2 others, it was above the glide slope. Interestingly, in the one known case of an MD-80 aircraft experiencing an ICTS event, the aircraft was recovered largely because it was configured early in preparation for a stabilized approach profile.

Thus, the flight crew should seriously consider the implications of icing on the type of approach that they are planning to fly. Configuration changes and circling maneuvers close to the ground should be avoided. Attitude changes, with the consequent changes in angle of attack, should be planned and managed carefully. It may well be appropriate to artificially increase the approach weather minimums in the case of some non-precision approaches to accommodate more conservative configuration and attitude changes. This notion is particularly important with regard to "fly-up" glide path corrections.

A case in point is TWA 924 at Gander in March of 1949. Although the investigation did not cite structural icing, the airplane was flying a ground controlled approach (GCA) in icing conditions that included freezing drizzle. The aircraft impacted ground structures while correcting back up to the glide path.[55] Other cases in which this could conceivably have played a role are the Hibbing Jetstream accident and the EMB-110 accident at Alpena, Michigan in 1985. At Alpena, the aircraft was also flying an ILS in icing conditions that likely included freezing drizzle. It crashed short of the runway with no apparent explanation except that the flight crew was not monitoring the altitude.[56] However, accidents such as Comair 3272 and Northwest 5 have shown how rapidly degradations can arise with increases in angle of attack.

Finally, the aforementioned FAA Order 8400.10 states that a visual or circling approach should be stabilized by 500 feet above the surface, and an approach in instrument conditions should be stabilized by 1000 feet above the surface. [57] The document states that, "Operational experience has shown that the stabilized approach concept is essential for safe operations with turbojet aircraft, and it is strongly recommended for all other aircraft." The icing event data suggests that, at the very least, an approach with ice accretion on the aircraft should be stabilized by 1000 feet above the surface under any circumstances, visual or otherwise. Further, the icing event data seems to provide "operational experience" which shows that with ice accretion, a stabilized approach is essential for any type aircraft, regardless of powerplant design.

The Go-Around

A fourth aspect is an extrapolation based on the number of approach events. The concentration of events within the approach phase suggests that there is a consequent exposure to the go-around phase. Continental 290 at Kansas City, Northwest 324 at Sandspit, and Air Canada 646 at Fredericton all took place within the go-around phase. The accident report for Air Canada 571 at Edmondton stated that "had the captain decided to overshoot during the final stages of the approach, the ice contamination would have been a detrimental factor in obtaining the lift performance required.". Consequently, operational planning for the go-around must take serious consideration of the icing situation. Both Air Canada events involved ceilings of 100 feet and visibilities of 1/4 mile or less. Such conditions increase the liklihood of a go-around considerably. Planning for such a go-around must include consideration of the ice contamination effects on required climb performance (including engine-out performance), configuring so that adequate bleed air is available during the final stages of the approach to maintain as clean a wing as possible, and considering the effects of go-around flight guidance, rotation rates, and configuration sequences on an ice contaminated wing and/or stabilizer.

Conclusion

The origins of the current operational understanding of the structural icing hazard can be traced back to the years before World War II. The current paradigm is based on some generalizations which easily lead to the misinterpretation of experience. The major tenets of this paradigm, as defined in the late 1930s, continue to be the areas of primary emphasis, while other aspects that have developed during the intermediary period have not been integrated into the paradigm. Generally, the industry has failed to capture many of the lessons learned in the accident record. Only when a series of contemporary, high profile accidents occur is the paradigm modified, and then only by means of bolted-on additional modules, such as those seen in the last ten years regarding ground icing and SLD conditions.

In particular, the concept of icing as a cumulative hazard is misleading. The accident data shows that the icing hazard is strongly influenced by the angle of attack and characterized by the nature of lift curve beyond the contaminated C_l max, evaluated across the wing span and at the horizontal stabilizer. This behavior is nonlinear and consequently not well described by the cumulative concept. Further, accident data and research data, some of it dating back many years, indicate that the relationship between the icing hazard and the quantity of the ice or the size of the formation is not linear, and that significant hazard exists due to thin, rough ice accretions.

Therefore, the paradigm must shift from one which is based on the concept of a cumulative hazard to one which recognizes the potential of very small, thin ice accretions and which emphasizes the role that angle of attack plays. While the current emphasis on the avoidance of flight through icing conditions is an important part of the paradigm, greater emphasis on the evaluation of approach conditions is required. Finally, the air carrier pilot's understanding of ice formations must integrate shape, roughness and location with the nature of ice formations expected before, during and following operation of the ice protection system, including pre-activation, intercycle, residual and runback ice formations.

Icing is widespread enough, and sufficiently difficult to forecast or preemptively detect, that an understanding of its effects on the flight characteristics and handling qualities of the airplane is critical. Perhaps no other hazard does more to disrupt the aerodynamic predictability of the flight vehicle while at the same time being so commonly encountered. It simply will not tolerate generalizations that are designed to simplify the discussion or to reduce training expenditure. In order for the pilot to operate competently in these conditions, he must have a comprehensive understanding which allows him to make wise decisions, substantiate those decisions, and correctly interpret his operational experience as it develops.

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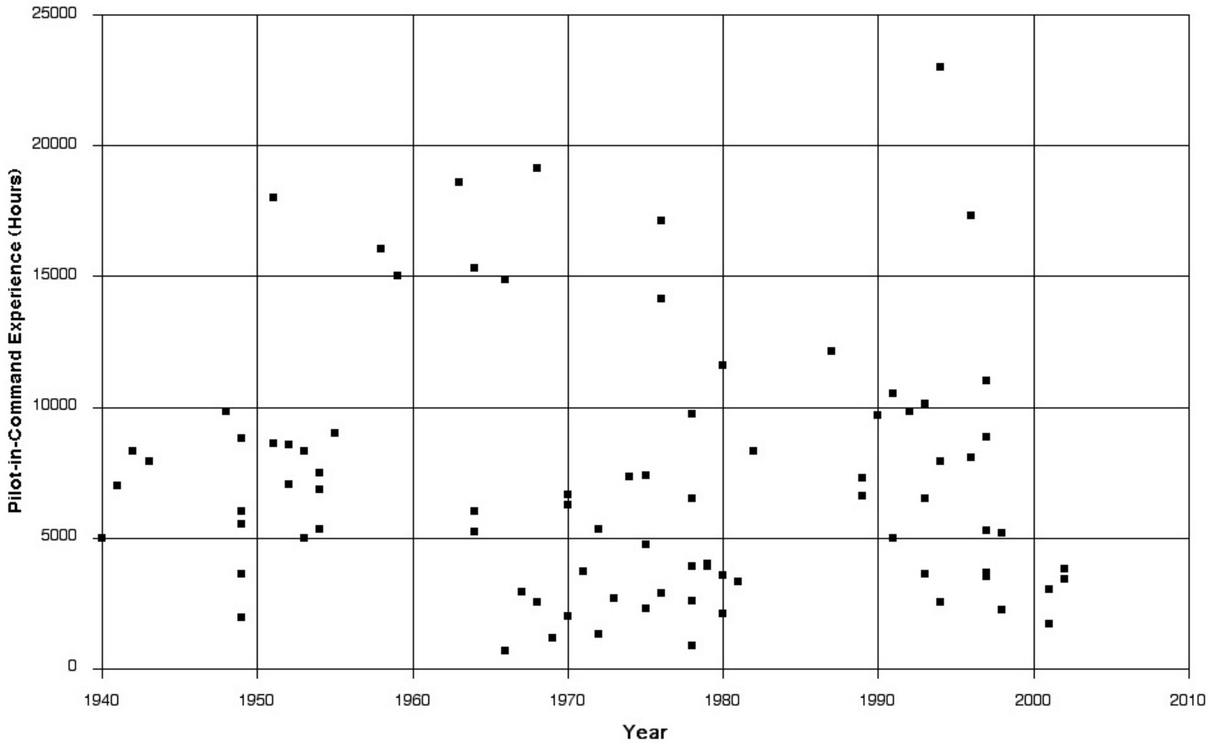

Figure 1 - Icing Accident Historical Pilot Experience Level

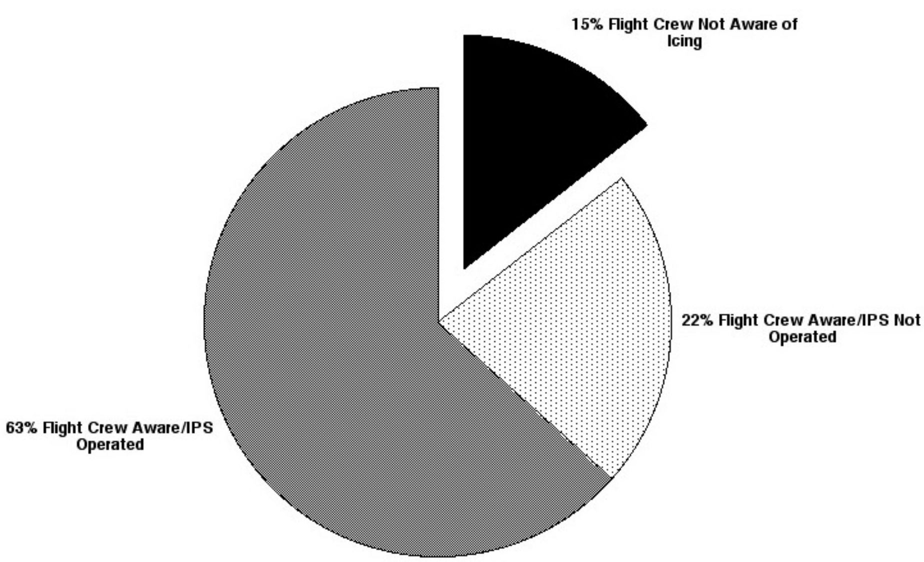

Figure 2 - Distribution of Flight Crew Awareness and IPS Operation (based on 312 event worldwide database)

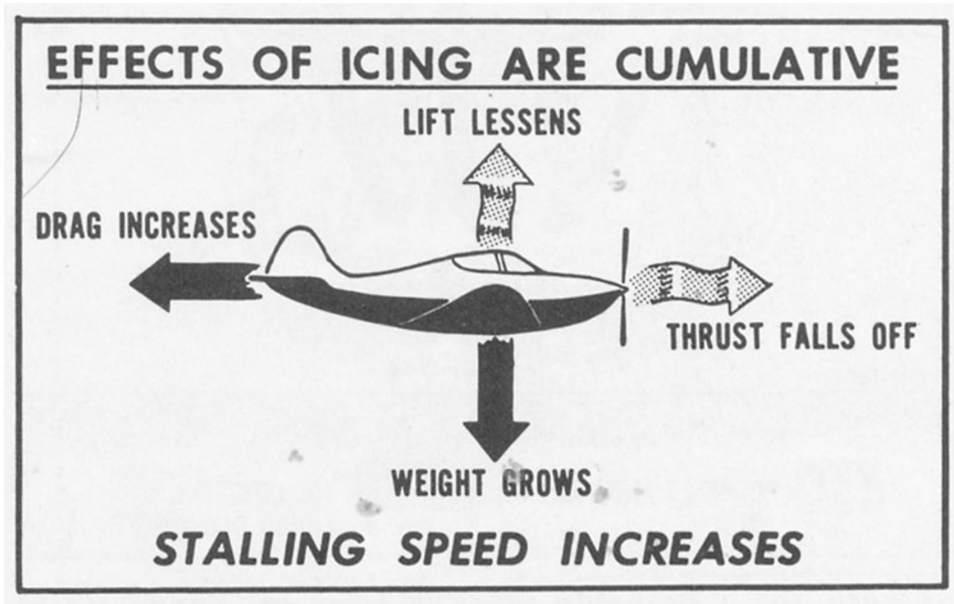

Figure 3 - CAA TM 104 Diagram of "Cumulative Effects" concept

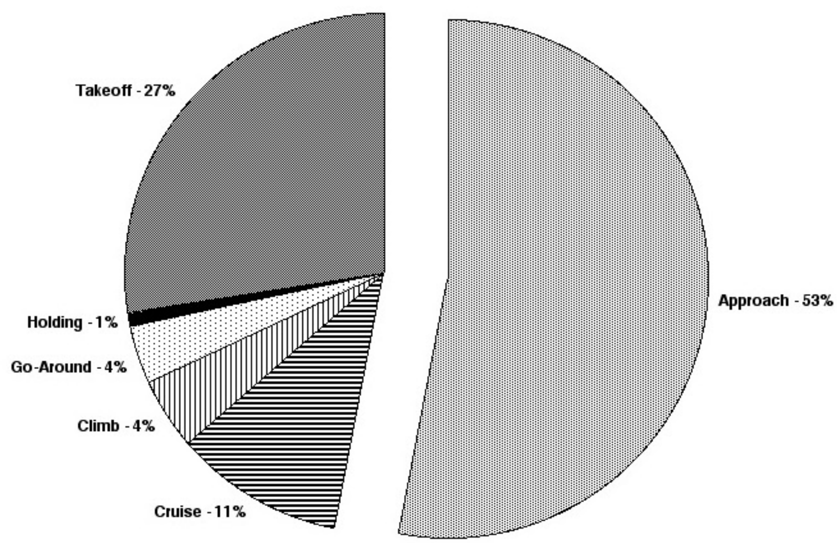

Figure 4a - Distribution of Accidents by Flight Phase

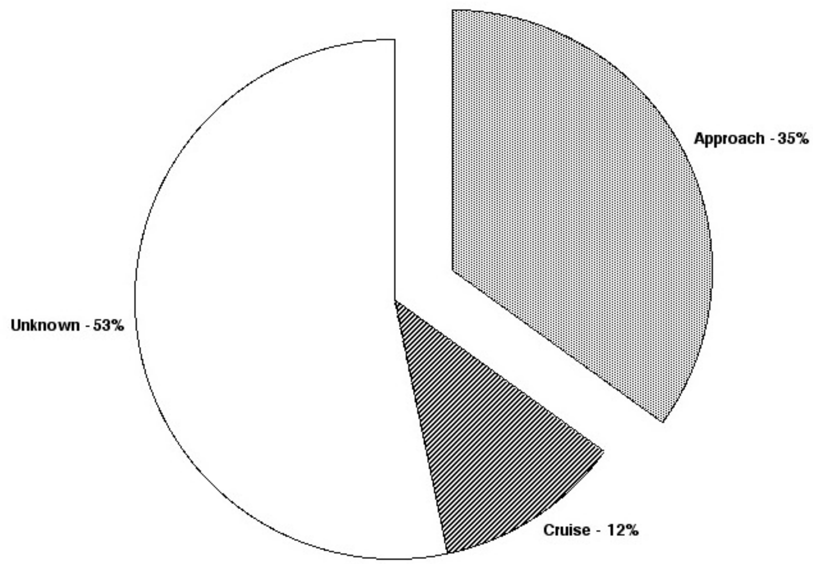

Figure 4b - Distribution of Phase of Flight in which Ice was Accreted (Approach Phase Accidents)

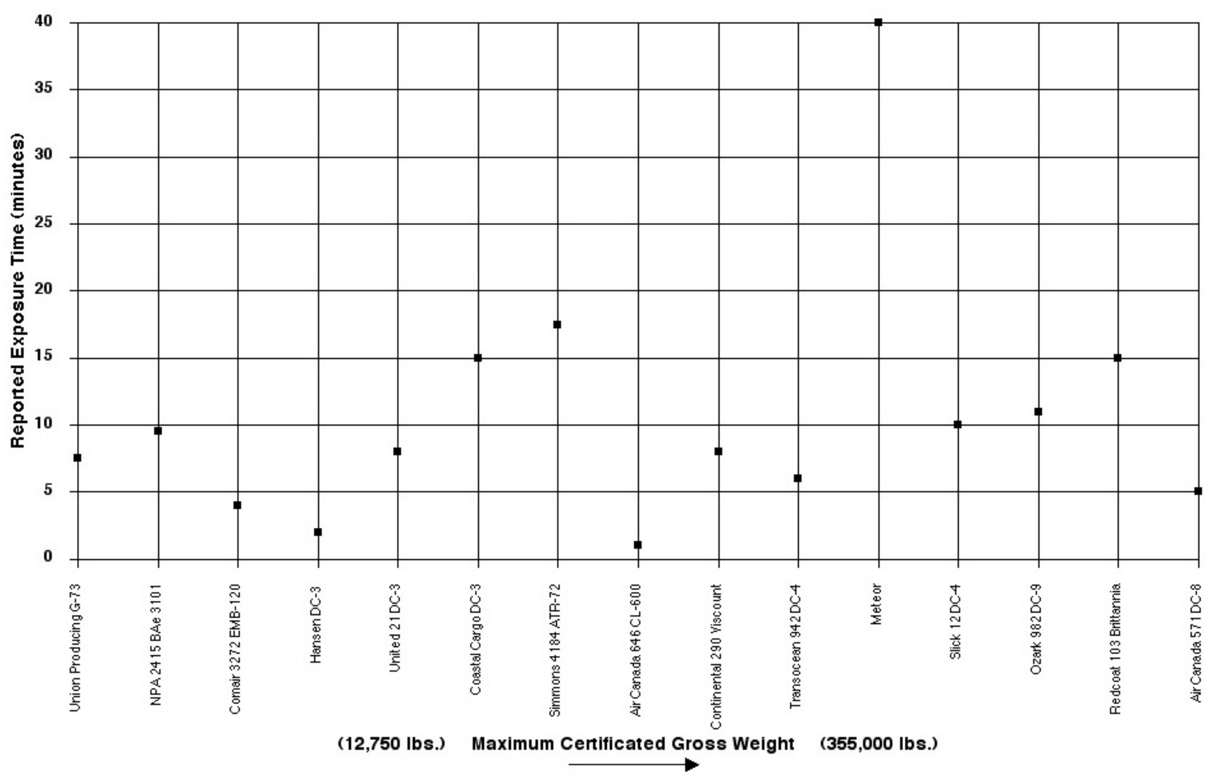

Figure 5 - Exposure Time to In-Flight Ice Accretion (In-Flight Events)

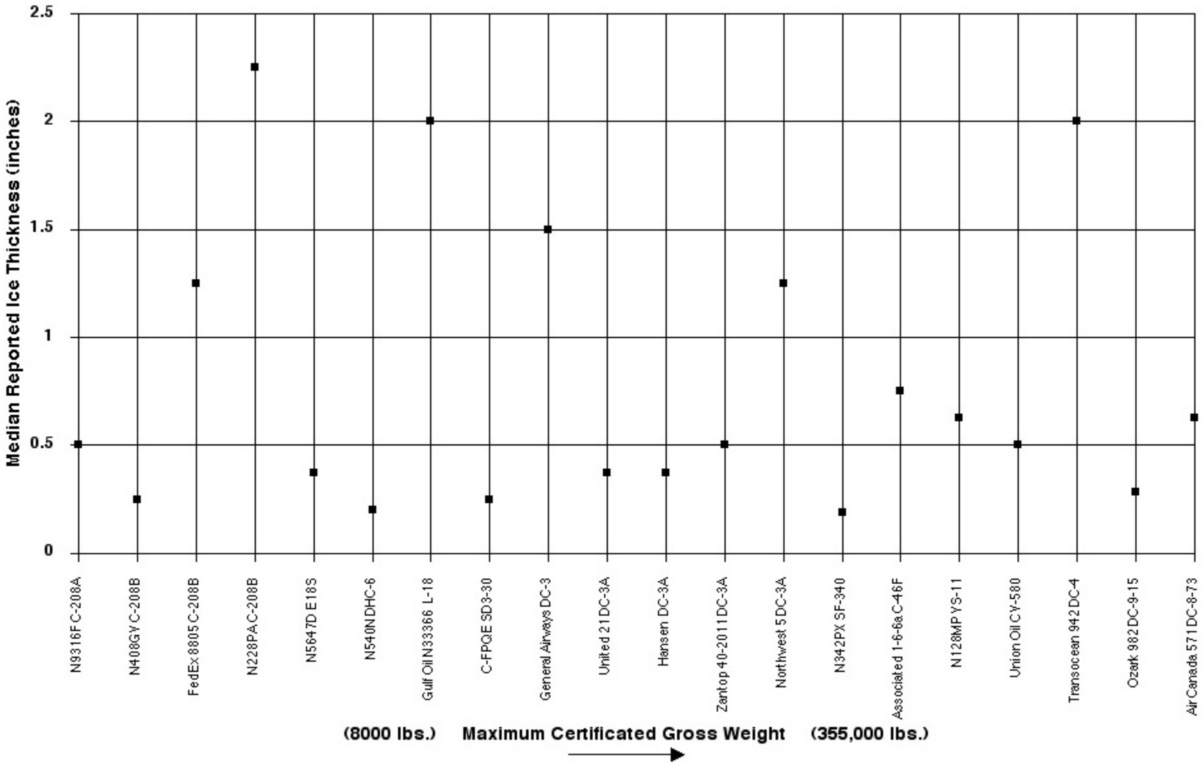

Figure 6 - Median Reported Ice Thicknesses (In-Flight Events)

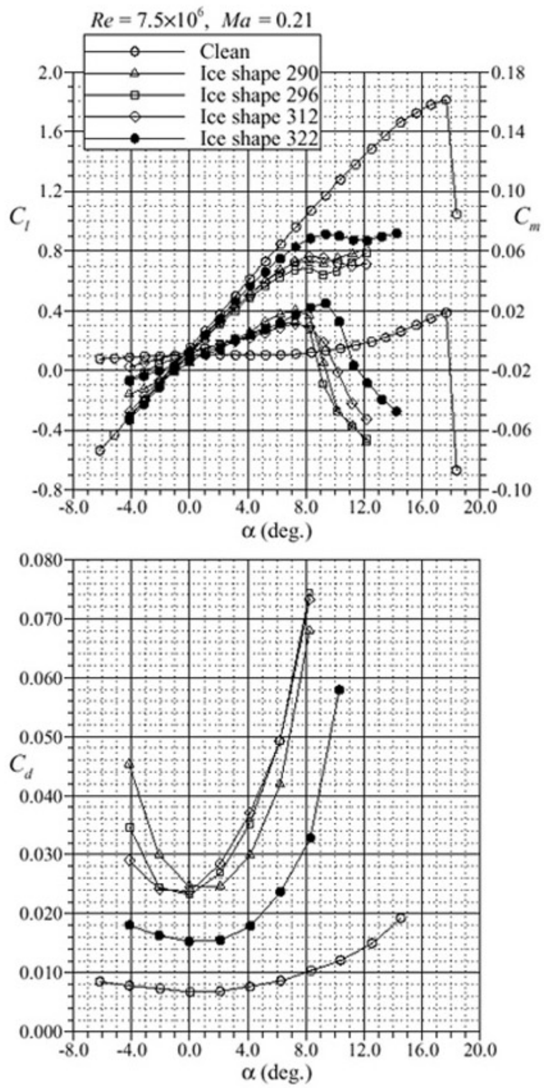

**Figure 7a - Broeren, et.al.
LTPT Data for Intercycle
Ice Shapes**

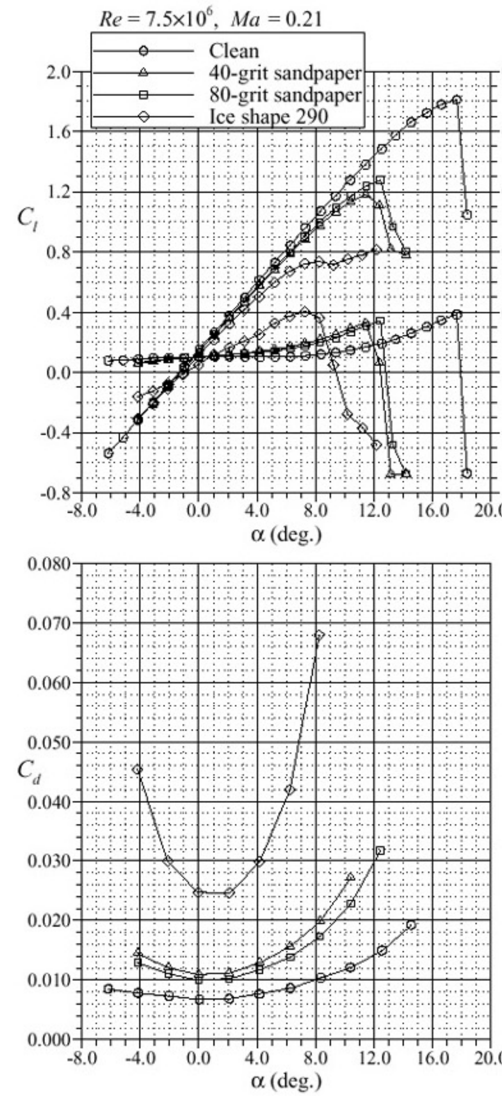

**Figure 7b - Broeren, et.al.
LTPT Data for Sandpaper
Roughnesses**

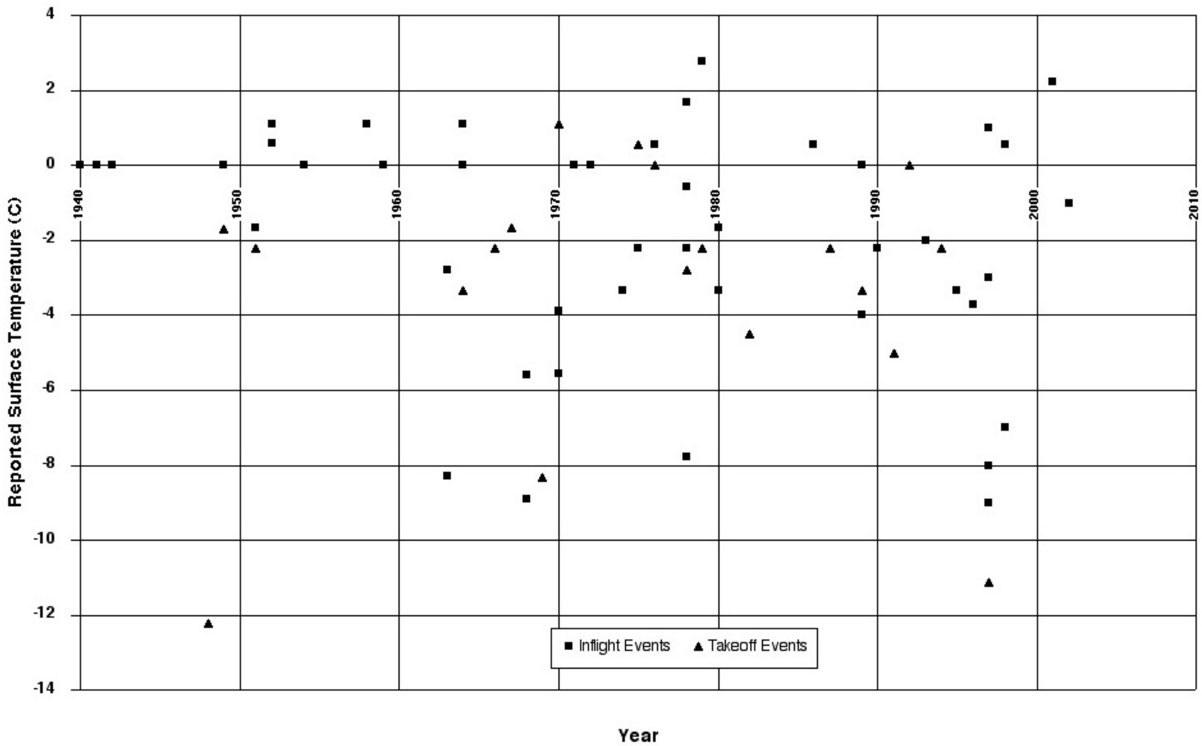

Figure 8 - Distribution of Reported Surface Temperature

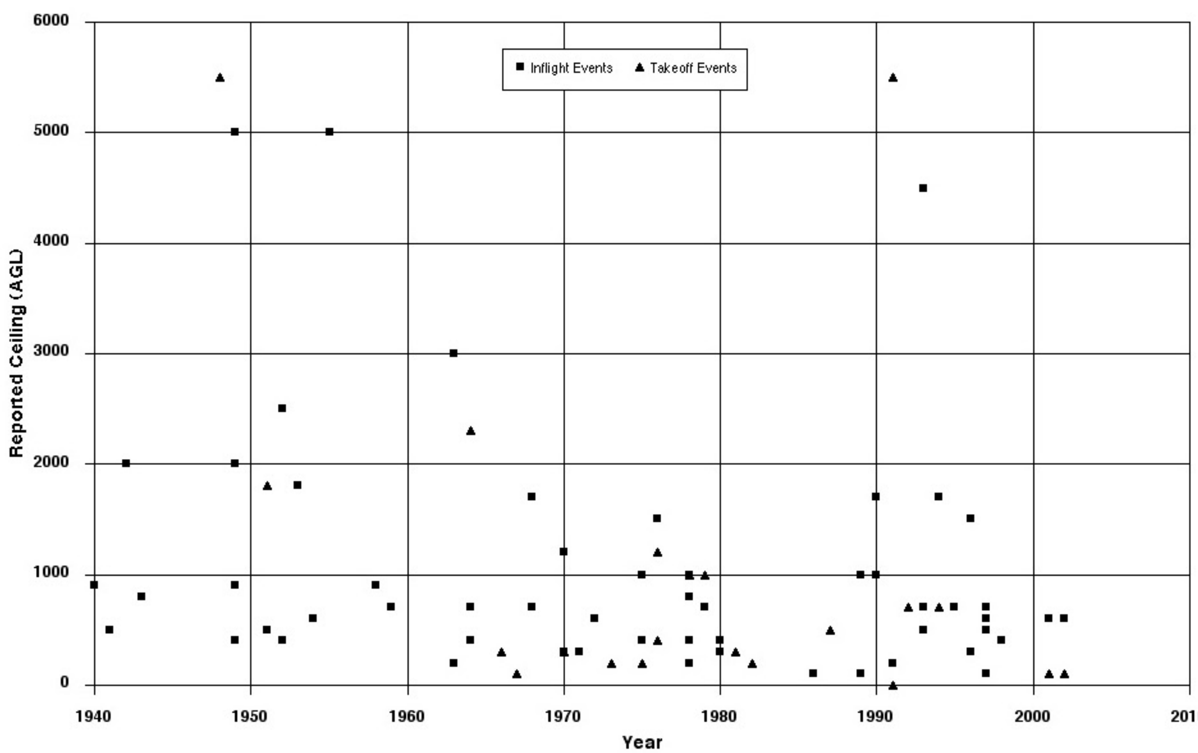

Figure 9 - Distribution of Reported Ceilings

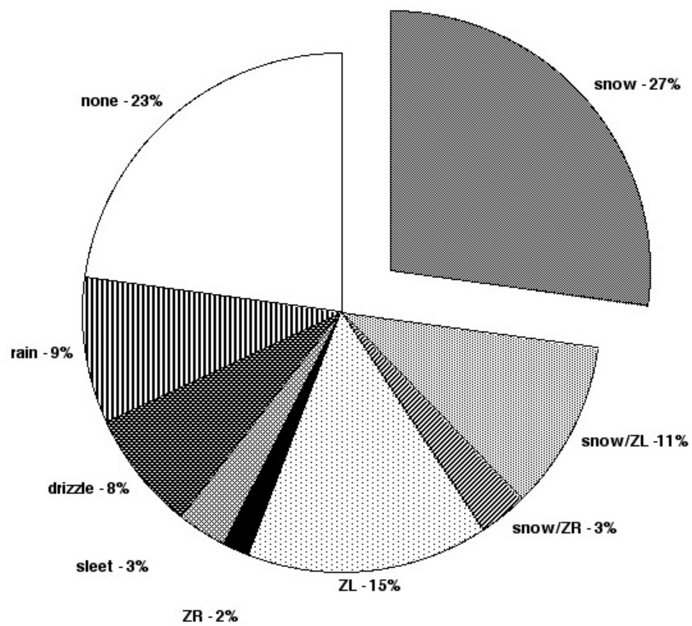

Figure 10a - Distribution of Surface Precipitation - Low Altitude Events

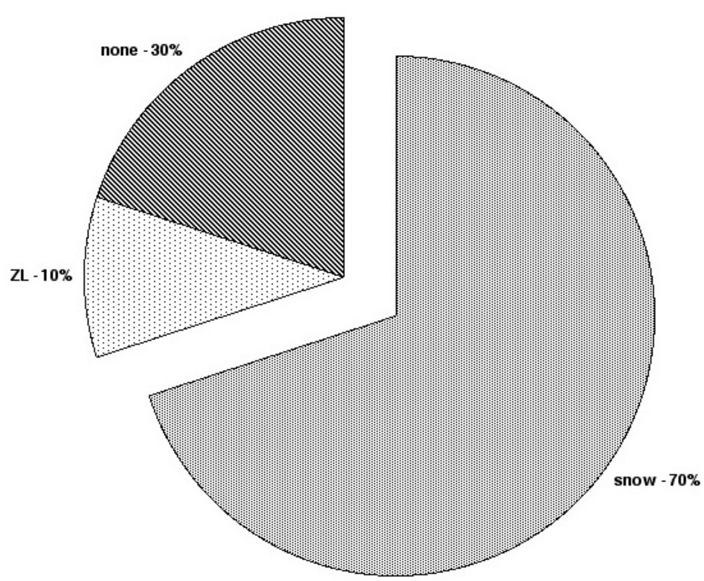

Figure 10b - Distribution of Surface Precipitation - Takeoff Events

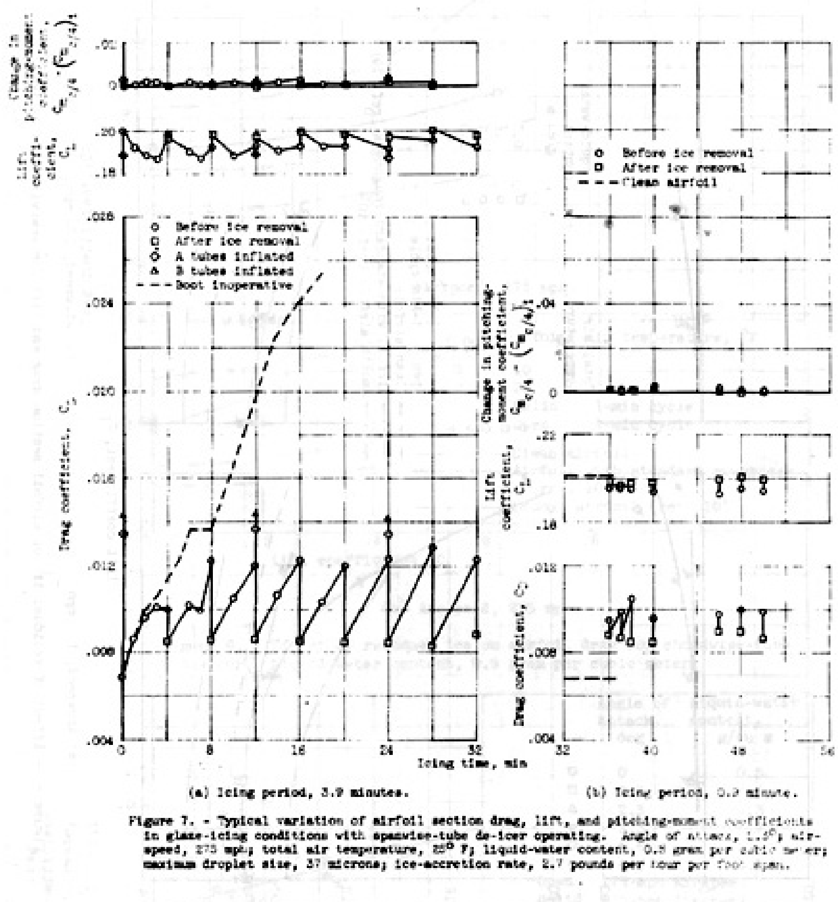

Figure 11 - Bowden's Data on Degradations During Deicer Cycling