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INTERRELATIONSHIPS BETWEEN COMMERCIAL AIRPLANE DESIGN AND OPERATIONAL REQUIREMENTS AND PROCEDURES

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Abstract

Commercial airplane design and operational requirements and processes have traditionally been handled as separate entities. The increased capability, complexity and integration of airplane, satellite and ground based systems results in the need to systematically account for the principle design and operational interrelationships. This need is illustrated by consideration of two examples: (1) airplane collision avoidance systems and procedures and (2) airplane icing encounter design and operational considerations. The development of these examples is used to suggest general conclusions: (1) The need for improved information relative to environmental conditions, (2) The need for improved information relative to human response characteristics and (3) The need to adjust procedures and organizations to better account for interrelationship considerations.

I Interrelationships

Until the time period of the 1970's, commercial airplane design and operational requirements and processes were handled as largely separate entities. Airplane design requirements and processes responded to established operational needs, and operational procedures recognized limits set by design capabilities. There was communication but only limited *interactive coordination*. Since the 1970's a number of factors have led to significantly higher levels of design-operations coordination. These include: the use of efficient, sometimes complicated, and often highly integrated airplane systems (e. g. fly-by-wire stability augmenting flight controls); advances in airplane and ground based guidance and communications systems (e. g. Air Traffic Control processes and Satellite Communications); and recognition of the safety and economic advantages that can result from interactive integration of design and operations factors.

It is the purpose of this paper to illustrate operational-design interrelationships by the use of two examples which are of substantial current interest. Examination of these examples will be used to provide an assessment of the present strong points and limitations in dealing with operational-design interrelationships, and will thus be useful to suggest areas of work that will lead to more effective procedures for dealing with these interrelationships.

II Examples of Design-Operational Interrelationships

II.A. Collision Avoidance Systems

It is certainly not the purpose of these paragraphs to describe the technical details of collision avoidance systems, it should be sufficient to state that it is the purpose of these systems to provide to the flight crews of properly equipped airplanes traffic advisory information and resolution information (maneuver commands) that will allow the avoidance of near mid-air collisions. These systems work in a total operational environment that involves: the collision avoidance system hardware and software, the airplane flight crew, the maneuver limitations of the airplane and the Air Traffic Control (ATC) system (hardware, software, communication links and traffic controllers). Assuming that the requirements for the collision avoidance system are correctly defined and assuming that all elements (hardware, software, pilot and controller) perform correctly then the total system will make a significant contribution to avoidance of near miss situations. If the system requirements are incomplete or incorrect, or if the system or human elements fail to perform correctly, the result may be failure to avoid a near-miss situation, or worse, contribution to the occurrence of near-miss situations.

Figure 1 is a greatly abbreviated version of one near-mid

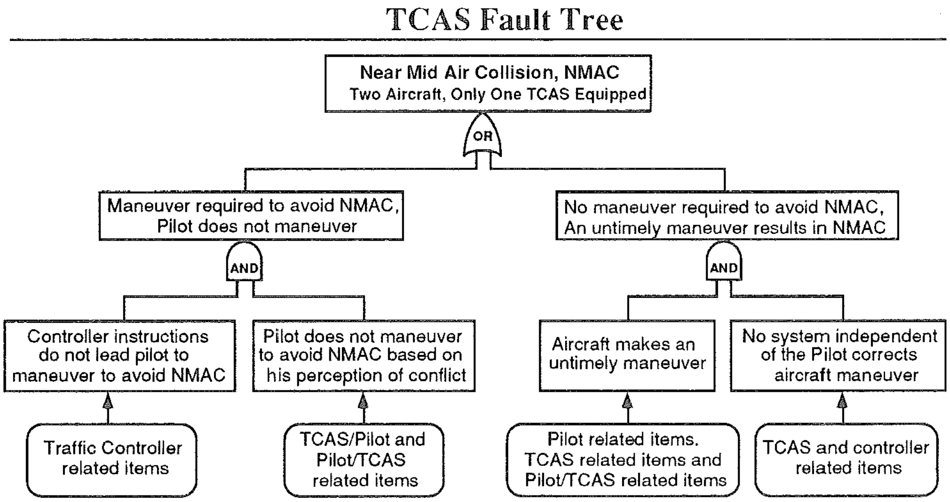


Figure 1 A very abbreviated version of an approximately 100 element, 7 level fault tree

air collision fault tree used to evaluate the TCAS II system currently being implemented. The actual fault trees from which Figure 1 was derived are quite detailed (approximately 100 event blocks with as many as six levels of detail below the top event "Near Mid-Air Collision".

Development of the fault tree has a number of technical virtues:

1. It formally recognizes the complexity of the complete system and that there are significant contributions from hardware, software, flight crew, traffic controllers, visibility conditions and airplane maneuver capability.
2. It reasonably establishes the interrelationships between the contributing elements.
3. It allows for some assessment of the relative importance of elements and paths of the fault tree.

This approach also has some significant limitations:

1. Its use for quantitative assessment requires assigning or deriving numerical values for individual elements. For those elements involving human action (flight crew, air traffic controller) there is a rather broad range of uncertainty and these uncertainties can lead to a low level of confidence in the quantitative assessment.
2. The employment of a fault tree assessment method and all of the attendant criticisms and discussions can detract from the development of methodologies other than the conventional fault tree approach for evaluating systems with very dissimilar contributory elements.

Evaluation of the TCAS II system based on in-service results has commenced. The process will employ flight information resulting from the growing level of TCAS usage in the United States. "Flight information" includes a small body of data from instrumented airplanes and much larger bodies of incident reports from pilots and air traffic controllers. It is expected that after a number of years of service it will be possible to reasonably assess the effectiveness of the system.

A number of conclusions are suggested by consideration of this example, however, development of these suggestions is deferred until a second example is discussed.

II.B. An Airplane Icing Scenario Issue

It seems appropriate to introduce this example by a statement of the obvious. Anyone who has had a substantial amount of flight experience has likely had encounters with atmospheric icing. These encounters are generally associated with at least a small amount of safety concern and quite frequently lead to vivid recollections. This anecdotal information is certainly sufficient to inspire continuing work to better understand the impact of icing conditions on aviation safety but is clearly insufficient as a source of information on which to build technical programs for the enhancement of flight safety.

A more comprehensive approach is suggested by Figure 2. The figure shows a flight scenario that includes principal icing encounter possibilities. These include:

1. A brief icing encounter during climb out.
2. Loss of an engine. On a large twin engine commercial airplane this will generally result in flight to an alternate or to the destination airport at altitudes in the range 15,000 to 27,000 ft. Icing can be encountered at these altitudes.
3. Loss of cabin pressurization. On most two, three or four engined commercial airplanes this will result in flight to an alternate or the destination airport at 10,000 ft. or lower. Icing condition encounters are possible.
4. Holding or go-around maneuvers in the vicinity of the alternate or destination airport may be required. For two, three or four engined airplanes these may involve icing encounters.

Considering these scenario elements, it is clear that assumption of an extreme worst case combination may lead to overly extensive design, testing and analysis requirements, or on excessive fuel loading to account for performance loss due to ice accumulations. Though there have not been accidents of large commercial jet airplanes associated with the Figure 2 scenario or its variations, requirements to deal with worst case type scenarios have been imposed for operation of twin jets on 180 minute ETOPS routes. The reason stated for these restrictions is that there is much uncertainty relative to icing encounter situations: likelihood of icing encounters, severity of encounters, etc. To clarify and hopefully resolve these uncertainties, work is underway to provide needed technical and operational information. This includes:

- Work to better define the ice accumulation characteristics of airplanes (wings, tail surfaces, engine/nacelles, etc.).
- Work to better define the likelihood and severity of atmospheric icing conditions.
- Work to define the range of flight crew and ATC actions that can be expected when icing conditions are predicted or encountered (for an airplane in normal or emergency operating condition).

Work being done to address each of these items is discussed below. It is believed that when completed this work will lead to conservative but not unreasonably restrictive design and operations requirements.

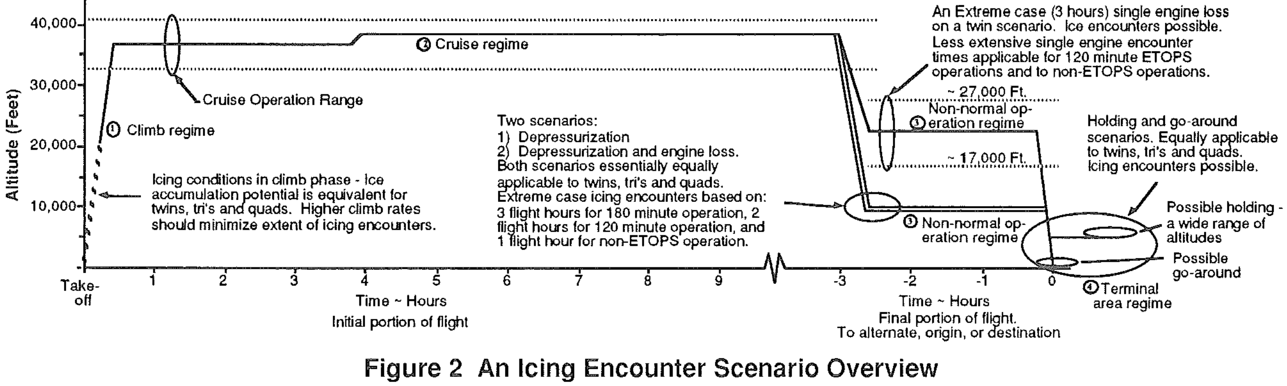


Figure 2 An Icing Encounter Scenario Overview

II.B.1. Airplane Ice Accumulation Characteristics

Many technical facilities and a great deal of work are dedicated to defining the ice accumulation characteristics of each airplane/ engine combination. Programs to predict ice accumulation characteristics are generally available: LEWICE in the United States, the RAE and ONERA programs in Europe, other programs devised to support specific military and space launch vehicle programs, etc. These programs give reasonably accurate ice accumulations predictions for two dimensional (2D) and 3D wing sections. However, more analytical work must be completed, and large computer assets will need to be available before the prediction technology will be capable of providing information for complete airplanes. Each step in this evolution process will need to be verified by comparison to icing wind tunnel test data and possibly to in-flight icing test data. It is believed that full development of icing prediction methods will require extensive work for at least the next ten years.

Since analytical prediction methods will require a great deal of work to achieve standalone capability, they are now, and will continue to be, supplemented by results derived in icing wind tunnels. A list of eight icing tunnel facilities in the U. S. and Canada is provided by NASA TM 81707. This paper also lists eight U. S. A. and Canada icing tunnels used to predict engine ice accumulation characteristics. The largest of the airplane icing tunnels is the NASA-Lewis facility with a test chamber of H=1.8 meters, W=2.7 m and L=5 m and with a speed range 10 to 470 km/hr. In this tunnel liquid water contents up to 3.0 g/m^3 can be achieved. There are also icing tunnel test facilities available in Europe with excellent capabilities. A number of facilities in the U. S. are now being improved (test chamber size, speed range and super cooled liquid water droplet generation capability).

Even with combined use of analytical prediction methods and icing tunnel test results some verification by natural icing flight tests will be required. The combined use of the three (analysis, icing tunnel tests, and flight test) are adequate but costly methods to address the issue of ice accumulation characteristics. Much work needs to be done and is underway; but progress will be realized at a moderate pace.

II.B.2. The Definition of Atmospheric Icing Conditions

A great deal of work, largely measurements made by properly instrumented airplanes, was done in the 1940s and 1950s to develop information about atmospheric icing conditions. Piston engine airplanes cruised in the altitude range where icing conditions could frequently be encountered. With the move to the jet era, cruise operations were normally above the regions of the major icing encounters and the impetus to continue these atmospheric icing condition studies was lessened. Many important papers were published and the available knowledge came together to result in the FAA and JAA airplane icing requirements (Appendix C of FAR 25 and JAR 25). These requirements have significant limitations when applied to airplane design and operational considerations:

a. They do not account for seasonal variations (summer and winter requirements are the same).

b. They account for design, but not operational situations differences (North Atlantic or North Pacific operations are the same as U. S. West Coast to Hawaii or Rio de Janerio to Miami).

c. They use liquid water content data obtained in sub-tropical clouds as a basis, probably not applicable to clouds in more temperate zones (see Special Investigation Memorandum 112 of the United Kingdom Meteorological Office "An Icing Climatology for Helicopters" by Roach, Forrester, Creive and Watt, 1984).

To move beyond these limitations new work will need to be accomplished and verifying data gathered. There are a number of current initiatives. One such set of initiatives is described in the following paragraphs.

The problems with gathering icing data by the use of instrumented airplanes are cost and time. There are so many geographic areas and altitudes to consider, so many seasonal effects to consider, and icing conditions are very sporadic.

One currently available possibility is to use the great amount of satellite and ground weather station data which is available to generate an icing climatology, and perhaps to make specific regular icing predictions for areas of interest. A possible methodology for development of an icing climatology was developed by Dr. Judith Curry of Pennsylvania State University as the result of a contract with the Boeing Commercial Airplane Group. The first paragraph from the abstract of this work (Assessment of Aircraft Icing Potential Using Satellite Data, Judith A. Curry and Guosheng Liu, submitted to the Journal of Applied Meteorology, July 25, 1991) is cited below:

> "This paper explores the potential of using satellite data to develop a climatology of aircraft icing probability in oceanic regions. The datasets employed in this analysis are: the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) microwave radiances; the U. S. Air Force Three-Dimensional Nephanalysis (3DNEPH); the European Center for Medium-Range Weather Forecasting (ECMWF) initialized analyses; and HIRS2/MSU satellite radiances. This analysis focuses on the middle latitude regions of the north Atlantic Ocean, encompassing the paths of most trans-Atlantic flights between the U. S. and Europe."

It is obvious that some icing climatology development can be derived from this method. There is, however, a proviso - can it be shown that the prediction method agrees reasonably well with actual observations?

To address this question a comparison program was undertaken during the winter and spring of 1992 with subsequent data analysis and evaluation. This program is characterized by Figure 3. It is seen that the program involves the comparison of satellite predicted icing conditions (the methodology of Dr. Curry) with synoptic weather prediction and observation information and with actual observed icing conditions (derived from Boeing funded adjuncts to the Canadian Atlantic Storms Program (CASP II)). CASP II will allow actual icing conditions to be measured at a range of altitudes in the same area and time period when satellite predictions are being made. If the satellite methods can be verified, a powerful tool will be available to generate icing climatologies for the principal air routes of the world. The work is sure to be a step ahead, but its full value will not be assessable until results are fully analyzed. [Note: It is expected that by the time of the ICAS 1992 meeting there will be at least preliminary results that can be discussed].

II.B.3. Flight Crew and ATC Actions That Can Be Expected When Icing Conditions Are Encountered

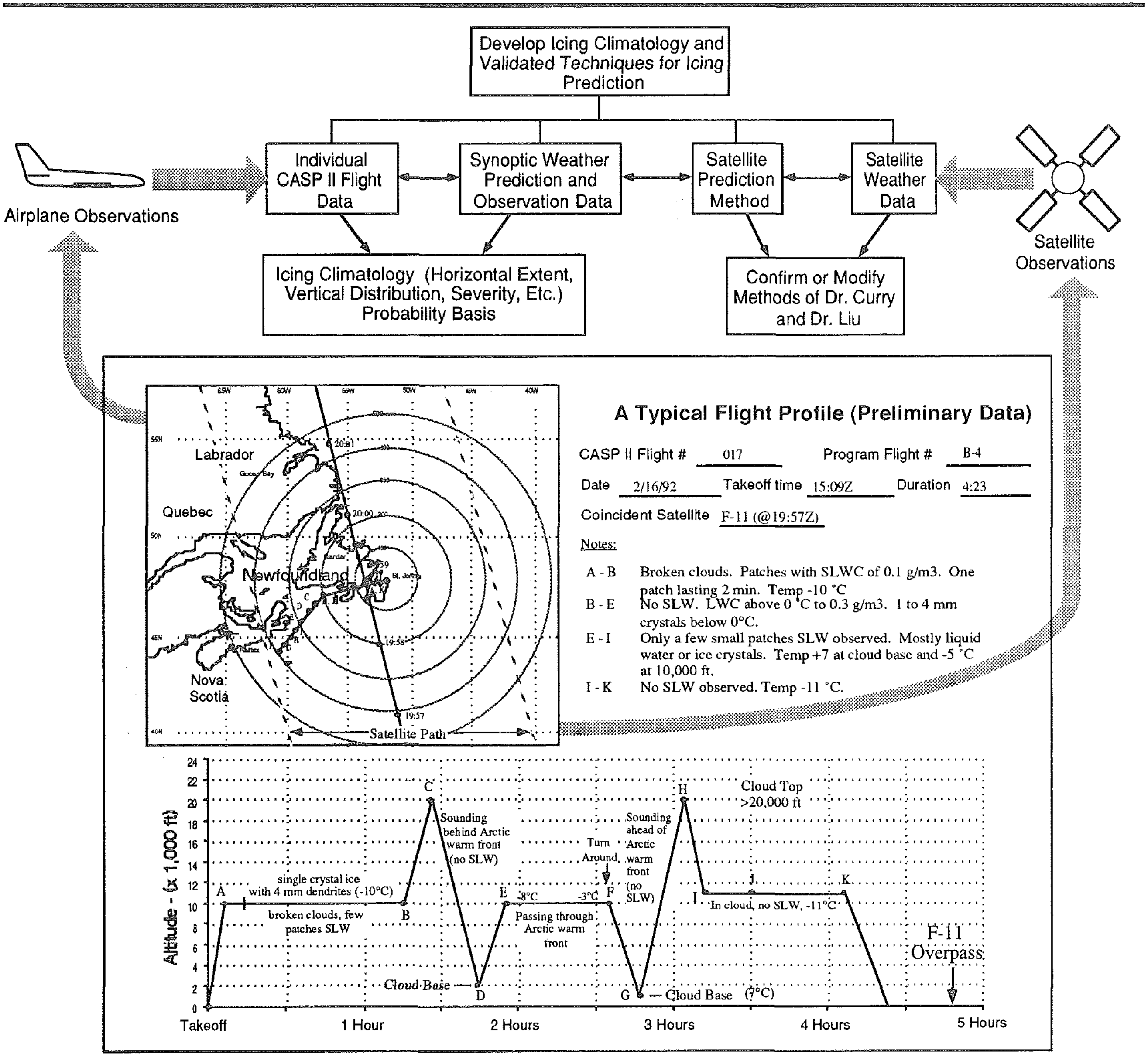
The use of the information described above (icing climatology and ice accumulation characteristics) will be constrained by assumptions made relative to flight crew and ATC actions. Will flight crews and ATC use available information to minimize encounters with of icing conditions on the approach to landing areas (avoidance by path changes, speed changes or altitude changes)? Will flight crews and ATC use available information to avoid terminal area holding patterns in areas of reported icing conditions (altitude bands and specific geographic areas)? Will special consideration be given to airplanes with engines shutdown or with declared emergency conditions? Very liberal answers to these questions could result in ice accumulation scenarios which are potentially insufficiently conservative. Overly conservative assumptions may lead to unnecessary fuel loading and design restrictions. Work is underway that should lead to the development of the range of operational scenarios that should be considered to allow for conservative, but not unnecessarily restrictive operational scenarios. This work and the icing climatology work discussed in the section above are obviously interrelated. Results can be expected to lead to future reviews of the requirements that aircraft hold in moderate to heavy icing conditions for as much as 30 to 45 minutes prior to landing (see FAR 121.165, paragraph b(4) and FAA Advisory Circular 20-73, Chapter 2, Section 3, Operational Factors). The reviews may also lead to differentiation between normal operations and operations of airplanes with shutdown engines or declared emergencies. Operational experience and judgment will be the keys to progress in these areas.

III General Conclusions Suggested by Consideration of the Collision Avoidance and Icing Scenario Examples

III.A. There is a well defined need for improved information relative to some environmental conditions. Such conditions include:

1. Icing climatology conditions.
2. Visibility conditions are assumed for "see and be seen" traffic avoidance.
3. Turbulence and gust conditions.
4. Encounters with particulate matter (volcanic ash, etc.).

III.B. There is a well defined need for improved information relative to human response characteristics (use of collision avoidance information or response to predicted or encountered


Atmospheric Icing Model Developments

A Typical Flight Profile (Preliminary Data)

CASP II Flight # 017 Program Flight # B-4

Date 2/16/92 Takeoff time 15:09Z Duration 4:23

Coincident Satellite F-11 (@19:57Z)

Notes:

A - B	Broken clouds. Patches with SLWC of 0.1 g/m3. One patch lasting 2 min. Temp -10 °C
B - E	No SLW. LWC above 0 °C to 0.3 g/m3. 1 to 4 mm crystals below 0°C.
E - I	Only a few small patches SLW observed. Mostly liquid water or ice crystals. Temp +7 at cloud base and -5 °C at 10,000 ft.
I - K	No SLW observed. Temp -11 °C.

Figure 3

environmental conditions). In these regards it may be well to consider that the improved information may be derived in formats that are not directly usable by currently used analysis techniques (fault trees, etc.).

III.C. When operational and design procedures need to be jointly considered to address complete safety or performance issues, current industry or regulatory organizational structures may be more of an impediment than a help. Organizational structures may benefit from some readjustments and most certainly will benefit by provisions for better inter-organization cooperation and communication.