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Risk Management of Aircraft Critical Surface Inspection, Volume 1 of 3
Methodology for Evaluating Comparative Risks

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16. Abstract

This study evaluated the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors. In this phase of the project, a methodology to evaluate the comparative risks was developed and applied using limited currently available data. Deficiencies in the data were identified and the additional data that should be collected to complete the analysis were recommended. Current regulations, airline procedures, sensor systems, and effects of fluid failure on aerodynamic performance and the likelihood of an accident were reviewed. Risk analysis trees were developed and fluid failure progression data were analysed to determine the risks. The study also included surveys of Canadian and U.S. pilots regarding clean wing inspection procedures, deicing frequencies, and their assessment of fluid failure.

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16. Résumé

Cette étude a consisté à évaluer les risques comparatifs associés à une inspection avant le décollage fondée principalement sur l'observation visuelle, sur un système de capteurs ponctuels, ou sur la détection à distance. La présente phase visait l'élaboration d'une méthodologie d'évaluation des risques comparatifs et sa mise en oeuvre à l'aide des données actuellement disponibles. Ayant cerné les trous dans ces données, les chercheurs ont formulé des recommandations quant aux compléments de données à acquérir pour terminer l'analyse. Les travaux ont comporté, outre le survol de la réglementation en vigueur et des procédures en usage dans les compagnies aériennes, l'examen des systèmes de capteurs et l'étude des effets de la dégradation des agents antigivrage sur les caractéristiques aérodynamiques de l'aéronef et sur la probabilité d'un accident. Des arbres d'analyse de risques ont été construits et appliqués aux données concernant la propagation de la perte d'efficacité des liquides antigivrage. L'étude a également consisté à sonder les pilotes canadiens et américains sur les procédures d'inspection des aéronefs avant le décollage, la fréquence des dégivrages, et leur appréciation de la cessation d'efficacité des agents antigivrage.

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Summary

Introduction

The occurrence of a number of accidents in the last decade has increased concerns about the risks of take-off in ground icing conditions. Regulatory authorities have enacted regulations, and airlines and pilots have improved procedures for ensuring that the aircraft is free of frozen contaminants prior to take-off. Improvements in anti-icing fluids have increased holdover times (HOTs), thus reducing the risk of fluid failure prior to take-off. With respect to the possibility of a fluid failure passing undetected, comprehensive regulations covering operator's management plan, use of holdover time tables and inspection procedures are in place to minimize such a possibility.

In accordance with the regulations for operations under winter conditions, the Pilot In Command (PIC) is responsible for ensuring that critical aircraft surfaces are free from ice, snow, or frost formations before take-off. The pre-take-off inspection called for in the regulations (or check as it is referred to in FAA regulations) is usually conducted at the runway hold area just prior to take-off without the assistance of ground crew. Visual observation by the PIC from inside the aircraft of the outer sections of aircraft wings under conditions of freezing precipitation at night, away from the terminal area lighting and with deicing fluid on the windows can be very difficult. Accordingly, both on-board and remote surface condition sensing systems are being developed and tested. However, the surface condition sensors currently available or being tested can survey only a limited part of the critical surfaces and, as with visual inspection, cannot guarantee that all critical surfaces are clean.

Objectives

In response to the recommendation MCR 48 of the Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario, the Transportation Development Centre (TDC) has established a research program to: *participate in and encourage research concerning devices that can allow pilots to assess the external state of the aircraft from within the flight deck.*

Within this program, TDC commissioned this project with the objective to: *evaluate the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.*

The specific objectives of this phase of the project were to:

- develop a methodology to evaluate the comparative risks;
- demonstrate the application of this methodology using currently available data; and
- identify deficiencies in the data and recommend the additional data that should be collected to complete the analysis.

Methodology

The approach used to conduct the comparative risk analysis was to:

- review the recent history of ground icing related accidents, and current regulations and airline practices relating to ground icing;
- review the capabilities, accuracy and reliability of sensors for detecting fluid failure and the presence of frozen contamination on the wing;
- review the likely consequences of the de/anti-icing fluid failing on part or all of the wing, and the effect of the location of the failed fluid;
- specify the chains of events that could lead to an accident due to ground icing in the form of risk analysis trees for visual and sensor based pre-take-off inspection;
- conduct a survey of commercial airline pilots in Canada to:
  - ◊ better understand current wing inspection procedures,
  - ◊ determine the frequency of deicing, pre-take-off inspections and re-deicing,
  - ◊ determine the importance of factors affecting the pilots' assessment of fluid failure,
  - ◊ determine pilots' confidence in their ability to detect fluid failure under a range of conditions,
  - ◊ determine how conservative pilots are in their decision to re-deice in different visibility conditions and holdover time situations, and
  - ◊ obtain pilots' views on the use of ice detection and fluid failure sensors;
- using data on the time and location of first fluid failure and the progression of the fluid failure across the wing, determine the best location for point sensors on the wing and estimate the risk at the time of take-off due to a sensor system not identifying the fluid failure;
- using data on the amount of the wing with failed fluid when an observer inside the cabin first observes the fluid failure, estimate the risks due to the pilot not identifying fluid failure at the time of the pre-take-off inspection;
- using data on aircraft taxi-delay times, weather conditions, protection times of fluids at given precipitation rates, and allowing for the variation in these parameters, estimate the risks due to fluid failure between the pre-take-off inspection and take-off; and
- using the risk analysis tree, compare the risks associated with conducting pre-take-off inspections based on visual observation and sensor systems.

Conclusions

The following conclusions were drawn from the study:

- The risks of conducting pre-take-off inspection based primarily on visual observation and point sensor systems can be compared using the methodology specified in this report. Extensions to this methodology can be made to account for take-offs where no visual pre-take-off inspection is done, and for point sensor systems with three or more sensors per wing.

- The take-off accident rate where wing ice contamination has been a contributing factor of zero since 1993 is significantly (statistically) less than the non-zero rate from 1985 to 1992, and is likely due to the additional safety measures instituted since 1993.
- An accurate assessment of the relative risks associated with identifying fluid failure using visual and sensor based inspection is restricted by the amount of field data available, and sensitivity testing is necessary to draw any conclusions regarding the relative risks.
- The following additional data are required to complete the analysis:
    - ◊ fluid failure times and locations visually observed from inside the aircraft and actual fluid failure progression on the aircraft over a range of conditions and aircraft types. The inside observations should be made under conditions typical of those experienced by a pilot and, where possible, should be made by pilots. The pilots should also indicate, if faced with an identical situation in a pre-take-off inspection and knowing the HOTs, whether they would have proceeded with the take-off.
    - ◊ fluid failure progression on high wing aircraft and small commuter jets;
    - ◊ times between pre-take-off inspection and take-off for a range of aircraft types;
    - ◊ taxi and delay times after deicing at a range of airports;
    - ◊ wind tunnel test data on the effect of small areas of fluid failure, and partial failure (slush formation on top of fluid) on the aerodynamic performance of low- and high-speed take-off aircraft, and
    - ◊ test data to determine whether contamination due to fluid failure present on the wing at the start of the take-off roll is still present at rotation and at lift-off.
- Based on the limited data currently available for low wing aircraft:
    - ◊ the use of Type IV rather than Type II fluids at large busy airports reduces the risks by a factor of 10;
    - ◊ risks with the visual inspection procedure associated with the delay between the pre-take-off inspection and take-off are significant, and the reduction of these risks would be an important benefit of sensor based systems;
    - ◊ the risks due to fluid failure using a point sensor system with two sensors on the leading edge of each wing are less than the risks using visual inspection from the cabin at the pre-take-off inspection; and
    - ◊ the risks using combined visual and sensor based inspection are significantly lower than using only a sensor based system.
- There is insufficient data to conduct a comparative analysis of the risks of conducting pre-take-off inspections based primarily on visual observation and on area sensors. The following types of data are required to conduct the analysis:
    - ◊ times of sensor indicated and visually observed fluid failure under a range of conditions in outdoor tests on aircraft;

    - the degree to which frozen contaminants are adhering to the wing surface when the sensors identify fluid failure;
    - the sensitivity of identification of fluid failure to localized or transient failures;
    - the view of the wing surface from the intended location of the sensor cameras; and
    - demonstrated use of system for identifying fluid failure in operational conditions.

- The following general conclusions were drawn from the results of the pilot survey:
    - pilots feel that recent changes in de/anti-icing procedures, standards, and fluids have significantly improved safety;
    - pilots feel that the long HOTs provided by Type IV fluids have greatly improved the safety margin, and called for the greater availability of anti-icing fluids at small and medium sized airports;
    - pilots cannot make an accurate assessment of the condition of the critical surfaces using visual inspection at night or when visibility is poor, especially during freezing rain/drizzle;
    - the training of pilots for recognizing fluid failure is inadequate;
    - most pilots do not frequently make pre-take-off inspections and very rarely identify fluid failure, and will therefore not learn how to recognize fluid failure through experience;
    - pilots rely heavily on the HOTs and are reasonably confident in their accuracy;
    - pilots have confidence in the representative surfaces. Therefore, these surfaces must truly reflect the areas of early failure and/or areas critical to safe flight, or the concept of representative surfaces should be abandoned;
    - pilots feel that they and the ground crew are conservative in their decision on the need to deice and re-deice aircraft. In their view, this reduces the risk of take-off with contaminated surfaces, but leads to much unnecessary deicing of aircraft;
    - there is widespread agreement that sensors for identifying fluid failure would improve safety, but pilots indicated that the sensors must be accurate and reliable with no false warning, and must be used in conjunction with visual inspection;
    - a method for determining whether cold, dry snow is adhering to the wing would reduce the number of deicing operations and eliminate a source of uncertainty and conflict;
    - communication between the deicing crews and the pilot needs to be improved;
    - a range in HOTs, rather than a single value, is preferred, but some pilots do not clearly understand what the upper and lower values in the range represent;
    - few pilots make the link to the risks associated with airborne icing when considering the HOTs available in freezing rain/drizzle conditions;
    - the de/anti-icing service at Vancouver Airport needs to be improved;
    - pilots feel that major improvements in safety would be achieved by locating the deicing pad near the end of the active runway and by having ATC coordinate the timing of deicing and take-off. With the long holdover times offered by the new anti-icing fluids, all take-offs could then be completed well within the HOTs.

Recommendations

The following recommendations are made:

- TDC collect data on:
  - ◊ the accuracy of visual inspection by the pilot from inside the aircraft in various conditions and for both low and high wing aircraft,
  - ◊ fluid failure progression, especially on high wing aircraft, and
  - ◊ taxi and delay times, and times between pre-take-off inspection and take-off;
- The risk analysis be extended to:
  - ◊ evaluate three sensors per wing,
  - ◊ include the risks associated with not conducting a pre-take-off inspection,
  - ◊ include allowance for pilots to use HOT, in conjunction with weather conditions and taxi and delay time, in deciding whether to proceed with take-off, and
  - ◊ test the sensitivity of the comparative risks to other parameters and assumptions;
- The risk analysis be conducted for specific aircraft types where sufficient data is available; and
- The risk analysis be conducted for high wing aircraft.

Sommaire

Introduction

Certains accidents d'avions survenus au cours de la dernière décennie ont ravivé les inquiétudes quant aux risques de décoller dans des conditions de givrage au sol. Les autorités ont promulgué des règlements, et les compagnies aériennes et les pilotes ont amélioré leurs procédures visant à garantir que l'aéronef soit libre de toute contamination solide avant de décoller. Aussi, les améliorations apportées aux agents antigivrage ont accru leur longévité et réduit d'autant le risque que s'altère leur efficacité avant le décollage. Quant au risque que la perte d'efficacité d'un liquide antigivrage passe inaperçue, une réglementation englobant les programmes d'inspection des transporteurs, le recours à des tables de durées d'efficacité et des procédures d'inspection des aéronefs sont autant de moyens mis en place pour parer à un tel risque.

Conformément aux règles touchant les opérations aériennes en conditions hivernales, il incombe au pilote commandant de bord de s'assurer, immédiatement avant le décollage, que les surfaces critiques de l'aéronef sont libres de glace, de neige ou de givre. L'inspection ultime avant le décollage prescrite par le règlement (ou la vérification, selon le règlement de la FAA) est habituellement effectuée lorsque l'aéronef se trouve en bout de piste et attend l'autorisation de décoller, c'est-à-dire sans l'aide du personnel de piste. Il peut alors être très difficile pour le commandant de bord de voir, de l'intérieur de l'aéronef, les zones extérieures de la voilure, en conditions de précipitations givrantes, en particulier lorsqu'il fait nuit, que l'avion n'est plus éclairé par l'aéroport, et que du liquide antigivrage obstrue le pare-brise. C'est pourquoi on s'attache à développer et à mettre à l'essai des systèmes de détection à distance, avec affichage en cabine, de l'état des surfaces de l'aéronef. Mais les capteurs qui sont présentement à l'étape de la commercialisation ou des essais en service réel ne peuvent examiner que des zones restreintes des surfaces critiques et ne peuvent donc, pas plus que l'inspection visuelle, garantir que toutes les surfaces critiques sont «propres».

Objectifs

En réponse à la recommandation n° 48 de la Commission d'enquête sur l'écrasement d'un avion d'Air Ontario à Dryden (Ontario), le Centre de développement des transports (CDT) a instauré un programme de recherche dans le but de : *participer à des recherches sur les dispositifs visant à permettre aux pilotes de déterminer l'état extérieur de l'avion à partir de l'intérieur du poste de pilotage.*

La présente recherche, commandée par le CDT dans le cadre de ce programme, avait pour but : *d'évaluer les risques comparatifs associés à une inspection avant le décollage fondée principalement sur l'observation visuelle, sur un système de capteurs ponctuels ou sur des capteurs de détection à distance.*

Les objectifs particuliers associés à la présente phase du projet étaient de :

- mettre au point une méthodologie d'évaluation des risques comparatifs;
- faire la démonstration de cette méthodologie au moyen des données actuellement disponibles;
- cerner les données manquantes et formuler des recommandations quant aux données complémentaires à acquérir pour terminer l'analyse.

Méthodologie

Voici la démarche adoptée pour mener l'analyse des risques comparatifs :

- passer en revue les accidents récents survenus en conditions de givrage au sol, ainsi que les règlements et les procédures des compagnies aériennes concernant le givrage des aéronefs au sol;
- revoir les fonctionnalités, la précision et la fiabilité des capteurs de givre, lorsqu'il s'agit de détecter la perte d'efficacité des agents antigivrage et la présence de contamination solide sur les ailes;
- examiner les conséquences probables de la cessation d'efficacité des liquides antigivrage sur une partie ou sur la totalité de la voilure, et étudier les effets associés à l'emplacement de la perte d'efficacité;
- préciser les enchaînements d'événements susceptibles de mener à un accident attribuable au givrage au sol, sous la forme d'arbres d'analyse de risques applicables à une inspection avant le décollage fondée sur une observation visuelle et sur des capteurs de givre;
- sonder les pilotes de ligne canadiens, afin de :
    - ◊ mieux comprendre les procédures d'inspection des ailes actuellement en vigueur;
    - ◊ déterminer la fréquence des demandes de déglaçage faites par suite d'une inspection effectuée avant le décollage, alors que l'aéronef a été déglacé une première fois,
    - ◊ déterminer l'importance des facteurs influant sur la perception par les pilotes de la cessation d'efficacité des liquides antigivrage,
    - ◊ évaluer la confiance des pilotes en leur propre capacité de percevoir la perte d'efficacité des liquides antigivrage, dans un éventail de conditions,
    - ◊ déterminer dans quelle mesure une décision de répéter le déglaçage de l'avion traduit une prudence de bon aloi (ou excessive) dans différentes situations (conditions de visibilité et durées d'efficacité des liquides antigivrage),
    - ◊ obtenir le point de vue des pilotes concernant l'utilisation de capteurs pour détecter la présence de givre et la cessation d'efficacité des liquides antigivrage;
- à l'aide des données concernant le moment et l'emplacement de la cessation d'efficacité des liquides antigivrage, et la propagation de cette cessation d'efficacité, déterminer les endroits les plus propices à l'implantation des capteurs sur l'aile et

évaluer les risques associés au défaut du système de capteurs de détecter la perte d'efficacité du liquide antigivrage, au moment du décollage;

- à l'aide des données concernant la proportion de l'aile sur laquelle le liquide antigivrage a cessé d'être efficace lorsqu'un observateur situé à l'intérieur de la cabine se rend compte de cette perte d'efficacité, évaluer les risques associés à la non-perception par le pilote de la cessation d'efficacité du liquide, au moment de l'inspection avant le décollage;
- à l'aide des données concernant les temps de circulation/d'attente au sol, les conditions météorologiques, les durées d'efficacité des liquides à des taux de précipitations donnés (et en faisant varier ces paramètres), évaluer les risques associés à la perte d'efficacité des liquides antigivrage pendant le délai entre l'inspection avant le décollage et le décollage;
- à l'aide de l'arbre d'analyse des risques, comparer les risques associés aux inspections avant le décollage fondées sur une observation visuelle et sur des systèmes de capteurs.

Conclusions

L'étude a mené aux conclusions suivantes :

- La méthodologie décrite dans le rapport permet de comparer les risques associés à une inspection avant le décollage fondée principalement sur une observation visuelle et sur un système de capteurs ponctuels. Il est possible de perfectionner cette méthodologie pour englober les décollages sans inspection visuelle préalable, et des systèmes de capteurs ponctuels ayant au moins trois capteurs par aile.
- Le taux d'accidents au décollage où la contamination de la voilure par les précipitations glacées a été un facteur contributif de zéro depuis 1993 est significativement (sur le plan statistique) inférieur au taux non nul enregistré de 1985 à 1992; ces chiffres encourageants sont vraisemblablement dus aux mesures de sécurité supplémentaires mises en place depuis 1993.
- L'évaluation exacte des risques relatifs associés à la détection de la perte d'efficacité des liquides antigivrage, par une inspection fondée sur l'observation visuelle et sur des capteurs, est limitée par la quantité des données d'exploitation disponibles, et les essais de sensibilité sont nécessaires pour tirer des conclusions concernant les risques relatifs.
- Il s'avère toutefois nécessaire de recueillir les données ci-après pour parfaire l'analyse de la méthodologie :
  - ◊ le moment et l'emplacement de la cessation d'efficacité du liquide antigivrage, tels qu'observés visuellement depuis l'intérieur de l'avion, et les caractéristiques réelles de la perte graduelle d'efficacité du liquide, dans une gamme de conditions météorologiques et pour un éventail de types d'appareils; dans la mesure du possible, les observations depuis l'intérieur de l'avion doivent être effectuées par des pilotes, dans des conditions qui se rapprochent des conditions opérationnelles; les pilotes doivent également indiquer s'ils auraient pris la décision de décoller ou

  non, en supposant qu'ils aient observé la même situation avant le décollage, en service réel, et qu'ils connaissaient les durées d'efficacité des liquides antigivrage;
  - ◊ la propagation de la cessation d'efficacité sur des avions à voilure haute et sur de petits avions-navettes;
  - ◊ le temps écoulé entre l'inspection avant le décollage et le décollage, pour un éventail de types d'avions;
  - ◊ les temps de circulation et d'attente au sol après le déglaçage, à une gamme d'aéroports;
  - ◊ des données d'essais en soufflerie concernant l'effet des petites surfaces sur la cessation d'efficacité des liquides, et la cessation partielle (formation d'une couche de *slush* recouvrant le liquide) sur les caractéristiques aérodynamiques des avions à vitesse de décollage faible et élevée;
  - ◊ des données d'essai pour déterminer si la contamination due à la perte d'efficacité des liquides antigivrage présente sur l'aile au début de la course au sol est encore présente lorsque l'avion atteint la vitesse de rotation et lorsqu'il décolle.

- D'après les données restreintes dont on dispose actuellement sur les avions à voilure basse :
  - ◊ dans les grands aéroports fortement achalandés, l'utilisation de liquides de type IV réduit 10 fois les risques, par rapport à l'utilisation de liquides de type II;
  - ◊ les risques de la procédure d'inspection visuelle associés au retard entre l'inspection prédécollage et le décollage sont importants, et la réduction de ces risques constituerait un avantage important des systèmes de capteurs;
  - ◊ les risques dus à la perte d'efficacité des liquides antigivrage utilisant un capteur ponctuel avec deux capteurs sur le bord d'attaque de chaque aile sont inférieurs aux risques émanant de l'inspection visuelle de la cabine lors de l'inspection au prédécollage;
  - ◊ les risques dus à l'utilisation d'une combinaison d'inspection visuelle et d'inspection par capteurs sont considérablement inférieurs aux risques entraînés par l'utilisation des capteurs seulement.

- On ne dispose pas actuellement des données nécessaires pour mener une analyse comparative des risques associés à des inspections prédécollage fondées principalement sur l'observation visuelle et sur des capteurs ponctuels. Voici les types de données à colliger pour effectuer une telle analyse :
  - ◊ le moment de la cessation d'efficacité du liquide, tel qu'indiqué par les capteurs et observé visuellement, lors d'essais réalisés sur des aéronefs, à l'extérieur et dans un éventail de conditions;
  - ◊ le degré de contamination de la surface de la voilure, lorsque les capteurs détectent la cessation d'efficacité du liquide;
  - ◊ la discrimination entre une perte d'efficacité vraie et une perte d'efficacité localisée ou transitoire du liquide;
  - ◊ la vue sur la surface de la voilure depuis l'emplacement prévu des caméras de détection;

    - ◊ utilisation établie d'un système de détection de la perte d'efficacité des liquides, en conditions opérationnelles.

- Le sondage auprès des pilotes a mené aux conclusions suivantes :
    - ◊ les pilotes pensent que les changements récents apportés aux procédures, normes et liquides de dégivrage/antigivrage, ont considérablement accru la sécurité;
    - ◊ les pilotes pensent que la durée d'efficacité prolongée des liquides de type IV assure une marge de sécurité beaucoup plus grande; les pilotes réclament en outre une meilleure disponibilité des liquides antigivrage aux petits et moyens aéroports;
    - ◊ il est difficile pour les pilotes de juger précisément de l'état des surfaces critiques par simple inspection visuelle, lorsqu'il fait nuit ou que la visibilité est réduite, en particulier sous la pluie/bruine verglaçante;
    - ◊ les pilotes ne sont pas adéquatement formés pour reconnaître les signes de la perte d'efficacité des liquides;
    - ◊ la plupart des pilotes n'effectuent pas fréquemment des inspections prédécollage et déterminent rarement les pertes d'efficacité de liquide : ils n'apprendront donc pas à reconnaître ces pertes par expérience;
    - ◊ les pilotes recourent régulièrement aux tables de durée d'efficacité et les jugent raisonnablement fiables;
    - ◊ les pilotes se fient aux surfaces dites représentatives; d'où l'importance que ces dernières représentent fidèlement les premières zones où les liquides cessent d'être efficaces et/ou les zones critiques pour le vol, sans quoi le concept même des surfaces représentatives devrait être mis au rancart;
    - ◊ les pilotes pensent qu'ils se montrent, tout comme le personnel de piste, très prudents dans leurs décisions de procéder au déglaçage (ou de répéter le déglaçage) de leur avion; une telle attitude atténue les risques de surfaces contaminées au décollage, mais occasionne un grand nombre de déglaçages inutiles;
    - ◊ les pilotes ne sont disposés à accueillir favorablement des capteurs pour détecter la perte d'efficacité des liquides antigivrage que si ces derniers sont précis et fiables, s'ils n'émettent pas de fausses alertes, et s'ils sont utilisés en complément de l'inspection visuelle;
    - ◊ le fait de disposer d'une méthode pour déterminer si une neige froide et sèche adhère à la voilure permettrait de réduire le nombre des opérations de déglaçage et d'éliminer une source d'incertitude et de conflit;
    - ◊ il y a lieu d'améliorer la communication entre les équipes de déglaçage et le pilote;
    - ◊ une plage dans les tables de durées d'efficacité, plutôt qu'une seule valeur, est préférée, mais quelques pilotes ne comprennent pas clairement ce que représentent les valeurs supérieure et inférieure de cette plage;
    - ◊ lorsqu'ils consultent les tables de durées d'efficacité des liquides antigivrage en conditions de pluie/bruine verglaçante, peu de pilotes tiennent compte des risques associés au givrage en vol;
    - ◊ les services de déglaçage de l'aéroport de Vancouver laissent à désirer;

- ◊ les pilotes pensent qu'il y aurait moyen d'améliorer grandement la sécurité en aménageant le tablier de déglaçage à proximité de l'extrémité de la piste en service et en chargeant le Contrôle de la circulation aérienne de surveiller le délai entre le déglaçage et le décollage. Grâce aux longues durées d'efficacité offertes par les nouveaux liquides de dégivrage/antigivrage, tous les décollages pourraient alors s'effectuer bien avant que soit atteinte la limite de durée d'efficacité indiquée par les tables.

Recommandations

Il est recommandé :

- que le CDT recueille des données sur :
  - ◊ le degré de précision de l'inspection visuelle effectuée par le pilote depuis la cabine de pilotage, dans diverses conditions et pour des avions à voilure basse et à voilure haute,
  - ◊ la propagation de la perte d'efficacité des liquides de dégivrage/antigivrage, en particulier dans le cas d'avions à voilure haute,
  - ◊ les temps de circulation et d'attente au sol, et le temps écoulé entre l'inspection prédécollage et le décollage;
- que l'analyse de risques soit étendue :
  - ◊ à l'évaluation d'une configuration comportant trois capteurs par aile,
  - ◊ aux risques associés à l'omission de toute inspection avant le décollage,
  - ◊ à l'inclusion d'une prime aux pilotes pour utiliser les tables de durées d'efficacité, conjointement avec les conditions météorologiques et le temps de roulage et de retard, en décidant s'il faut décoller,
  - ◊ à l'essai de sensibilité des risques comparatifs aux autres paramètres et hypothèses;
- qu'une analyse de risques soit réalisée pour certains types d'aéronefs précis, pour lesquels on dispose de données suffisantes;
- qu'une analyse de risques soit réalisée pour un avion à voilure haute.

RISK MANAGEMENT OF AIRCRAFT CRITICAL SURFACE INSPECTION, VOLUME 1 OF 3
METHODOLOGY FOR EVALUATING COMPARATIVE RISKS

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Glossary of Terms

APS	Company APS Aviation Incorporated who have conducted winter testing programs for TDC
AC	Advisory Circular
ARP	Aerospace Recommended Practice (SAE)
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
Critical surfaces	Wings, control surfaces, rotors, propellers, horizontal stabilizers, vertical stabilizers or any other stabilizing surface of the aircraft critical to the aerodynamic performance of the aircraft
C/FIMS	Point sensor system developed by AlliedSignal and Instrumar (developed from sensor known as CWDS)
CWDS	Point sensor system developed by Instrumar (further developed into sensor known as C-FIMS)
Fluid Failure	Fluid failure is the term currently used to describe a condition of visible ice crystal contamination on or in the anti-icing fluid film covering a surface, with crystal absorption taking place at a slower rate than the precipitation rate of the contaminating material.
Holdover Time	Holdover time is the estimated time the anti-icing fluid will prevent the formation of ice and frost and the accumulation of snow on the treated surfaces on an airplane; official values for each fluid type are derived from tests on plates based on fluid failure conditions covering one-third of the plate and are published as (SAE) Holdover Time Tables.
HOT	Holdover time (as above)
K	Height of the roughness
C	Length of the wing cord
NRC	National Research Council Canada
PIC	Pilot In Command
Pireps	Pilot reports
Pre-Take-off Inspection	Inspection of critical surfaces made immediately prior to take-off
Representative Surfaces	Surfaces identified by the manufacturer that can be readily and clearly observed by the flight crew during day and night operations and are suitable for judging whether critical surfaces are contaminated or not.
SAE	Society of Automotive Engineers
TC	Transport Canada
TDC	Transportation Development Centre
UQAC	Université du Québec à Chicoutimi
V_2	Aircraft speed on take-off at the 35-foot screen height
V_s	Aircraft stall speed

1. INTRODUCTION

1.1 Background

The occurrence of a number of accidents in the last decade has increased concerns about the risks of take-off in ground icing conditions. Regulatory authorities have enacted regulations, and airlines and pilots have improved procedures for ensuring the aircraft is free of frozen contaminants prior to take-off. Improvements in anti-icing fluids have increased holdover times, thus reducing the risk of fluid failure prior to take-off. With respect to the possibility of a fluid failure passing undetected, comprehensive regulations covering operator's management plan, use of holdover time tables and inspection procedures are in place to minimize such a possibility.

In accordance with the regulations for operations under winter conditions, the Pilot In Command (PIC) is responsible for ensuring that critical aircraft surfaces are free from ice, snow, or frost formations before take-off. The pre-take-off contamination inspection called for in the regulations (or check as it is referred to in FAA regulations) is usually conducted at the runway hold area just prior to take-off without the assistance of ground crew. Visual observation by the PIC from inside the aircraft of the outer sections of aircraft wings under conditions of freezing precipitation at night, away from the terminal area lighting and with deicing fluid on the windows can be very difficult. Accordingly, both on-board and remote surface condition sensing systems are being developed and tested. However, the surface condition sensors presently available or being tested can survey only a limited part of the critical surfaces and, as with visual inspection, cannot guarantee that all critical surfaces are clean.

An evaluation is required of the comparative risks of conducting inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.

1.2 Objectives

A research program was originally established by the Transport Canada Dryden Implementation Project and subsequently assumed by the Transportation Development Centre (TDC) in response to the recommendation MCR 48 of the Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario:

> *MCR 48 participate in and encourage research concerning devices that can allow pilots to assess the external state of the aircraft from within the flight deck.*

Within that research program work is being conducted with the objective to:

> *encourage development, test and evaluation of an on-board device for detecting, characterizing and identifying contamination of aircraft surfaces during winter precipitation.*

The objective of this project is to:

> *evaluate the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.*

It is planned to conduct the project in two phases with the work carried out in the second phase depending on the outcome of the first phase. The specific objectives of the first phase of the project are to:

- develop a methodology to evaluate the comparative risks;
- demonstrate the application of this methodology using currently available data; and
- identify deficiencies in the data and recommend the additional data that should be collected to complete the analysis.

1.3 Recent Accident History

Recent take-off accidents where wing ice contamination was considered to be one of the contributing factors are listed in Table 1.1. Since 1985 there have been approximately 87 million jet aircraft departures in the US and Canada, 10.9 million of these in near or sub-zero temperatures. The accident rate for jet aircraft on take-off where wing ice contamination has been a contributing factor, as shown in Table 1.2, is approximately 5.5×10^{-7} per departure in near or sub-zero temperatures. The single accident in Canada over the period is in line with the US accident rate for this type of accident. There have been no take-off accidents in North America involving jet aircraft due to wing contamination since 1993. The accident rate over the shorter period from 1985 to 1992 was significantly higher at 8.5×10^{-7}. The probability of zero accidents since 1993 given the underlying level of safety was the same as during the period 1985 to 1992, is 0.041[1]. The degree to which wing ice contamination was a contributing factor is not known with certainty in some of these accidents and the sensitivity of this probability was therefore examined. If one of the six accidents between 1985 and 1992 had be wrongly classified, the probability of zero accidents since 1993 increases to 0.067, still an unlikely outcome. Thus, it is unlikely that the zero accidents since 1993 is due to chance. The drop in the accident rate is therefore most likely due to the additional safety measures instituted since 1993.

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[1] Probability calculated assuming the number of accidents follows a Poisson distribution and the expected number of accidents equals the product of the accident rate between 1985 and 1992 and the number of departures between 1993 and June 1997 [$8.5 \times 10^{-7} \times 3{,}800{,}000$].

Table 1.1 Take-off Accidents Involving Jet Aircraft in US and Canada Since 1985 where Wing Ice Contamination was Considered to be a Contributing Factor

Date	Airline	Location	Aircraft Type	Major Consequence	Precipitation Observations
5 Feb 85	Airborne	Philadelphia	DC-9-10	2 serious injuries aircraft destroyed	"Light freezing rain, ice and snow pellets, fog"
12 Dec 85	Arrow Air	Gander	DC-8-63	256 fatalities	"Light freezing drizzle, snow grains"
15 Nov 87	Continental	Denver	DC-9-10	28 fatalities	"Moderate snow, fog"
03 Mar 89	Air Ontario	Dryden	F28	24 fatalities	"Steady snow"
17 Feb 91	Ryan Intern.	Cleveland	DC-9-15	2 fatalities	"Snow dry and blowing"
22 Mar 92	USAir	LaGuardia	F-28	27 fatalities	"Light snow and fog"

[Source: references (17), (26) and (27)]

Table 1.2 Take-off Accident Rate where Wing Ice Contamination was a Contributing Factor for Jet Aircraft in US and Canada Since 1985

	1985-96			1985-92
	Canada	US	Total	Total
Total Departures (million)*	5.52	81.6	87.1	56.6
Estimated % in Sub-zero temps#	34%	11%		
Winter Departures (million)	1.88	8.98	10.9	7.1
Total Accidents	1	5	6	6
Accident Rate per 100,000 deps.	0.053	0.056	0.055	0.085
Accident Rate	5.3×10^{-7}	5.6×10^{-7}	5.5×10^{-7}	8.5×10^{-7}

* US jet departures approximated by scheduled departures from *ICAO Statistical Year Book, Civil Aviation Statistics of the World* 1986 to 1994 editions. Canada jet aircraft movements from *Aircraft Movement Statistics*, TC, TP577, 1985 to 1996.

\# Percentage of departures at temperature of 1°C or below: percentage for Canada is average given in survey of pilots, value for US estimated from mean monthly temperatures and number of departures at 136 largest airports in the US.

Only in one accident, involving the USAir F-28 in 1992, was the aircraft deiced prior to take-off. In this accident, Type I (or similar) fluid was used and the holdover time given in the SAE holdover time tables (HOT) was far exceeded.

Five of the accidents involved either F-28 or DC-9 aircraft which had no leading edge devices (they are commonly referred to as having "hard leading edges"). These types of aircraft appear to be more susceptible to wing contamination on take-off, especially considering the small proportion of these type of aircraft in the fleet. Based on the accident and departure data, the icing related accident rate for these types of aircraft is approximately 1.4×10^{-6}, while for other aircraft the rate is about 1×10^{-7}.

In addition to these accidents there have been numerous incidents involving deicing/anti-icing operations which never resulted in an accident. Many of these types of incidents have been reported to the Aviation Safety Reporting System (ASRS). ASRS undertook a study of the 53 reported incidents between January 1986 and January 1993 which involved air carrier operations and mentioned ground deicing/anti-icing or frozen contaminants not being removed from the critical surfaces before take-off (1)[2]. Incidents were classified by the phase in which the first major problem occurred. The percentages of incidents in each phase were as follows:

- 25% - pre-flight inspection phase
- 50% - removal of ice and initial verification that critical surfaces were clean
- 25% - holdover and final verification that critical surfaces were clean

Table 1.3 summarizes the consequences of take-off attempts with contaminated aircraft surfaces for these incidents. Many of these incidents were serious and could have resulted in an accident.

Table 1.3 Consequences of Incidents where Take-off was Attempted with Contaminated Aircraft Surfaces

Engine anomalies, damage or failure due to ice ingestion	16	30%
Aircraft control difficulties/anomalies	9	17%
Return to land at departure airport	9	17%
Rejected take-off	6	11%
FAA/company disciplinary action threatened or feared	4	7%
Emotional trauma	3	6%
Failure or inability to adhere to air traffic control (ATC) clearances	3	6%
Emergency declared	2	4%
Significant delays	1	2%
Total	53	100%

Source: see footnote 2 below

The incident rate based on these reported incidents is approximately 10 x 10^{-6} [=53/5,200,000] per winter departure. The reported incidents include those where an accident was not likely. However, there are, no doubt, other serious unreported incidents, many where the pilot was unaware how close to stall the aircraft was, which would increase the incident rate.

These accident and incident rates will be used to verify that the risk models used in the comparative risk analysis are giving risks of the correct order of magnitude.

These accident/incident risks can be compared with generally accepted severity of aircraft accidents and incidents and the probability of their occurrence. The British Civil Aviation Airworthiness Authority produced a chart showing this relationship (see Figure 1.1).

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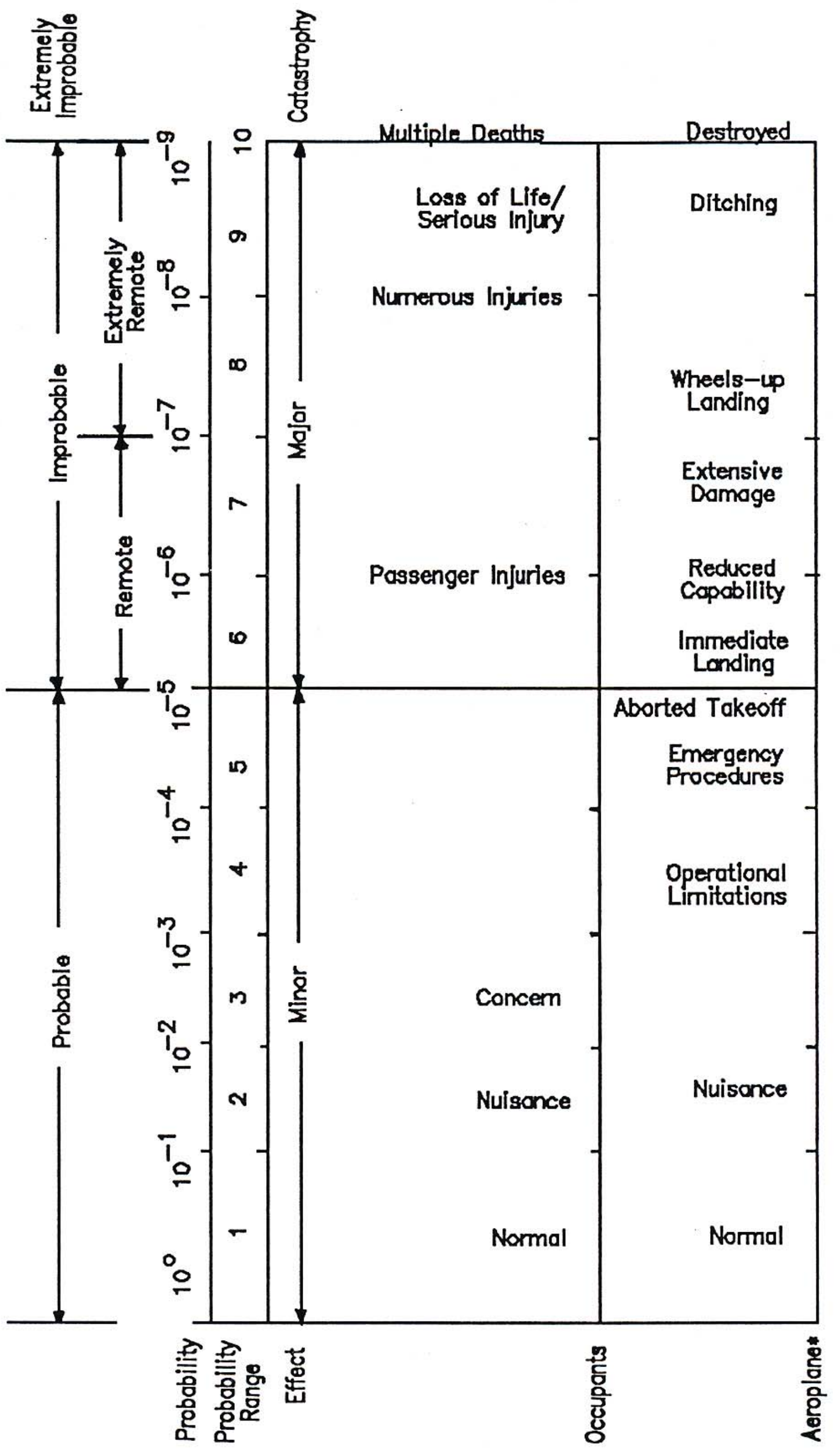
[2] Numbers in brackets designate references listed at the end of the report.



*The positions of some of the items on this scale will vary for different aeroplane designs

Figure 1.1 Relationship Between Probability and Severity of Effect for Aircraft Accidents and Incidents

[Source: British Civil Airworthiness Requirements, Paper No. 670, 3 Sept. 1976.]

Canadian and US authorities have not produced such a chart, but their aircraft accident and incident history follows the chart quite well. The risks associated with accidents due to contamination of critical surfaces prior to 1993 were clearly higher than those shown in the British chart and these high risks prompted a number of measures to be implemented to improve safety in ground icing conditions.

1.4 Risk Analysis Overview

The objective of the risk analysis was to assess the comparative risks of using the current Canadian visual inspection procedures for determining anti-icing fluid failure with using point or area detection sensor systems. Consideration was given to the effects of differences between Canadian and US inspection procedures on the comparative risks.

The departure of aircraft in icing conditions is controlled by regulations to ensure that a high degree of safety is maintained. It is, however, impossible to guarantee safe flight. To compare the safety associated with different procedures, a risk analysis can be used to estimate the likelihood of an accident, or alternatively a safety analysis can be used to estimate the probability of a safe take-off. In this project, the risk analysis terminology and measures of safety were used.

Risk is the expected loss due to an unwanted outcome and includes both the probability of that outcome and the loss suffered due to that outcome. The failure of the de/anti-icing fluid itself does not represent a loss; it is the chain of events after the failure that leads to the loss. The critical sequence of events leading to a loss considered in the risk analysis and the principal factors affecting those events are summarized in Figure 1.2.

An important difference between the visual and sensor detection procedures is that sensors provide continuous monitoring of fluid failure, unlike the visual method which involves inspections at defined stages and may require the pilot to go into the cabin to assess the wing contamination. With the visual method, the fluid may fail between the pre-take-off inspection and take-off. The sequences of events can therefore be refined as shown in Figure 1.3. A third sequence for visual inspection where the aircraft could take-off within the minimum HOT and the pilot opted not to conduct a pre-take-off inspection was not considered. This sequence is not an issue in the US where pre-take-off inspections are required if deiced and precipitation is falling. In Canada, pre-take-off inspections are mandatory if the HOT has expired, but limitations are given in the HOT tables and pilots are strongly advised to conduct an inspection if there is any doubt about the fluid. Estimation of the risks associated with this sequence is not within the scope of this project, but these risks may be a significant disadvantage of visual based procedures.

The first point of difference in the sequence between the detection procedures is at the detection of fluid failure. The consequences, and therefore the actual risk, depend on subsequent events and the factors affecting those events. Initially the risk analysis focuses on the probabilities of identifying fluid failure, and of fluid failure after pre-take-off inspection, and the factors and conditions affecting those probabilities. The likelihood and consequences of subsequent events was then considered to assess the risks of the two detection procedures. The amount and location of contamination on the critical surfaces at take-off is the main factor in determining the likelihood of an accident. Since the consequences of an accident (fatalities, injuries and aircraft damage) are not dependent on the inspection method, visual or sensor based, the analysis focuses on the comparative probabilities of an accident.

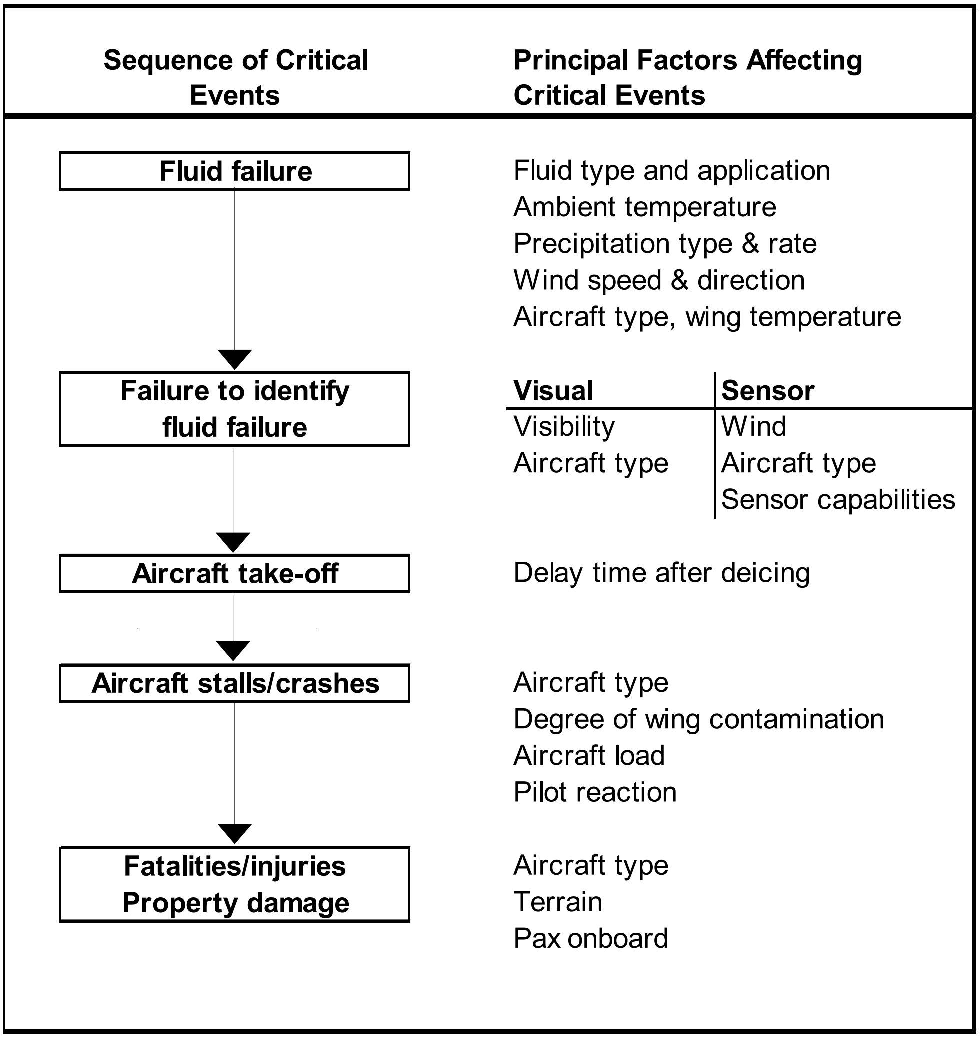
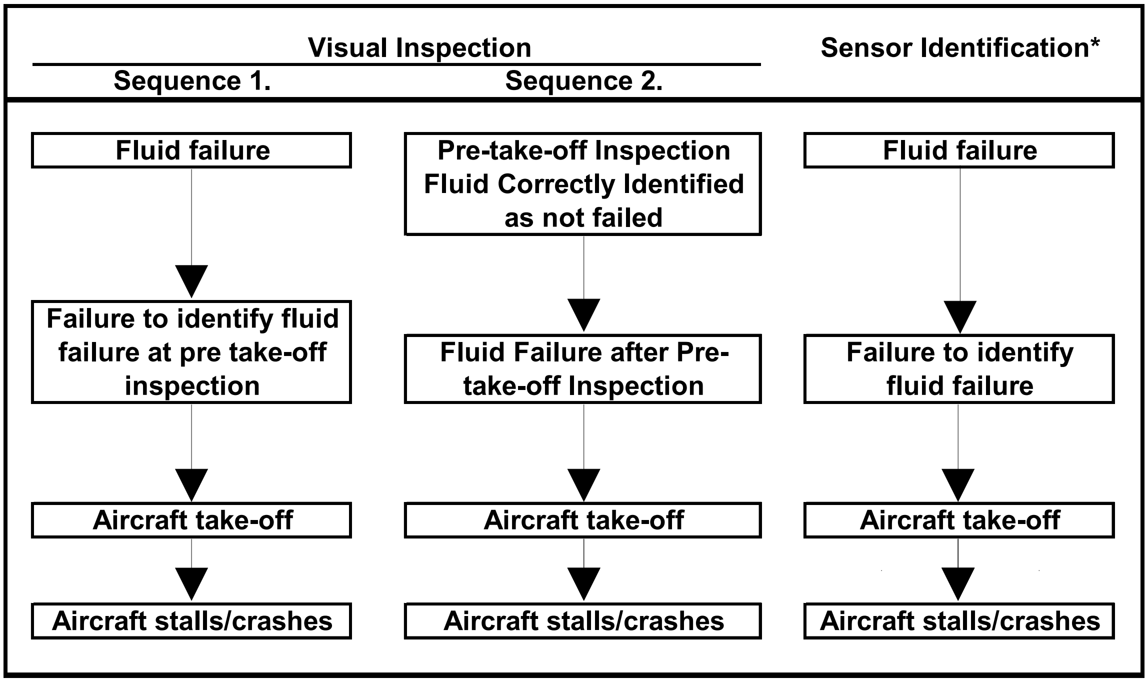


Figure 1.2 Risk Analysis Critical Sequence of Events and Principal Factors Affecting those Events



* Sensor provides continuous monitoring and time of pre-take-off inspection is not important

Figure 1.3 Risk Analysis Critical Sequence of Events for Visual and Sensor Procedures in Relation to Pre-Take-off Inspection

The various ground icing related decisions and events that can occur which will affect the outcome of the take-off can be put into the form of an event tree as shown in Figure 1.4. A similar tree is given for sensor based inspection procedures in Figure 1.5. If the conditional probabilities associated with each branch can be estimated, the probability of each outcome can then be estimated. The event sequences given in Figure 1.3 relating to pre-take-off inspection are included in the bottom half of the tree. The top half of the tree, where deicing is not conducted following the pre-flight inspection, is not the focus of this risk assessment, but could also lead to significant reductions in risk using sensor based systems.

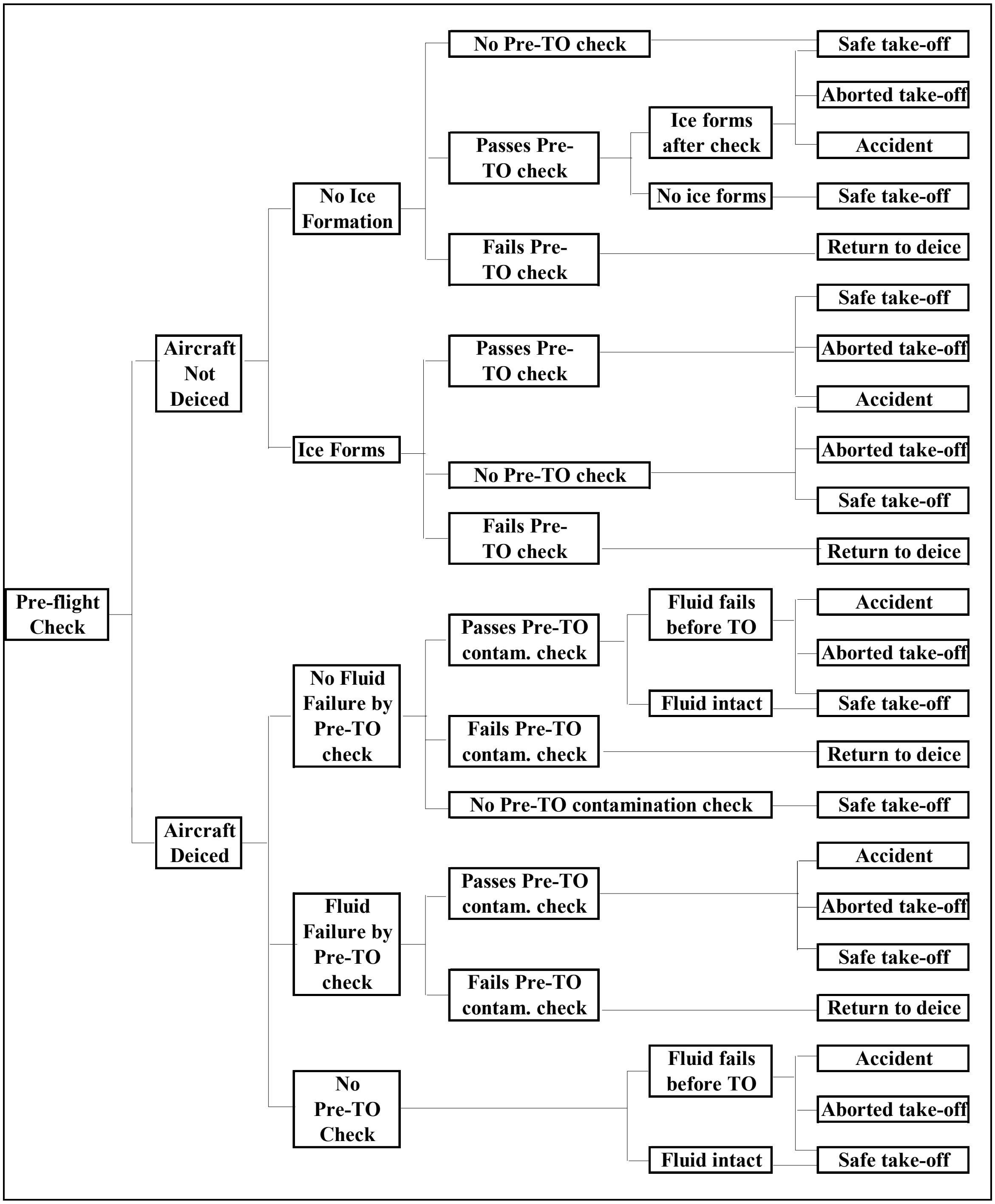


Figure 1.4 **Risk Analysis Tree for Take-off in Ground Icing Conditions Using Current Inspection Procedures**

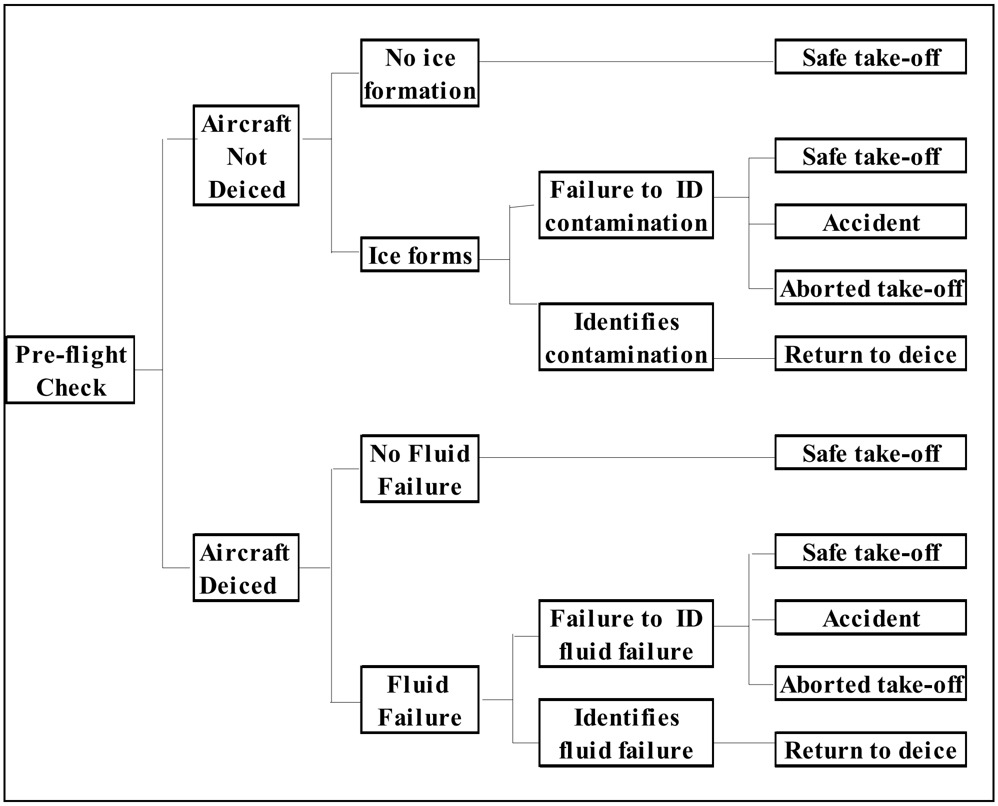


Figure 1.5 **Risk Analysis Tree for Take-off in Ground Icing Conditions Using Sensor System to Identify Wing Contamination**

2. METHODOLOGY

The analysis is broken into four main components:

A. Background
B. Fluid failure and assessment
C. Comparisons of fluid failure identification accuracy
D. Implications on reduced accident risk

A flowchart showing these components and the steps undertaken in the comparative risk analysis is given in Figure 2.1. The review of "current airline practices for de/anti-icing" and the review of sensors do not provide a comprehensive description of those topics. Rather, they look at those topics from the perspective of the assessment of the condition of the wing and concentrates on areas that could affect the comparison of the risks. Not all elements of the risk analysis shown in Figure 2.1 were conducted in this phase of the project. In particular, the risks of different aircraft types at all airports, and estimates of the number of false alarms and changes in the number of unnecessary deicings were not evaluated.

It should be noted that this study did not include the collection through field trials of any new data or the development or investigation of any new relationships between the identification of fluid failure and the factors and conditions affecting failure, or the effect of failed fluid on aerodynamic performance. The data used were collected by TDC, the developers of the sensors, National Research Council Canada (NRC), and other research organizations.

Surveys of airline pilots in Canada and the US were conducted to determine:

- the types of procedures used by pilots and their frequency of use;
- their training and level of confidence in assessing fluid failure under various conditions, the importance of various factors, and the effect of HOTs and poor viewing conditions on their decision whether to re-deice; and
- the frequencies of deicing, pre-take-off inspections, re-deicing, etc.

The surveys were conducted through the pilots' associations and responses were confidential and anonymous. This allowed pilots to state their actual procedures and experiences without fear of recrimination.

During the course of the project, deficiencies in the available data were identified. Ways of proceeding with the analysis were sought, and specific data to be collected were identified. In the latter case, estimates were made of the missing data and the sensitivity of the final results to these estimates was investigated. If, and when, the data becomes available, the final results can be updated using the analysis procedures developed.

Figure 2.1 Flowchart of Steps of Comparative Risk Analysis

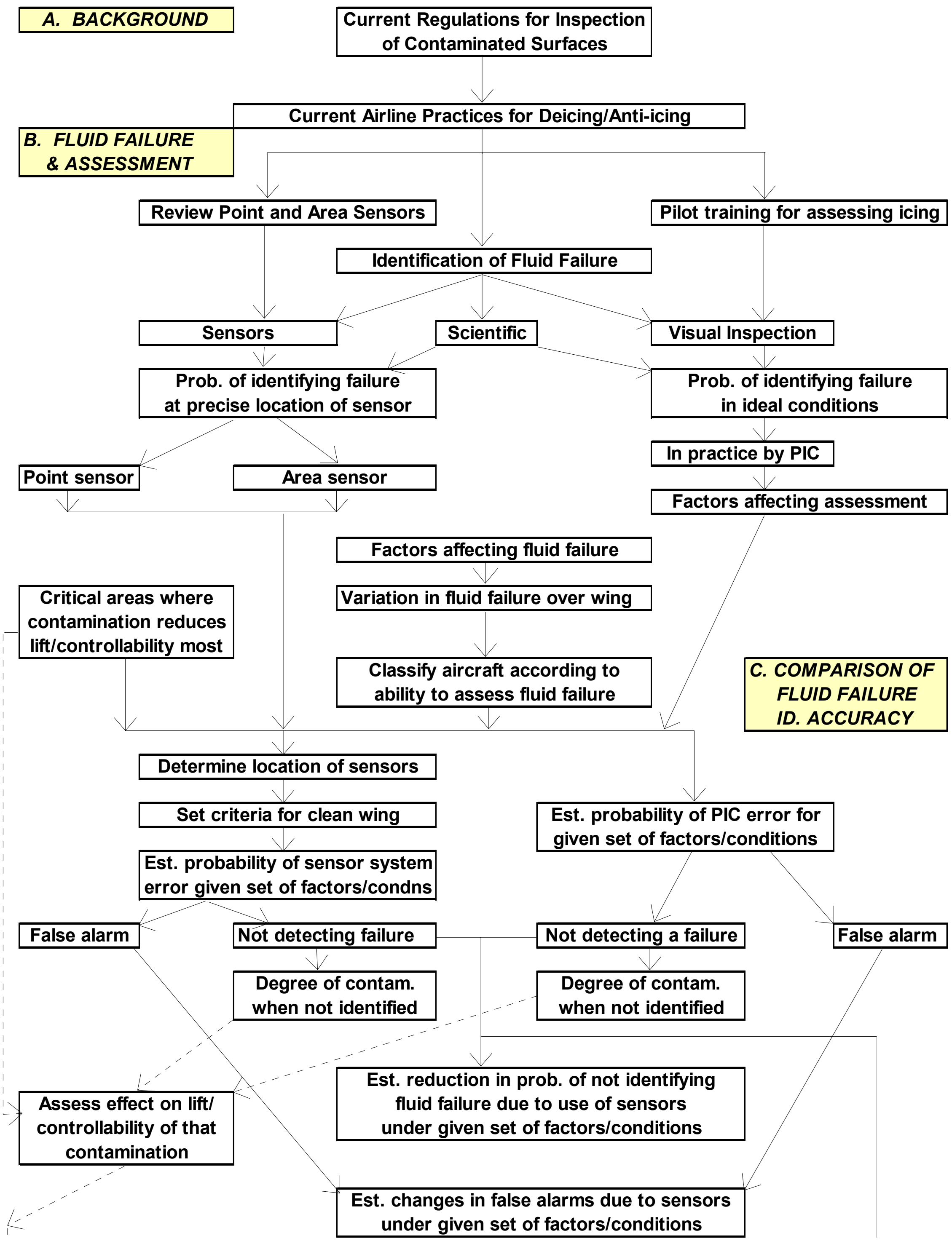


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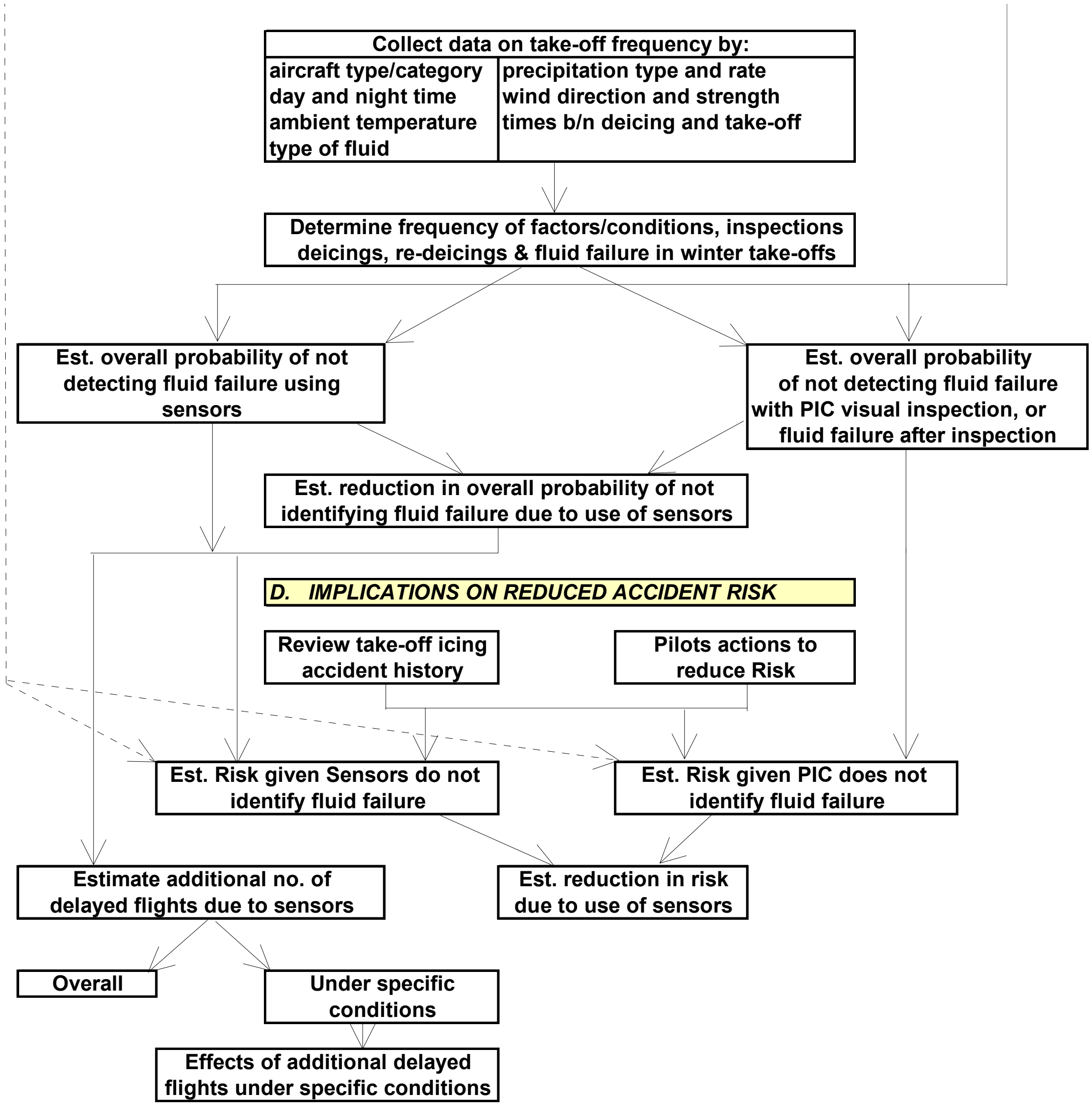
Figure 2.1 Flowchart of Steps of Comparative Risk Analysis (Continued)



3. CURRENT REGULATIONS, PROCEDURES AND PRACTICES

3.1 Canadian and US Regulations

The current Canadian Regulations covering ground icing are given in CAR 602-11. Important aspects of the regulations which relate to the comparative risks associated with pre-take-off inspection based on visual observation and sensors are as follows:

- take-off should not be attempted in an aircraft which has frost, ice or snow adhering to any of its critical surfaces - the PIC is responsible for ensuring the aircraft is “clean” before initiating take-off;
- the operator must have a program established in accordance with standards specified in the **Ground Icing Operations Standard,** and dispatch and take-off of the aircraft must comply with that program;
- the aircraft must be inspected as part of the **pre-flight check** to determine if deicing is required; and, unless other procedures have been approved, tactile external inspection must be conducted on aeroplanes without leading edge devices such as the F-28, Canadair RJ, Dash 8 and BAe 146;
- a **post de/anti-icing check** must be performed immediately after de/anti-icing by the PIC or qualified ground personnel to verify that all contamination has been removed from the critical surfaces, especially areas which are not visible to the PIC from inside the cockpit or cabin. Once completed, the aircraft should be released for take-off as soon as possible;
- a **pre-take-off contamination inspection** is required if the take-off cannot be made within the lower time given in the pertinent section of the holdover time tables (HOTs)[3];
    - ◊ the check is performed shortly before the aircraft takes the active runway for take-off, or initiates the take-off roll,
    - ◊ components that are visible from inside the cockpit and cabin should be inspected; these vary by aircraft design. PIC may request qualified ground personnel to assist.
    - ◊ depending on the aircraft type and the airline’s operating procedures, the pre-take-off contamination inspection is performed as either a visual or tactile check of fluid condition on the critical or representative surfaces of the aircraft,
    - ◊ pilots are warned that the protection time of the fluids may be less than the published HOTs in certain conditions and that under these conditions a pre-take-off contamination check should be conducted,
    - ◊ approved ground icing programs allow aircraft a 5 minute period in which to take-off after the pre-take-off inspection; this time period is not mentioned specifically

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[3] FAA regulations still require a pre-take-off check, similar to the pre-take-off contamination check, even if aircraft can take-off within the lower HOT value.

in the regulations or the Ground Icing Operations Standard, but is given in the SAE Recommended Practices, ARP4737.

- The PIC has the ultimate responsibility for ensuring that the aircraft is clean and that the aircraft is in a safe condition for flight.

An important difference between Canadian and FAA regulations is that the FAA regulations still require a pre-take-off contamination check even if take-off can be commenced before the HOT has expired[4].

The are a number of limitations associated with using HOT tables and carrying out the inspections called for in the regulations. These limitations are well described by Allied Signal (2) and are summarized briefly below.

- It is difficult to determine the actual condition of the critical surfaces, especially in poor weather conditions, poor lighting and with high wing aircraft;
- Due to difficulty in determining actual conditions, aircraft are sometimes de/anti-iced unnecessarily. Usually this will not adversely affect safety. However, in some conditions such as very cold temperatures and light blowing snow, with no fluid the snow may not adhere to the aircraft, but with fluid applied the snow will be absorbed into the fluid and thus risk fluid failure;
- Environmental factors which can significantly affect the protection time of fluids are not incorporated in the HOTs. Pre-take-off inspections are required if the take-off cannot be made within the minimum time of the HOT range, but under some conditions fluid failure may occur before then;
- Tactile checks performed by ground crews near the runway apron are logistically difficult to perform at busy airports and introduce concerns for safety of the ground crew;
- Fluid failure can sometimes be difficult to visually detect, especially from inside the aircraft; and
- Fluid failure could occur after the pre-take-off inspection but before take-off.

3.2 Departure and Inspection Procedures

The survey of pilots in Canada was used as a basis for summarizing the departure and inspection procedures used in conditions conducive to ground icing. Detailed results of the survey are reported in (3) and the questionnaire and a summary of the results are given in Appendix E.

A significant number of pilots (20%) indicated that pre-flight data are not available on the type of precipitation, pireps (pilot reports) concerning critical precipitation and the

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[4] The HOT tables include a range of times for each precipitation type and temperature category. When referring to “the HOT” (i.e., a single value), the minimum value in the range is being referenced.

possible need to reduce take-off weight. Many (30% - 50%) indicated that these data were only available at some airports.

There is a strong reliance on the HOTs when deciding on the need to re-deice the aircraft, especially in poor visibility and/or in freezing rain/drizzle. Most pilots (82%) have medium to high confidence that the HOTs reliably indicate the earliest that the fluid could fail. Most of the pilots (84%) find the range in the HOTs more useful than a single value. Generally they feel that the range provides some flexibility and allows pilots to use their judgment in the various weather conditions that can prevail. The few pilots who do not favour a range find it confusing and would like only a single minimum protection time value as they only use this value. Several pilots indicated that with a range being given, the maximum is used, e.g., “With the urge to depart the maximum value of the range is normally used”. From the survey it can be concluded that a range in HOTs is preferred, but some pilots do not clearly understand what the upper and lower values in the range represent.

In conditions conducive to ground icing, but when the aircraft has not been deiced, most pilots will make a pre-take-off inspection either always (63%) or in certain conditions (25%). These conditions typically relate to the type and intensity of precipitation, temperature and due point, humidity, etc. Changes in weather conditions were also noted as a reason to re-check the aircraft. About 10% rarely or never check the aircraft just prior to take-off. A number of pilots mentioned that in conditions conducive to icing they always deice.

Location and Method of Inspection

Most pilots indicated that at airports equipped with a deicing pad, their air carrier requires a critical surface inspection prior to push-back from the gate. Some indicated that this is done to assist in coordinating use of the deicing pad. Others indicated that the check is done by the pilots themselves during their pre-flight “walk around” inspection or by ground crew.

Most pilots (70%) indicated that it is not possible to make the pre-take-off inspection from the cockpit. Of those pilots who could inspect the wing from both the cockpit and cabin, 85% found the cabin better in low wing jet aircraft and 25% found the cabin better in low wing turboprop aircraft, as shown in Figure 3.1. In high wing aircraft, very few pilots found inspection better from the cabin. Pilots who could make the inspection from either but that found the cabin better, make their inspection from the cabin most of the time (60%), while those who found the cabin and cockpit similar would only go back to the cabin 15% of the time.

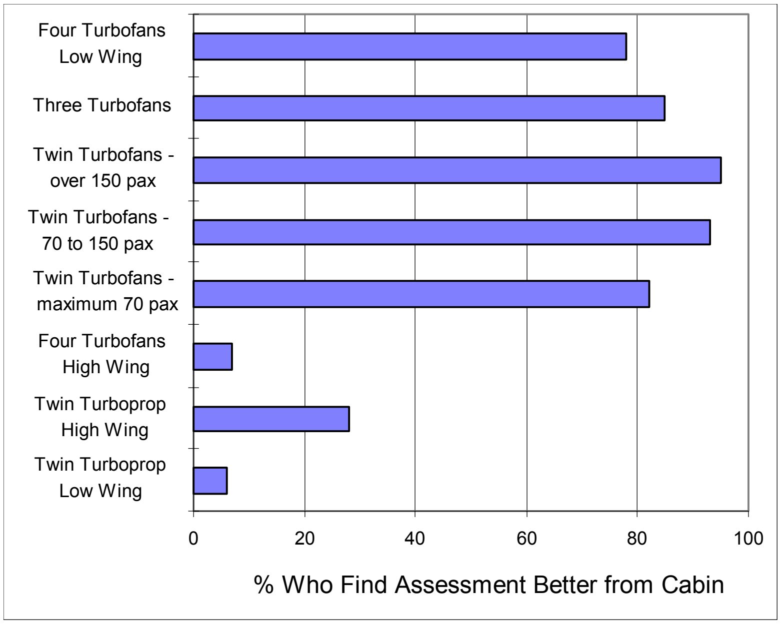

Figure 3.1 **Percentage of Pilots Who Could Inspect Wing From Both the Cockpit and Cabin* Who Find Assessment Better from the Cabin and the Cockpit**

* 70% of pilots indicated that it is not possible to make the pre-take-off inspection from the cockpit.

The option of opening the door to visually inspect the upper wing surface is used by over a third of pilots of high wing aircraft, most of these only when conditions warrant a close inspection. Many indicated that, although opening the door is not an option for pre-take-off inspection, many use it for the pre-flight inspection.

Many pilots indicated that a tactile check was the only way of really knowing the condition of the wing; they often requested this to be done, or obtained (or would like to have had) a ladder to check it themselves. About 60% indicated that they have had a tactile check done for the pre-take-off inspection. Those that do, for the most part only have the tactile check done infrequently (less than 20% of the time), but some (10% of pilots) always have a tactile check done. The use of tactile inspections does not vary greatly between aircraft categories, but (surprisingly) appears to be done more for the larger aircraft. [Note: there may have been some confusion between pre-flight and pre-take-off inspection when answering this question - answers may be more representative of pre-flight inspections.]

Representative Surfaces

The majority of pilots indicated that they believe the representative surfaces represent the surface condition of the wing well or very well; 12% indicating very well. About 7% indicated that they believe those surfaces represent the wing poorly. As discussed in Section 7, fluid failure tests conducted by APS on a number of aircraft types under various conditions have found the locations of first fluid failure to be variable and to rarely occur on the representative surfaces. The fact that the majority of pilots think the representative surfaces work well is possibly not a good sign. As most pilots do not have a lot of experience with recognizing fluid failure, it could be an indication of false confidence in these surfaces. Comments by many pilots refer to inspection of the "rep. surfaces" rather than the critical surfaces or wing, and give the impression they only inspect the representative surfaces. The pilots responding "not well" and "poor" gave many examples of contamination on the other areas of the wing prior to contamination on the representative surfaces.

Some of the comments on representative surfaces suggest that both sides of the aircraft should be inspected and that fluid failure is easier to detect on dark coloured surfaces.

Link Between HOT for Freezing Drizzle and Airborne Icing

In the survey pilots were asked, "given that you are within the HOT limits for light freezing drizzle, does this mean you are can safely take-off in those conditions?" About half the pilots indicated that it was safe; the other half that it was not safe. Most of those pilots indicating that it was not necessarily safe commented that in those conditions they make a visual inspection and/or that HOTs are only a guide. A number pointed out the risks due to runway contamination and cross winds. However, very few pilots (1%) recognized that, although the wing may be clean and the aircraft may be able to take-off, once airborne, the freezing drizzle may cause contamination on the leading edge of the wings making the aircraft potentially unsafe. HOT tables published by TC have been revised for the 1997/98 winter to include a note cautioning the user that "fluids used during ground deicing are not intended for and do not provide ice protection during flight".

Pilot's Views on Current Procedures

The survey of pilots found that the majority of pilots feel that the recent improvements in de/anti-icing standards and procedures have moderately or greatly improved safety. Pilots of turboprop or small jet aircraft are more likely to have found safety to be greatly improved than pilots of larger aircraft. Some of their comments on the standards and procedures include statements such as:

- greater awareness, less individualism, education benefit;
- everybody now agrees on a clean wing; prevents cutting corners, less pressure on pilots, especially those in small airlines;
- safety was already high, little need for change, overkill; and
- there is too much de/anti-icing, deicing frequently unnecessary, at a great cost, and harmful to environment.

Approximately 20% of pilots are still not comfortable with the current de/anti-icing procedures. Pilots of high wing aircraft are less comfortable with the procedures than pilots of low wing aircraft. The pilot's most common concern was that there is too long a delay after deicing, and they suggested that deicing pads should be located near the end of the active runway and that deicing and take-off be coordinated through ATC. Other concerns included: decisions are now out of hands of the pilots; there is lots of unnecessary deicing, especially when very cold and light dry snow is falling; and that at some airports there is inferior equipment and a lack of availability of anti-icing fluids. Improvements in communication, training of ground staff and more education were also suggested.

3.3 Training

The Ground Icing Operation Standard requires the operator's training program to include:

- initial and recurrent training for all operational and ground/maintenance personnel who have responsibilities within the program; and
- testing of crew members and other operations and ground/maintenance personnel.

The requirements of the training programs are very comprehensive and include the use of HOTs, relationships between holdover times and fluid type and concentration and precipitation intensity, and techniques for detecting and recognizing contamination on the aircraft.

The survey of pilots indicated that training on the recognition of fluid failure is inadequate. Less than 60% of pilots have received verbal instructions on how to recognize fluid failure and only 15% to 20% have seen pictures or videos of fluid failure. When asked to describe how they recognize fluid failure, only 80% could give a response for failure during snowfall, and only 66% for failure during freezing rain/drizzle or ice pellets. Of the pilots who responded, the responses indicate that most have a general idea of what to look for. Many mentioned more training is required or they use HOTs. Many were confused about the difference between the failure properties during snowfall and freezing drizzle/rain. Clearly, if pilots are expected to assess the condition of the wing during the pre-take-off inspection, better training on recognition of fluid failure is required.

Over 50% of the respondents thought that training of flight and ground crews was fully satisfactory, despite the lack of knowledge about fluid failure recognition. Some suggestions for improvements included:

- better training on fluid failure recognition - pictures, videos, hands-on, etc.;
- better timing of recurrent training - just before winter;
- better training for ground crews, especially contract ground crews:
  - ◊ more standardization (application, fluid type, start of HOT),

- ◊ improve communication (ground crews should communicate what areas of the aircraft they are deicing),
- ◊ importance of removing snow from fuselage of aircraft with rear mounted engines,
- ◊ too much turnover in ground crew for them to become experts,
- ◊ ground crews need better training on “adhering” contamination - often unnecessary deicing in very cold conditions, and
- ◊ better training at small stations.

Most pilots do not frequently make pre-take-off inspections and very rarely identify fluid failure, and will therefore not learn about fluid failure “on the job”.

3.4 Quality of De/Anti-icing Services Provided

Based on the survey, most pilots are satisfied with the ground deicing service provided,. Many found the service to be excellent and have had no problems. Over 75% of pilots did not have reason to question the quality or capability of the deicing service provided and 70% are very confident that the aircraft is clean when cleared by the deicing crew. As mentioned above, many pilots thought ground crew training could be improved. Some ground crew are not sure at what point during the deicing procedure the HOT starts. About 35% of pilots stated they were informed of the fluid type without asking at some airports and not others, while 10% are not routinely informed of the type. Many pilots commented that they found the deicing service better in Canada than the US.

Despite the generally good performance of the deicing service, there were many reported incidents where the deicing was not properly done, e.g., wings still contaminated, or where the prop was not deiced or only deiced on one side of the aircraft. Inconsistent application of fluid can lead to fluid failure prior to expiry of the HOTs. Since the pre-take-off inspection is not mandatory prior to the HOT, instances of fluid failure due to improper fluid application may not be identified and could significantly jeopardize safety. These types of mishaps appear to occur infrequently, but are too frequent given the possible consequences. It is very important that cases of improper or inconsistent fluid application be identified in the post-deicing check.

The majority of pilots are aware of their company’s quality management program to assess the quality or capability of the deicing service. However, 35% are not aware of the program and a few pilots indicated their company does not have a program.

There is a strong acknowledgment of the benefits of anti-icing fluid, especially among pilots of small to medium sized jet aircraft. Pilots were particularly impressed by the long holdover times of Type IV fluids and called for the greater availability of anti-icing fluids at small and medium sized airports.

Generally, pilots found the quality of de/anti-icing service to be better at large airports, but there is considerable variability within the large and small airport groups. Small airports often don't have anti-icing fluid available, usually have inferior equipment, especially in northern areas, and in extreme cases cannot even deice the aircraft within the HOT. This is offset to some extent by the shorter taxi and delay times at those airports. The quality of personnel providing deicing service varies greatly at small airports. Location, rather than size, was mentioned as an important factor. Vancouver was frequently cited as having a poor deicing service.

4. FLUID FAILURE

4.1 Fluids and Protection of the Wing

Deicing fluids are used to clean existing winter precipitation contaminants off the aircraft using heat and hydraulic pressure. Anti-icing fluids are applied to provide protection against subsequent contamination from the freezing of either deicing fluid or further winter precipitation, and this protection is intended to last for a period of time sufficient for the aircraft to taxi to the runway and take off safely.

Anti-icing fluids are designed so that, as the aircraft accelerates during take-off, the increasing air velocity will strip them off. During this process the fluid forms waves that create a roughness on the lifting surfaces, disturbing the aerodynamic boundary layer and causing some reduction in lift.

Current anti-icing fluids are qualified for use on aircraft by meeting test criteria laid down in SAE AMS 1424 and 1428. These include aerodynamic tests on a flat plate that are designed to evaluate the effects of the fluids on aircraft performance at take-off conditions.

A lift loss of no more than five per cent at maximum lift conditions has been deemed acceptable. This criterion has been translated into a test of the equivalent boundary layer displacement thickness on a flat plate covered with 2 mm of fluid and subjected to simulated take-off conditions. This aerodynamic test is performed at a range of temperatures, but with no contamination.

Under conditions of precipitation the fluid becomes diluted and the viscosity and thickness change. This impacts on the wave formations of the fluids under take-off conditions. In the early stages of contamination the wave heights will be reduced and the lift loss alleviated. However as exposure to precipitation continues, crystals take longer to be absorbed into the fluid and begin to build up on the fluid surface. This results in a thickening effect that increases the effective roughness of the surface and the lift loss effect will increase. At some level of roughness the effect on the boundary layer flow will surpass the limit prescribed for qualification of the uncontaminated fluid. Up to this point there is no doubt that the fluid is providing protection; beyond this point, with continuing precipitation, serious aerodynamic effects will be felt and catastrophic local lift losses may result; but just how long it takes to reach this condition is not well understood.

The build up of ice crystals in the fluid is difficult to see, particularly at night in precipitation conditions. Generally for it to be evident to the observer positioned several feet from the surface, an area of several square inches must show visible contamination at the surface (often from bridging of ice crystals on top of the slowly absorbed crystals below). Small areas of slush are not likely to be adhering to the subsurface and, once they slide aft of the leading edge, their disturbance to the airflow will be minimal and will not cause severe loss of lift. However in continuing precipitation, the areas will grow until much of the wing surface is covered with evident contamination. Eventually the crystals will penetrate to the solid wing surface and bond, producing a very severe (and lasting) roughness that could be catastrophic.

The problem of visually observing fluid failure is that the condition whereby the fluid fails to protect the underlying surface occurs when there is substantial amounts of slush on top of the fluid, obscuring the surface and the severity of the contamination. Therefore, in the absence of any better indicators, the beginnings of visual contamination of the surface has been accepted as a safe boundary condition for the use of the anti-icing fluid. It is this condition that has been used to establish the safe time for exposing the fluid to contamination. This safe exposure time is called the holdover time.

The holdover time does not represent a failure condition; it is not the time at which the fluid ceases to protect the surface. On the contrary, the holdover time represents the duration of protection that the fluid will provide, when exposed to the environment specified in the holdover time tables. There can, however, be no guarantee as to how long after this time that the fluid will provide protection and thus there needs to be continuous checking of the surface by the crew once the holdover time is exceeded.

Supporting this interpretation of holdover time is the evidence from limited wind tunnel tests that to date have shown that contaminating precipitation, lasting as long as the holdover times currently in use, do not result in catastrophic lift losses. Also, no accidents have occurred where the aircraft has taken-off within the holdover time since holdover times have been specified by the SAE (since 1990).

4.2 How is Fluid Failure Determined?

Currently, fluid failure is determined by visually observing the fluid and assessing whether set criteria are met. A scientific test known as the Brix test has been used by a number of organizations to determine whether the fluid has failed. The Brix test requires a sample of the fluid to be taken and only indicates the condition of the fluid at that point. It is therefore not well suited for verifying fluid failure during pre-take-off inspections.

The criteria used in TDC holdover time tests for identifying fluid failure are as follows (6):

- *During falling snow precipitation:* when there is a visible accumulation of snow (not slush but white snow) on the fluid surface. This occurs when the deicing fluid can no longer accommodate or absorb anymore precipitation
- *During freezing rain/drizzle/fog or ice pellets precipitation:* when precipitation or frosting produces a “loss of gloss” (i.e., a dulling of the surface reflectivity) effect on the surface of interest. This definition applies in mixed snow and freezing rain/drizzle/fog or ice pellets.

The Transport Canada document on aircraft critical surface contamination training, "When in Doubt… Small and Large Aircraft" gives the following instructions for identifying fluid failure:

> "…. Aircraft surfaces should appear glossy, smooth, and wet. Frost, ice or snow on top of the deicing or anti-icing fluids must be considered as adhering to the aircraft and take-off must not be attempted."

The FAA Pilot Guide for Large Aircraft Ground Deicing gives similar instructions in the section on pre-take-off check:

> "If the aircraft has been treated with FPD fluids, aircraft surfaces should appear glossy, smooth, and wet. If these checks indicate accumulations of ice, snow, or frost, the aircraft should be returned for deicing ….."

SAE guidelines (7) states that each carrier must define type-specific, pre-take-off contamination check procedures and that these must cover all critical parts of the aircraft and be performed from points offering sufficient visibility on these parts. However, it does not provide any criteria or guidelines for determining whether or not a fluid has failed. Draft SAE guidelines *Training Requirements for De/anti-icing of Aircraft on the Ground* (ARP 5149) will include a section on aircraft surface contamination recognition which will be based on AC120-60.

Union Carbide in their information to users of their de/anti-icing fluids does not specifically address identification of fluid failure. Those interested are referred to SAE procedures. Union Carbide does have training information, including a video showing fluid failure, which notes the two main factors for identifying fluid failure are the loss of gloss and the failure of the fluid to absorb further precipitation.

The Brix test gives the freeze point of the fluid from the refractive index measured on small samples of fluid. If the freeze point is less than the ambient temperature, the fluid has failed. In tests conducted in 1996, APS found the freeze points of failed fluids taken on flat plates in a laboratory match the ambient temperature (8). However, the freeze points of failed fluid samples taken on an aircraft wing did not consistently match ambient temperature. In other tests, NRC has successfully correlated the Brix failure point with a drop in aerodynamic performance.

Point and area sensors used to identify fluid failure have been calibrated to match the visually observed failures. Their accuracy is discussed in later sections.

4.3 Consistency of Fluid Failure Identification

The assessment of fluid failure is made by visual observation and is therefore open to interpretation and human error. It is also affected by the conditions under which the observations are made. Assessments made in a laboratory under the best possible conditions, given the precipitation, would be expected to be the most accurate. A good degree of consistency has been achieved in standard flat plate tests where ice formations progress from the top of the plate. However, in field tests with an aircraft at night in freezing rain or snow, identification of fluid failure is difficult and less consistent.

Another cause of variation is that when slush formation occurs, it usually occurs well before ice formation and can lead to significant variation in visually observed fluid failure calls. Inconsistency in fluid failure times can also occur due to variable snowfall rates. During heavy snowfall, snow can collect on top of the fluid giving the appearance that the fluid has failed, but if the rate of snowfall gets lighter, the snow on top may be absorbed into the fluid indicating the fluid has not failed.

Instrumar (9) conducted an analysis of the relationship between fluid failure time and precipitation rate based on tests conducted by NRC, the University of Quebec at Chicoutimi and APS. Instrumar used a standard deviation of 2 minutes as an estimate of the nominal error introduced by an observer during the identification of fluid failure. This corresponds to a 95% confidence interval for the true failure time of ±4 minutes around the observed value. They note that “this is a generous estimate” of the possible error. In their report, Instrumar, gave a number of examples of inconsistencies in the visually determined fluid failure times by observers positioned and equipped as best they could to make the assessment. The examples include:

- In a comparison of failure times using Type I fluids for tests conducted over a range of precipitation rates, a failure time of 28.8 minutes was recorded in an outdoor test. This compared with the sensor reading of 4.5 minutes in that test and visually observed failure times between 4 and 6 minutes in 6 different laboratory tests conducted at similar precipitation rates. Although times to failure are also dependent on factors other than precipitation rate, these factors do not explain the much higher time observed in the outside test.

- In a set of laboratory tests conducted using Type III fluid, two visual failure times at almost the same precipitation rates were identified to be 14 and 49 minutes, a difference of 35 minutes. The sensor indicated failure times of 20 and 36 minutes, a difference of 16 minutes. Visual failure times in other tests at precipitation rates around the value in question indicate the failure time would be expected to be around 26 minutes.

The vast majority of visual assessments appear to be consistent, but cases like these highlight the difficulty of reliably assessing fluid failure visually, especially in actual outdoor conditions and using different observers.

Visual observation can also lead to errors when weather conditions or inconsistent fluid application causes failure times to be very different from the expected holdover times. For example, during one test conducted by APS on a Canadair Cargo 737 with Type IV fluid and light freezing rain, the sensor detected fluid failure much earlier than expected from the HOTs (10). The observer was not looking for fluid failure at that time and did not identify the fluid as failed until much later. It was confirmed by tactile inspection that the sensor had been correct in predicting the early fluid failure.

Precise times of fluid failure are not known and this makes the evaluation of sensors for identifying fluid failure difficult. Visually observed failure times are often recorded only to the nearest minute due to their imprecise method of observation. Differences between visually observed failure time and sensor predicted times could be due to observer variation, or due to differences in what the sensor and the visual observer are identifying.

4.4 Frequency of Fluid Failure Prior to Take-off

Fluid failure prior to take-off is common in the chain of events leading to an accident for both the visual and sensor based procedures for pre-take-off inspection. The timing of the fluid failure, whether it is before or after the pre-take-off inspection, is also important for the risk comparison. Approximate estimates of the probability that a fluid fails prior to take-off are found in two ways:

- based on the frequency of times that HOTs are exceeded and the number of times the aircraft must be re-deiced due to take-off delays; and
- using the distribution of times between fluid application and take-off and the distribution of fluid failure times for departures from several airports.

4.4.1 Frequency of Fluid Failure Based on Pre-take-off Inspections and Re-deicing

Survey of Canadian Pilots

The deicing and re-deicing experience of Canadian pilots responding to the survey indicates that:

- pilots deice their aircraft on average 25 times per year (5.5% of take-offs);
- about 40% of deicing operations are to turboprop or very small jet (less than 70 seats) aircraft, 40% to jet aircraft in the 70 to 150 seat range, and the remaining 20% to larger aircraft;
- one quarter of deicing operations are to high wing aircraft;
- a pre-take-off inspection was necessary after about 20% of deicing applications due to HOTs being exceeded;
- the aircraft is re-deiced after about 3.2% of deicings;
- turboprop and very small jet aircraft and, surprisingly, very large aircraft (4 jet engine, low wing) are more likely to require re-deicing than the medium size jet aircraft; and
- over 50% of the aircraft that were re-deiced were turboprop or very small jet aircraft.

Generally take-offs can be completed prior to the HOTs expiring. Almost 50% of pilots reported that pre-take-off inspection was required rarely or never due to expiry of the

HOT. About 6% indicated the inspections were necessary frequently. On average pilots made about five pre-take-off inspections last winter and re-deiced on average 0.8 times; i.e., after 16% of pre-take-off inspections.

A fluid failure could occur prior to the HOT, but is unlikely as the HOT represents the minimum time, approximately, that the fluid can be expect to protect the aircraft under a range of conditions. A second deicing is not necessarily indicative of fluid failure because in poor viewing conditions pilots tend to be conservative when assessing the wing condition and may return to deice the aircraft when the fluid has not failed. Thus, these percentages only provide an indication of the likely order of magnitude of the probability of fluid failure. Based on these frequencies, the probability of fluid failure prior to take-off, given the aircraft was deiced, is estimated to be in the in the order of 1×10^{-2}.

Allied Signal - Midway Airlines

Allied Signal conducted an evaluation of the C/FIMS sensor system on an F-100 aircraft operated by Midway Airlines during the winter of 1996/97 (11). The following data were monitored for 82 take-offs: ground icing conditions, pilots assessments of aircraft condition, fluid application and sensor readings on the of the condition of the wing. The majority of take-offs were from Raleigh-Durham to east coast destinations. The ambient temperatures were below 6°C for 30 (36%) take-offs and precipitation was falling during 9 (11%) take-offs. De/anti-icing fluids were applied prior to 8 of the 82 take-offs as given in Table 4.1. Fluid failure occurred prior to take-off after one of the eight fluid applications (12%). The one failure occurred with Type I fluid and considering only departures using that fluid, failure occurred after one third (33%) of applications.

Table 4.1 Summary of Fluid Application and Fluid Failures in Tests on Midway Airlines F-100 Aircraft

	Type I Fluid Only	Types I and II Fluids
No. of applications	3	5
Time between deicing & take-off	9 - 13 min.	9 - 23 min.
No. times re-deicing required	1	0[a]

[a] C/FIMS sensors system indicated fluid failure on one departure prior to minimum value of HOT, but pilot’s assessment was that the wing was clean and take-off was continued.

Instrumar - Air Atlantic

An evaluation of a CWDS system of four sensors (one on each wing and one on each horizontal stabilizer) on a BAe 146 aircraft operated by Air Atlantic was conducted by Instrumar (12). Data were recorded for 312 flight legs, deicing was considered on 43 occasions and was deemed necessary on 20 of those occasions. The aircraft was re-deiced after one of these 20 deicings. Five detailed time plots of sensor reading when the aircraft was deiced were analysed and indicated:

- the CWDS sensors indicated that deicing was only required three of the five times;
- the sensors indicated that the fluid had failed prior to take-off on three occasions, the times to fluid failure were 7 & 10 minutes during freezing drizzle and 14 minutes during snowfall;
- the times to fluid failure were near or above the published HOTs of 1 - 3 minutes for freezing drizzle and 6 - 15 minutes for snow; and
- the time from deicing to take-off varied from 12 to 15 minutes when the fluid failed.

The three fluid failures identified by the sensor system are likely correct given that the higher times in the HOT ranges were exceeded. Thus, the fluid failure rate on aircraft after deicing was at least 15% [= 3/20]. Only Type I fluids were used and most departures were at medium to large airports (93% were at Halifax, Dorval, St. John's or Ottawa).

TDC - Dorval Airport

Data were collected at Dorval Airport, Montreal, over the period between October 15th 1996 to April 30th 1997, a total of 197 days, to estimate frequency of aircraft deicing (13). The data are summarized in Table 4.2. Only 8.4% of winter departures required deicing, 4.5% of annual departures, and 20% of those were to remove overnight frost. A further 20% was due to precipitation which had ceased by the time of deicing. In only 40% of deicing operations (1.8% of annual departures) was there any risk of fluid failure due to precipitation and in approximately 12% of these cases the precipitation was "heavy" (classification of heavy was not well defined, but generally estimated at greater than 25 gm/dm^2/h). For these 12% of deicing operations the risk of fluid failure is greatest.

Table 4.2 Summary of Deicing Operations at Dorval During 1996/97 Winter

No. of days on which deicings were conducted	139	70% of winter days
No. of commercial departures	47,280	
No. of deicing operations	3,976	8.4% of winter departures
Deicing operations for frost only	~800	20% of deicing operations
Deicing following precipitation (no precipitation at the time)	~1600	40% of deicing operations
Departures during precipitation	~1600	40% of deicing operations 3.3% of winter departures
Departures during "heavy" precipitation	~200	5% of deicing operations 0.5% of winter departures
Percent where anti-icing fluids applied	≤ 10%	

The percentage of aircraft to be deiced based on the pilot survey (5.5%) is slightly greater than at Dorval (4.5% when based over the full year). However, the Dorval data indicated that only 40% of deicings were done during precipitation when there is a risk of fluid failure. If a similar proportion of deicings at other airports in Canada are done during precipitation, the aircraft would be deiced and at risk of fluid failure for approximately 2% of departures in Canada.

4.4.2 Frequency of Fluid Failure Based on Distributions of Delays and Weather Conditions

The probability of fluid failure before take-off is dependent on the time period between deicing and take-off and the protection time of the fluid. The variation in fluid application/taxi/delay times after deicing is critical in determining the likelihood of fluid failure, especially the frequency of longer times.

Fluid protection times vary depending on fluid type and dilution and the weather conditions, especially the precipitation rate. Other conditions such as wind, wind-blown snow, ambient and wing surface temperature and humidity can be important. Given the large number of combinations of fluids, dilutions, airports and weather conditions, it was not feasible to estimate a single probability of fluid failure prior to take-off for all departures in Canada. Instead, estimates were obtained for a number of typical cases. The following approach was used:

- the fluid application/taxi/delay time distributions for a large busy airport and for typical small airports with short and long taxi times were estimated;
- expected protection times of fluids for given precipitation rates and types and ambient temperatures were estimated;
- the variation in protection times around this expected value to allow for other factors (type of precipitation, wind, humidity, etc.) was estimated;
- the joint probability distributions of precipitation rate and type and temperature (distribution for Ottawa used) was estimated;
- variation in flight frequency and temperature distribution by time of day was allowed for;
- the fluid failure time for particular values of each of these factors and the probability of that combination of factors were estimated, and for each combination:
  - ◊ fluid failure times with each value of the range of possible fluid application/taxi/delay times were compared,
  - ◊ the joint probabilities of that fluid failure time and fluid application/taxi/delay time were summed over values of fluid failure times less than the fluid application/taxi/delay time; and
- the calculations were repeated to determine the frequency that fluid failure times were less than the application/taxi/delay times for the large airport using Types II fluid and Type IV fluid, and for the small airports using Type I fluid (Types II and IV fluids are assumed to be at 100% concentration).

A detailed description of the statistical analysis and derivation of the probability distributions used in this analysis is given in Appendix A.

Taxi/delay time data for Lester B. Pearson International Airport in Toronto and Dorval Airport in Montreal collected in a short study by ARC (14) were used to represent conditions at large busy airports. This data did not include the time to apply the fluid, so allowance of between 3 and 7 minutes, with a mean of 5 minutes, was added to the taxi/delay times to account for final application of the Type II or IV fluid[5].

For small airports, estimates were obtained for two distributions of the total fluid application, taxi and delay times. They have been termed short and long taxi time small airports and are assumed to have the following characteristics:

- Short taxi time airport: average = 5.5 min., SD = 2 min.
- Long taxi time airport: average = 8 min., SD = 2.5 min.

The distributions of application/taxi/delay times used in the analysis for large busy airports and the two types of small airports are shown in Figure 4.1.

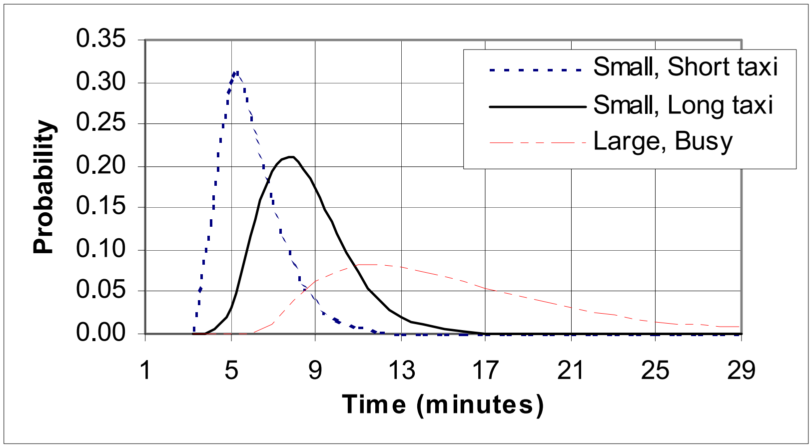

Figure 4.1 Estimated Frequency Distributions of Application/Taxi/Delay Times for Three Airport Types Used in Analysis

HOT tables provide a guide to the protection times that could reasonably be expected in a range of fairly typical weather conditions. At high precipitation rates or with high wind or ice pellets, protection times will be less than the minimum values of the HOT range. Conversely, in many conditions, protection times may be greater than those given in the tables.

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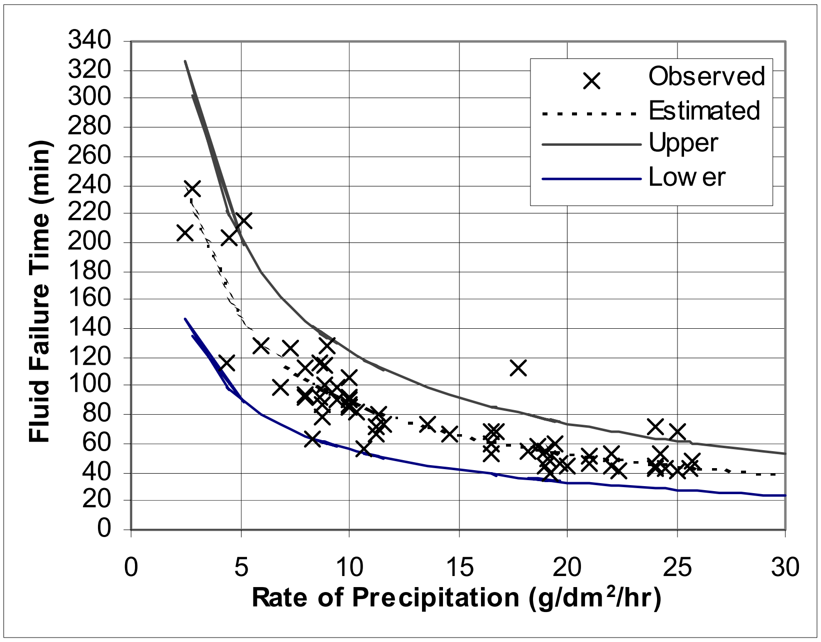
[5] Since the risk analysis is considering the amount of fluid failure on all parts of the wing and this is predicted from the time since application, its is not necessary to use the full application time in the analysis; allowing for communication delays after deicing, about 70% of the application time is likely more appropriate.

Actual test data were used to determine the fluid failure time distributions. The distributions are discussed in detail in Appendix A. An example of the distribution of fluid failure times for Type IV fluid is shown in Figure 4.2. The estimated expected failure time (dotted line) and the 95% confidence interval of the failure time for given precipitation rates are shown in the figure. Actual failure times could fall anywhere around the expected value (dotted line), with the spread in points caused by the effect of other factors (e.g., wind speed, humidity, etc.). This spread in points around the expected value is accounted for when estimating the probability of fluid failure.



[Source: reference (8), Figure 3.4, pp. 28]

Figure 4.2 Observed Fluid Failure Times for Type IV Fluids (100% concentration) for Simulated Freezing Drizzle and Light Freezing Rain from Flat Plate and Airfoil Tests, and the Estimated Expected Values and 95% Confident Interval

The precipitation rate and temperature distribution was derived from hourly weather data for Ottawa Airport obtained from Environment Canada. Precipitation rates, in units of $g/dm^2/hr$, were estimated from this distribution as described in Appendix A. The estimated cumulative distribution of precipitation rates for Ottawa in icing conditions, given that it is precipitating, is given in Figure 4.3. Icing conditions were taken to be when precipitation occurs at temperatures between 0°C and -20°C, or when frozen precipitation occurs at above zero temperatures. From the figure it is evident that precipitation rates are usually low in icing type conditions. For example there is only about a 10% chance that the rate will be greater than 15 $g/dm^2/hr$ in icing type conditions.

Using the joint distributions of precipitation rates and temperatures derived from the Ottawa data and the distributions of fluid failure times for given precipitation rates and temperatures given in Appendix A, the distributions of times to fluid failure for Type I, II and IV fluids (Types II and IV at 100% concentration) were estimated. The three distributions are plotted in Figure 4.4. The non-smooth nature of the curve is due to it being estimated from points with different types of precipitation and ranges of discrete rates of precipitation and temperatures.

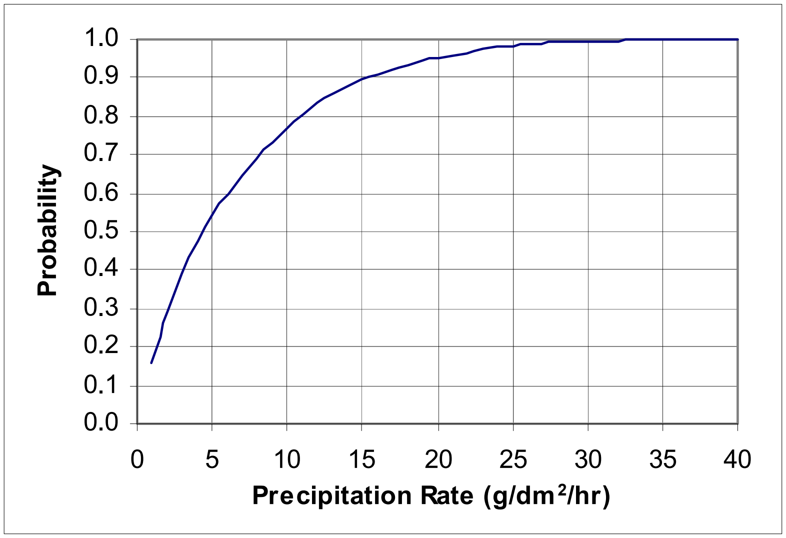


Figure 4.3 Estimated Cumulative Distribution of Precipitation Rates for Ottawa in Icing Conditions

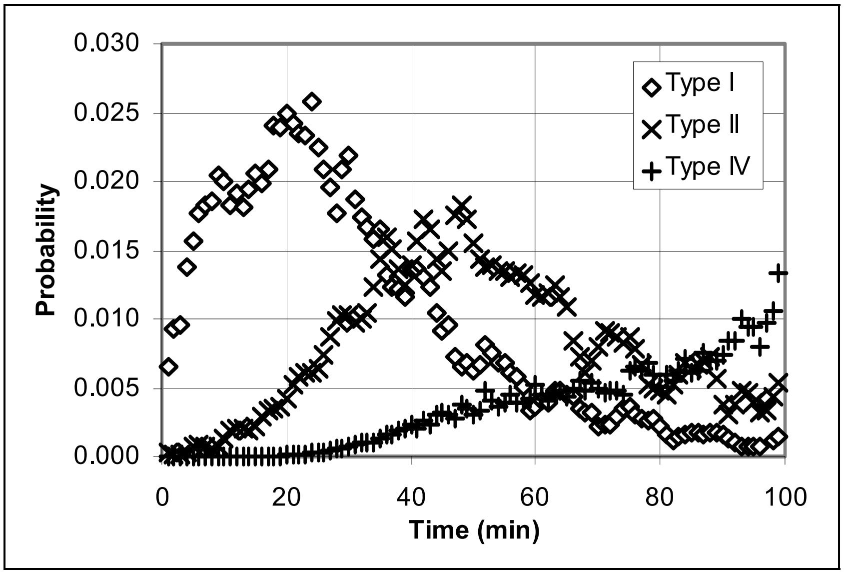


Figure 4.4 Estimated Distributions of Times to Fluid Failure for Type I, II and IV Fluids (Types II and IV at 100% Concentration) for Weather Conditions at Ottawa Airport

Estimated Fluid Failure Probabilities

The probability that the fluid failure time would be less than the fluid application/taxi/delay time was then estimated based on the distributions of application/taxi/delay time and fluid failure time. Considering aircraft deiced during precipitation, the percentages which will suffer fluid failure prior to take-off were estimated to be:

- Large airport Type II fluid 1.2%
- Type IV fluid 0.1%
- Small airport, Type I fluid short taxi time 2.4%
- long taxi time 5.5%

The estimated fluid failure probabilities are consistent with the overall percentage of deiced aircraft to be re-deiced (3.2%) discussed in Section 4.4.1.

The analysis also estimated that if Type I fluid was used exclusively at large airports, the fluid would fail prior to take-off in approximately 14% of cases where the aircraft was deiced during precipitation. This estimate is consistent with the observed frequency of re-deicing using Type I fluid at medium to large airports discussed in Section 4.4.1.

It should be noted that, since these probabilities are applicable to aircraft that have been deiced, they will not differ greatly between airports in milder climates such as Vancouver, and airports with more severe climates such as Ottawa. The probability of fluid failure, given the aircraft has been deiced, may in fact, be greater at Vancouver than Ottawa due to higher precipitation rates when it is snowing. This will be offset by the lower probability of aircraft requiring deicing at Vancouver.

Major Assumptions

The major assumption made in determining these estimates, the reason for the assumption and their likely effects are given below.

- Distributions of fluid application, taxi plus delay times for large and small airports follow those given above.
  - ◊ Reason: lack of better data for a range of airports.
  - ◊ Effect: results not indicative of any particular airport or all airports, but provides an estimate of the likely magnitude of the probability of fluid failures.

- In estimating the percentages of failures for a given fluid type, it is assumed that only that fluid type is used.
  - ◊ Reason: information on expected taxi/delay times at the time of deicing were not recorded, data for Toronto Airport did not include the type of fluid used, and data is not available for small airports.

  - ◊ Effect: provided anti-icing fluids are applied whenever there is significant precipitation, the assumption should have little effect on the estimates. If Type I fluid is used during precipitation, the percentages of fluid failures will be greater.

- Fluid application/taxi/delay times are independent of precipitation rate (given deicing due to recent or current precipitation).
  - ◊ Reason: no data available on the relationship.
  - ◊ Effect: likely leads to underestimation of probability of fluid failure because, when precipitation is heavy, taxi and delay times will likely be longer and fluid failure will likely occur earlier.

- The variation in protection times due to factors other than precipitation rate follows a normal distribution with the mean being the expected value for the given precipitation rate, and variance being proportional to the expected value.
  - ◊ Reason: effect of other factors not well understood, and data on frequency of these factors not readily available and their use would greatly increase complexity of analysis.
  - ◊ Effect: could lead to under- or overestimates if distribution of factors not well represented in HOT test data used to estimate fluid failure time function.

- Protection time distribution for a given fluid type is dependent on the precipitation rate (g/dm^2/hr) but not the precipitation type, except for ice pellets that reduce protection times significantly.
  - ◊ Reason: effect of precipitation type given the rate is small, assumption simplifies analysis, ice pellets known to reduce HOTs but exact amount not known.
  - ◊ Effect: could lead to under or over estimates if distribution of precipitation types not well represented in HOT test data used to estimate fluid failure time function and times are very dependent on precipitation type (for a given precipitation rate).

- Weather data for Ottawa representative of winter weather conditions in Canada.
  - ◊ Reason: detailed data for other airports not readily available.
  - ◊ Effect: results not indicative of airports in general, but since results are for aircraft given they are deiced, frequency of icing conditions in data is not critical. Probability of fluid failure could be underestimated for airports with heavier but less frequent precipitation and less frequent very cold temperatures than Ottawa.

4.4.3 Frequency of Fluid Failure Before and After Pre-Take-off Inspection

The probability that the fluid will fail after the pre-take-off inspection and before take-off is estimated in a similar way to the probability of fluid failure (see Appendix A). The analysis requires the distribution of the time interval between pre-take-off inspection and take-off and its relationship to weather conditions. No data has been collected to estimate this distribution; however, airline ground icing procedures in the US under FAA regulations allow the aircraft to take off provided that the take-off roll can be commenced within 5 minutes of the pre-take-off check. Given this, it was assumed that the time interval would have a mean of 2 minutes and a standard deviation of 1 minute. Due to the lack of data, no relationship with weather conditions was included. The distribution used is shown in Figure 4.5.

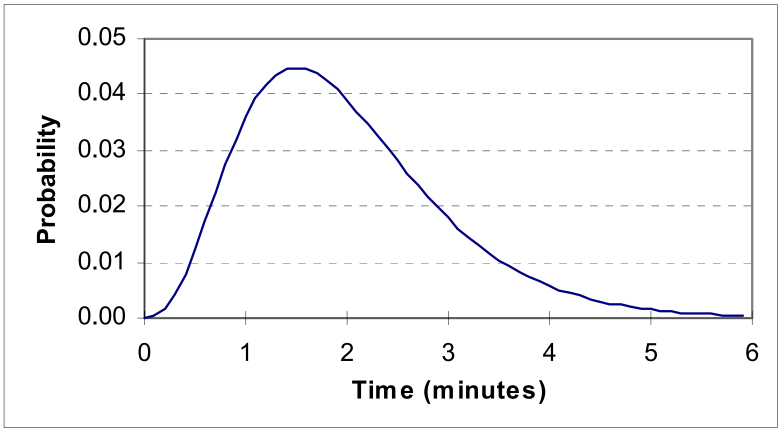


Figure 4.5 Hypothetical Distribution of Time Interval Between Pre-Take-off Inspection and Take-off Used in the Analysis

The probability that the fluid will fail prior to the pre-take-off inspection can be found by subtracting the probability of it failing between the inspection and take-off from the probability of it failing before take-off.

Using the distributions of times between fluid application and take-off and the weather conditions given in Section 4.4.2, the following probabilities of fluid failure prior to the pre-take-off inspection and the probabilities that it fails after the pre-take-off inspection and before take-off, given that it has not failed at the time of pre-take-off inspection, were estimated. The estimates are summarized in Table 4.3.

Table 4.3 Estimated Probabilities of Fluid Failure Prior to the Pre-take-off Inspection and Between this Inspection and Take-off

Airport and Fluid Type			Prior to Pre-TO Inspection	Between Pre-TO Inspection & Take-off
Large airport	Type II fluid		0.83%	0.32%
	Type IV fluid		0.077%	0.036%
Small airport, Type I fluid		short taxi time	0.99%	1.4%
		long taxi time	3.1%	2.3%

The analysis also estimated that if Type I fluid was used exclusively at large airports, the fluid would fail after pre-take-off inspection prior to take-off in approximately 3.6% of cases where the aircraft was deiced during precipitation.

The extent of fluid failure at the time of take-off is examined in Section 8 and the comparative risks are considered in Section 9.

5. SENSORS

Ice detection sensors have been in use on aircraft since the mid-1980s. These sensors were restricted to sensing significant ice buildup at particular locations and were not capable of identifying fluid failure. Their primary use was for identifying clear ice buildup over wing fuel tanks on aircraft with rear mounted engines. Significant work in developing more robust sensors has been carried out in the 1990s. A review of sensors then available and under development was conducted by Bombardier in 1995 (15). Note that a number of the sensors have been further developed and tested since the time of that report. A summary of the roles of sensors provided in that report is given in Table 5.1. The major roles of sensors include determining whether deicing is necessary (i.e., whether ice has developed on the aircraft prior to deicing), verifying the aircraft is clean following deicing, monitoring the state of the fluid until the time of take-off, and monitoring any lift losses during taxiing or the take-off run. This study is primarily concerned with pre-take-off inspection (role 4); sensor capabilities during take-off (role 5) are not considered.

Table 5.1 Summary of the Roles of Sensors

Role	Description of Role and Application
1	**Determination that Ground Icing Exists**
1a	Critical surfaces subject to fuel cooling
1b	Other critical surfaces
2	**Critical Surface Inspection**
3	**Holdover Time Remaining**
3a	Critical surfaces subject to fuel cooling
3b	Other critical surfaces
4	**Pre-take-off or Pre-take-off Contamination Inspection**
4a	Critical surfaces subject to fuel cooling
4b	Other critical surfaces
5	**Contamination or Lift Loss During Take-off**
5a	Contamination on critical surfaces subject to fuel cooling
5b	Contamination on other critical surfaces
5c	Lift loss - stall speed determination

Source: *Ground Icing Sensors*, report by Bombardier Inc., TC report no. TP 12460E, March 1995.

Sensors that detect/measure surface contamination can be divided into two main categories:

- Point or small area sensors; and
- Scanning or mapping sensors, either mounted on aircraft or remote.

These two categories of sensors are discussed in Sections 5.1 and 5.2. The data and performance characteristics for some of the sensors discussed are, as indicated in the reference list, based on brochures and information provided by the companies involved.

5.1 Point Sensors

A number of point ice detection sensors are currently certified and have been used on aircraft to detect clear ice buildup over fuel tanks. These types of sensors have been used on aircraft with rear mounted engines to reduce the risk of built-up ice breaking off and being ingested in the engines. A number of the more recently developed sensors can also detect the presence and failure of de/anti-icing fluid; these include:

- Allied Signals/Instrumar C-FIMS (2), (9), (11), (12), (15), (24), (34), (37)
- Intertechnique - On Ground Ice Detection System (OGIDS) (15), (29)
- Vibro-meter - Clean Wing Alert System (CWAS) (15)

The three sensors are circular with a diameter of about 5 cm (2 inches) and only measure properties of the contaminant over the sensor head. Other properties measured by some of these point sensors include the thickness of the ice, the temperature of the wing surface and an estimate of the remaining protection time. The above systems have been installed on a number of in-service aircraft and have been tested both in-service and in static tests on the ground.

The Rosemount HALO sensor (15), (28) measures properties of the contaminant over a small area of approximately 80 cm (3 feet) long and 10 cm (4 inches) wide. Development of this sensor for detection of fluid failure is presently on hold (38).

Point ice detection sensors are currently used on some aircraft to detect ice buildup on the leading edge both during flight and as part of the pre-flight check. Extension of the system to detect ice or fluid failure on other parts of the wing could be a cost-effective method of introducing a system for use in monitoring the condition of the wing in the post deicing phase.

An area of concern with point sensors is their ability to predict the condition of the entire wing. As stated in a presentation to the SAE G-12 sub-committee (16): “The contamination can be distributed irregularly, e.g., from blowing snow or a wide dispersion of freezing rain droplets. Local spot sensors will not always detect it, unless a significant number are installed.” Point, or small area, sensors must be duplicated and statistically positioned for better coverage and increased reliability. However, installation of a large number of sensors sunk into the wing could affect the structural integrity of the wing. The reliability of using a limited number of sensors to verify the wing is clean is considered in Section 7.

5.2 Scanning/Area Sensors

Scanning/area sensors have an advantage over point sensors in that conditions over a large portion or the whole wing can be assessed. The area sensors are being developed to give flight and ground crews a quick, clear and reliable indication of the presence of ice, snow or frost with and without de/anti-icing fluids and distinguish ice from rain and fluids.

Three companies are currently developing area sensors for scanning critical surfaces; they are:

- RVSI (Robotic Vision System Inc.) - Ice Detector (15), (6), (34), (35), (36), (37)
- Spar Aerospace and Cox and Company - Aircraft Ice Detection System (15), (30), (31), (32)
- NRC Institute for Marine Dynamics - Laser Ice and Fluid Depth Gauge (15)

The more advanced systems give a warning of imminent fluid failure. The systems can detect ice contamination as thin as 0.2 mm and can measure the depth of the ice. The surface being inspected is viewed through a camera or on a computer monitor and areas with ice, snow, and fluid are shown in different colours or colour intensities (31). Laboratory tests indicate that the sensors can identify frozen precipitation (ice, snow, slush) from water, fluids and a range of aircraft surface materials and colours with extremely high reliability.

Area sensors are currently in use at a number of airports for verifying that the aircraft is clean after it has been deiced. The sensors are attached to the bucket of the deicer and operated by the deicing personnel. Use of area sensors for post deicing inspection improves the consistency and reliability of de/anti-icing and thus reduces the risks associated with incomplete removal of ice and/or misapplication of anti-icing fluid. The performance of area sensors in use during the 1996/97 winter was limited by a number of factors including:

- the distance from the surface they are scanning;
- the angle of incidence of the surface being viewed (especially if mounted on aircraft);
- visibility during very heavy snowfall;
- the non-metallic material on the surface being viewed;
- the size of the scanner may preclude use as an aircraft mounted device; and
- difficulty in demonstrating the level of reliability required for certification.

The RVSI sensor has been tested for three years and the sensors have proved to be very reliable (6), (34), (35), (36), (37).

Sensors currently under development have overcome many of the limitations of those now in use. The SPAR sensor system is capable of identifying contamination at distances in excess of 20 m, at low angles of incidence, during heavy snowfall and on aircraft with metallic surfaces. Testing of the system indicates that (30):

- it works well in a range of conditions and can operate through Plexiglas windows;
- inspections can be done very fast (e.g., about 10 seconds for DC10 wing); and
- the system works well in real time.

SPAR's latest prototype system is mounted on a pan-tilt unit in the bucket of the deicing truck and the results are viewed on a computer in the cab of the truck. The system requires good lighting and uses spotlights attached to the camera to work at night.

Use of sensors to assess the condition of the wing during pre-take-off inspection requires the sensors to be either mounted on the aircraft or on a vehicle which could be located near the start of the runway where the pre-take-off inspection takes place. Due to safety and cost considerations, use of a vehicle-mounted system has not been used.

No area sensors have been mounted on an aircraft for use in pre-take-off inspections. Further development and testing are required before area sensors can be used in this way. Spar does not anticipate having aircraft-mounted sensors available for at least several more years. RVSI recently received a contract from the FAA to develop a prototype on-aircraft wide area ice detection system for flight testing. RVSI is undertaking a major upgrade of their system and does not expect to have an aircraft mounted version certified for use for another five years (33).

One concern with area sensors is that they will identify very small and localized amounts of frozen contamination and use of the sensors may result in a large increase in the number of aircraft being re-deiced. The sensor cannot determine whether the frozen contaminants that it detects are actually adhering to the wing and are a threat to safety. Thus, many of the fluid failures it detects may not effect the risk of an accident and re-deicing the aircraft may be unnecessary. Using current visual inspection procedures it is likely that small levels of fluid failure are occurring without the aircraft being re-deiced and these levels appear to have only a minor affect on aerodynamic performance (as discussed in Section 6). The sensitivity of area sensors to low levels of fluid failure is an issue that needs to be addressed before the risks can be evaluated.

Due to the lack of test data and operational experience for the area sensors identifying fluid failure, the risk comparisons concentrated on point sensors. Prototype aircraft-mounted area sensors are likely several years away, thus full evaluation of these systems is not presently possible. The comparative assessment of risks using primarily visual and point sensor based systems can easily be extended to include area scanning sensors. Initial indications are that the scanning sensors will be able to identify the presence of frozen contamination either prior to deicing, or after fluid failure, with high reliability on all surfaces that can be viewed by the camera. Thus, if mounted on the aircraft, the location of the camera and the view of critical surfaces from that location will be important. A good view of the leading edge will be especially important due to the effect of leading edge contamination on performance (see Section 6) and the frequent occurrence of fluid failure in this location. To conduct a comparative risk assessment using area scanning sensors mounted on the aircraft, tests will be required to determine exactly on which areas of the wing the sensor will be able to identify contamination for each of the possible camera locations.

The following types of data are required to conduct a comparative risk analysis for area sensors:

- times of sensor indicated and visually observed fluid failure under a range of conditions in outdoor tests on aircraft;
- degree to which the frozen contaminants are adhering to the wing surface when the sensors identify fluid failure;
- sensitivity of identification of fluid failure to localized or transient failures;
- view of the wing surface from the intended location of the sensor cameras; and
- demonstrated use of system for identifying fluid failure in operational conditions.

5.3 Pilot's Views on Sensors for Identifying Fluid Failure

In the survey of pilots, their views on the safety benefits of sensors for identifying fluid failure were sought. There is widespread acceptance that the use of sensors for identifying fluid failure will improve safety: over one third of pilots responding to the survey feel the sensors will greatly improve safety. Pilots of high wing aircraft are most positive about their benefit to safety and many pilots noted their benefit in conditions with poor visibility. There were, however, many caveats expressed regarding the use of sensors. These include:

- they should be used in conjunction with visual inspection;
- they must be accurate, reliable ("fail safe") with few/no false warnings (previous experience with ice detectors has tempered the enthusiasm of many pilots);
- pilots would need to gain confidence in the sensors before they would trust them; pilots should be able to self test the system;
- they should account for possible variation in location of fluid failure along wing span; and
- they should have a simple display in cockpit.

Pilots who saw little or no benefit in sensors commented that the benefit will depend on the technology; the sensors will likely be too sensitive and they are weary of false alarms. They also commented that reliability will be a problem and unless the sensors are 100% reliable and give few or no false alarms, they will be disregarded by crews. Some pilots are wary of sensors or simply "don't trust them".

Many pilots feel that visual inspection is more reliable than sensors, but in cases where visual inspection is almost impossible (high wing aircraft and poor lighting and visibility), reliable, accurate sensors will offer a real benefit.

6. AERODYNAMIC CONSEQUENCES

6.1 Major Effects

The most predominant adverse effect of ice contamination is on the lifting characteristics of the wing. Small reductions in lift occur at low angles of attack, but large reductions in the maximum attainable lift occur at higher angles of attack resulting in potential risks of the aircraft stalling prematurely. Asymmetric reductions in lift can cause serious stability and control consequences after lift-off. Ice contamination on the critical surfaces also results in increased drag, partly due to the increase in the angle of attack required to obtain the required lift. The increase in weight due to fluid and contamination is small and increases take-off distances and reduces the climb rate. Effects on climb rate or obstacle clearance could be critical if an engine failure occurs.

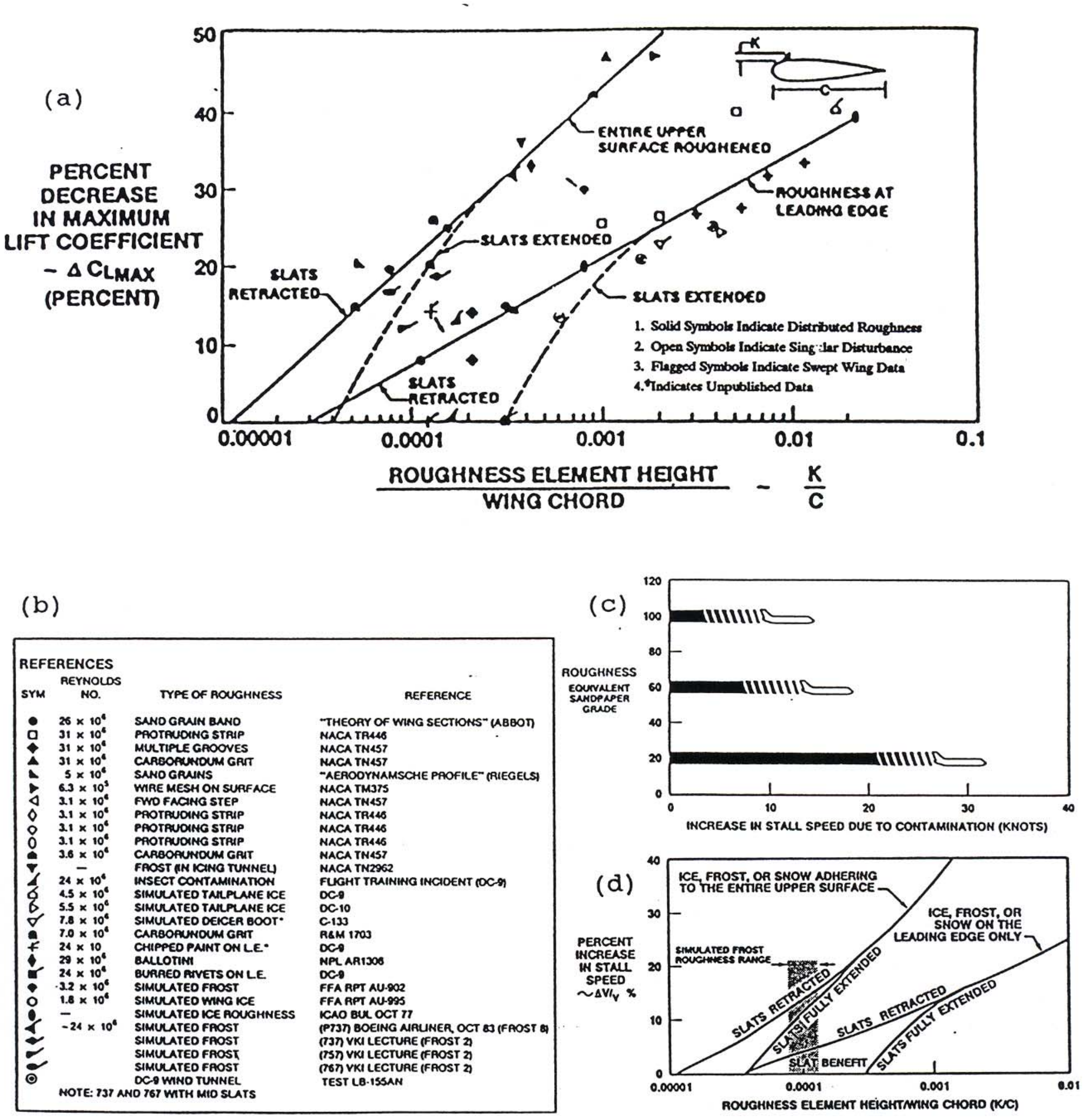
The result of attempting a take-off with some form of ice contamination on the wing can range from little or no significant control problems, to total disaster.

The angle of attack for maximum lift is reduced as much as 4° to 8° by wing contamination. The reduction in the angle of attack at which stall occurs can have important safety implications as the stick shaker and stall warning devices are set relative to the angle of attack at maximum lift for a clean wing. The warning systems may not be activated prior to stalling with a contaminated wing if the stall occurs at a lower angle of attack than that used to set off the warning devices.

6.2 Wind Tunnel Test Results

The effects of wing ice contamination on aerodynamic performance has been the subject of numerous wind tunnel test studies. The tests have shown that the main cause of the worsening in aerodynamic performance is not due to the thickness of the ice, but due to its form and surface condition, or roughness.

The results of many tests to study roughness in general have been consolidated into a single figure (17), sometimes referred to as “the Brumby Curve”, which is shown in Figure 6.1. The effect of roughness on maximum attainable lift is characterized by the ratio of the height of the roughness, K, to the length of the wing chord, C. Thus, larger aircraft are more tolerant to a given level of roughness. The figure includes two main curves, the upper one where the entire wing surface is contaminated, and the lower curve where only the leading edge is contaminated.



REFERENCES

SYM	REYNOLDS NO.	TYPE OF ROUGHNESS	REFERENCE
●	26×10^6	SAND GRAIN BAND	"THEORY OF WING SECTIONS" (ABBOT)
□	31×10^6	PROTRUDING STRIP	NACA TR446
◆	31×10^6	MULTIPLE GROOVES	NACA TN457
▲	31×10^6	CARBORUNDUM GRIT	NACA TN457
◣	5×10^6	SAND GRAINS	"AERODYNAMSCHE PROFILE" (RIEGELS)
▶	6.3×10^5	WIRE MESH ON SURFACE	NACA TM375
◁	3.1×10^6	FWD FACING STEP	NACA TN457
◇	3.1×10^6	PROTRUDING STRIP	NACA TR446
○	3.1×10^6	PROTRUDING STRIP	NACA TR446
0	3.1×10^6	PROTRUDING STRIP	NACA TR446
●	3.6×10^6	CARBORUNDUM GRIT	NACA TN457
▼	—	FROST (IN ICING TUNNEL)	NACA TN2962
◢	24×10^6	INSECT CONTAMINATION	FLIGHT TRAINING INCIDENT (DC-9)
◇	4.5×10^6	SIMULATED TAILPLANE ICE	DC-9
▷	5.5×10^6	SIMULATED TAILPLANE ICE	DC-10
▽	7.8×10^6	SIMULATED DEICER BOOT*	C-133
●	7.0×10^6	CARBORUNDUM GRIT	R&M 1703
+	24×10	CHIPPED PAINT ON L.E.*	DC-9
◆	29×10^6	BALLOTINI	NPL AR1306
■	24×10^6	BURRED RIVETS ON L.E.	DC-9
◆	3.2×10^6	SIMULATED FROST	FFA RPT AU-902
○	1.8×10^6	SIMULATED WING ICE	FFA RPT AU-995
●	—	SIMULATED ICE ROUGHNESS	ICAO BUL OCT 77
▲	$\sim 24 \times 10^6$	SIMULATED FROST	(P737) BOEING AIRLINER, OCT 83 (FROST 8)
◆		SIMULATED FROST	(737) VKI LECTURE (FROST 2)
◣		SIMULATED FROST	(757) VKI LECTURE (FROST 2)
●		SIMULATED FROST	(767) VKI LECTURE (FROST 2)
⊙		DC-9 WIND TUNNEL	TEST LB-155AN

NOTE: 737 AND 767 WITH MID SLATS

[Source: Brumby - reference (17)]

Figure 6.1 Comparison of Effect of Wing Surface Roughness on Maximum Lift and Stall Speed

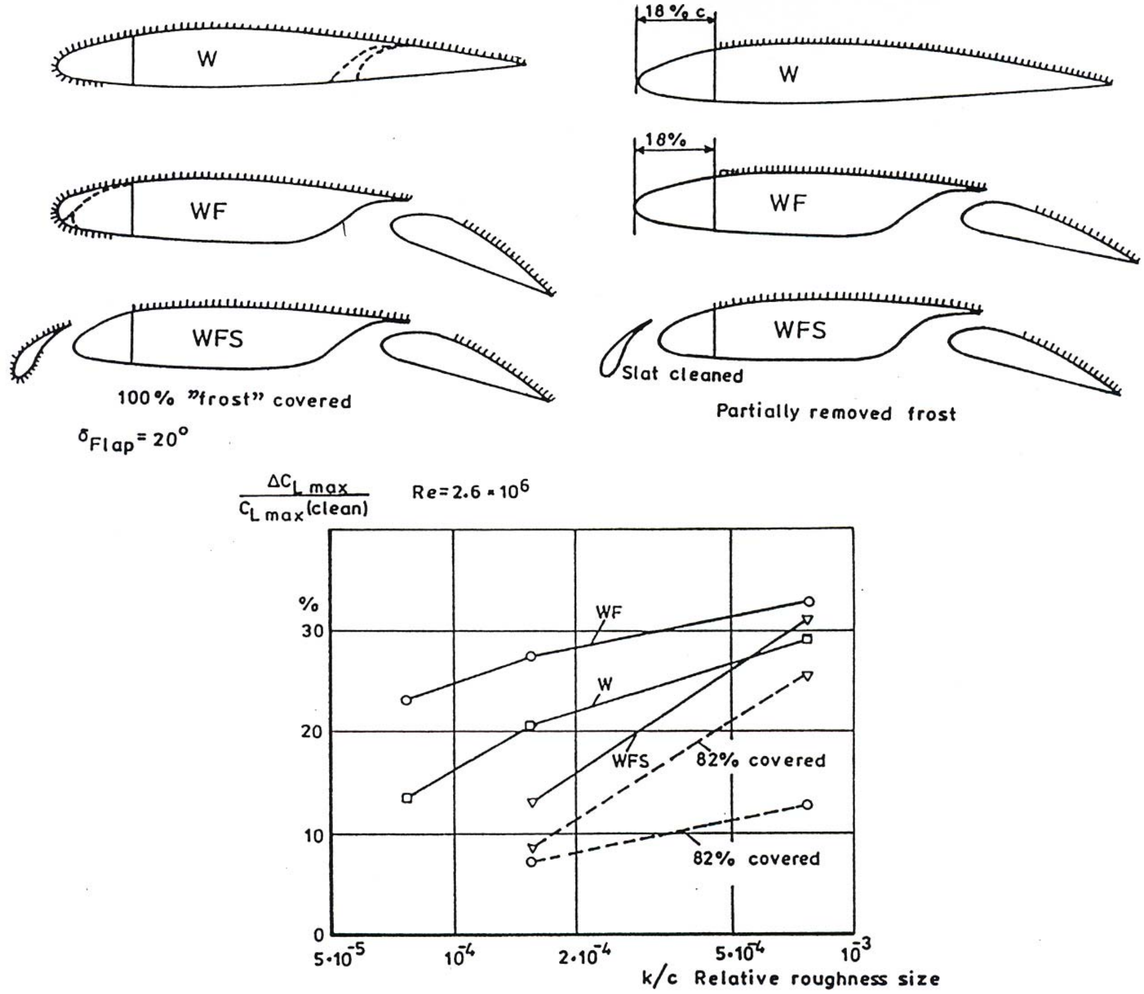
As discussed in Section 7, fluid failure does not occur over the entire wing surface simultaneously; rather, small sections, typically on the leading or trailing edges, fail first. Thus, the decrease in the maximum lift coefficient when various portions of the wing become contaminated is important for determining the risks associated with fluid failure. The analysis by Brumby and others gives some indication of the effects on maximum lift of contamination on only the leading edge.

Figure 6.2 shows the effect of simulated hoar frost on the maximum lift for an NACA 65_2A215 wing section demonstrated in wind tunnel tests (18). The decrease in the maximum lift coefficient is significantly less when only the mid and trailing sections of the wing are contaminated. The decrease is, however, much less for the wing with both flaps and slats.

Boer and van Hengst (19) conducted tests on a 60% span wing section of the Fokker F-28 versions with and without slats. Tests were conducted with three different distributions of roughness. Several tests were conducted with different densities of roughness peaks for roughness distributed over the full wing. The percentage decrease in the maximum lift coefficients varied from 31% to 35% over the four densities with the greatest decrease occurring at the "medium" density.

The National Research Council Canada (NRC) conducted a series of tests on the effects of fluid failure on the lift characteristics of an aerofoil. This data source is important as no other data are available on the effects on lift of actual failed fluid . The open circuit design of the NRC wind tunnel is able to simulate snowfall and freezing drizzle/rain when outdoor temperatures are less than -6°C. The facility can simulate take-off velocity profiles and angle of attack changes of turboprop type aircraft (rotation speeds of 35 m/s reached in 20 seconds). A NASA LS(1)-0417 aerofoil section was used, typical of commuter aircraft. The aerodynamic effects of Types I, II and III fluids on the wing subject to snowfall or freezing drizzle/rain of varying durations were examined. At the time of this analysis, only interim results of the testing were available(20). Several important conclusions of these tests were that:

- "Visual observation of the fluids on the aerofoil undergoing freezing precipitation shows that the fluids fail first near the leading and trailing edges of the aerofoil.
- The visual observation of fluids contaminated by [simulated] snow corresponds well to the onset of significant lift loss. Aerodynamic performance degrades rapidly with additional snow accumulation."



[Source: reference (18)]

Figure 6.2 Effect of Simulated Hoar Frost on the Maximum Lift for an NACA 652A215 Wing Section

Tests were conducted with failed fluid on a number of parts of the airfoil section:

- entire wing surface;
- leading edge section (up to 18% of chord) only;
- back from leading edge (leading edge clean); and
- triangular section about 60 cm wide at edge extending 34 cm (18% of chord) towards the middle of the wing. This represents about 2% of the leading edge section of the wing.

Precise measurements of the height of the roughness were not taken during the NRC tests. However, from photos of the snow contamination taken with a ruler showing the depth, estimates of typical roughness heights were made:

- fluid partially failed < 0.75 mm (3 tests)
- fluid fully failed 0.75 to 1.5 mm (6 tests)

Several extreme cases of fluid failure during snowfall had a roughness height of 2.5 to 3.5 mm. APS analysed photographs of fluid failure during snowfall taken during three tests in their 1997 Winter Testing Program. Their analysis found that the density and height of the peaks varied over the wing depending on the stage of the failure:

- density 115 peaks/in^2 average height 1.0 mm (maximum 1.5 mm)
- density 100 peaks/in^2 average height 0.75 mm (maximum 1.0 mm)
- density 50 peaks/in^2 average height 0.5 mm (maximum 0.75 mm)

Fluid failure during freezing rain/drizzle produced a different form of roughness. The peaks in the roughness were not as sharp, and in many cases were fairly rounded. Initial failure of the fluid can be very smooth. No photographs or measurements of the height of the roughness after freezing rain were made.

The decrease in the maximum lift coefficient estimated by NRC due to contamination on these sections is compared with results from other sources in Table 6.1. In the comparison, a range of roughness heights between 0.75 and 1.5 mm was used. With the entire wing surface contaminated the percentage decrease in the maximum lift coefficient in the NRC tests is a little less than that for the full wing given by the other three sources. The NASA LS(1)-0417 aerofoil used by NRC has a slightly more rounded leading edge than many of the new aerofoils developed for maximizing cruise performance and this property makes it slightly more tolerant to roughness.

The percentage decrease in the maximum lift coefficient with just the leading edge contaminated, at that same K/C ratio, for the NRC tests is similar to the value on the Brumby Curve - 12% compared to 6-16%. However, Boer and van Hengst found the leading edge to be far more sensitive to roughness with decreases in the maximum lift only marginally less than for the full wing contaminated. The percentage reduction in the maximum lift with all <u>but</u> the leading edge contaminated for the NRC test is less than the percentage reduction found by Ljungstrom for an aerofoil with similar flaps and slats (4% compared to 10-13%), but similar to Boer and Hengst. Photographs of the contamination on the middle and trailing edge section indicate that the fluid failure was not uniform and that in some areas the fluid had only partially failed. Ljungstrom's data indicates the decrease in the maximum lift is much greater with all but the leading edge contaminated for wings with slats and flaps, but Boer and Hengst found the percentage reduction to be similar with and without slats. Use of the NRC data to estimate the reductions in the maximum lift coefficient due to contamination of the trailing edge may underestimate the actual lift loss.

Table 6.1 Comparison of the Decrease in the Maximum Lift Coefficient for Various Wing Types and Sections of the Wing Subject to Contamination for Roughness Typical of Fluid Failure During Snowfall

Source	Surface Contaminated	Non-slatted Wing		Slatted Wing	
		% Decrease Range[1]		% Decrease Range[1]	
NRC	Full Wing	28%			
	Not leading edge	4%			
	Leading edge	12%			
	Small Part of LE	5%			
Ljungstrom	Full Wing	31%	33%	23%	31%
	Not leading edge	10%	13%	18%	25%
Boer & van Hengst	Full Wing	35%	38%	28%	32%
	Not leading edge[2]	4%		6%	
	Leading edge[2]	33%		24%	
Brumby	Full Wing	34%	41%	34%	41%
	Leading edge	6%	16%	14%	19%

Notes: 1 K/C ratio 0.0005 to 0.001 based on range of roughness K of 0.75 to 1.5 mm
2 Percentage decrease only available for K/C = 0.0002

Tests on the effect of surface roughness on lift were also conducted by Canadair during the 1996/97 winter. Results from these tests were not available at the time of conducting this analysis, but, if available, the analysis will be updated in Phase II of the project.

NRC measured the lift coefficient for fluids in various stages of fluid failure by repeating the tests for a range of snowfall durations between fluid application and take-off. Figure 6.3 shows the aerofoil's lift coefficient at 15° angle of attack[6] plotted against the snowfall duration for various fluid types. The 15° angle of attack corresponds, approximately, to the maximum lift coefficient. The "A" and "B" in the fluid type refer to "Brand A" and "Brand B". The distance below the horizontal line labeled "Clean" indicates the change in lift due to the contamination. At duration zero, the small reduction in lift at the 15% angle of attack is due to the fluid applied to the wing. This reduction in lift of between 5% and 7% is similar to that found in other studies (21). For small snowfall durations, as the fluid is diluted by the contamination, the lift coefficient increases to almost that of a clean wing[7].

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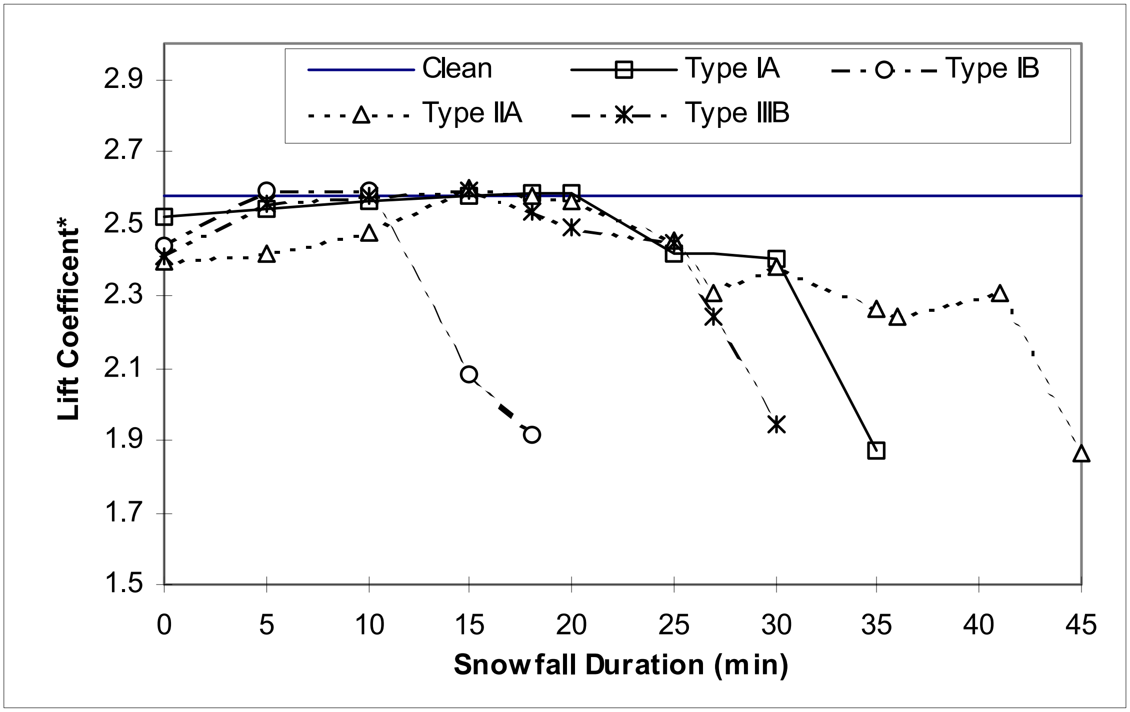
[6] Corresponds to an angle of attack of about 10 deg in a full size wind tunnel.

[7] This effect is very slow for the Type II fluid, taking 18 minutes to be diluted enough to come close to the lift of a clean wing. This poorer performance of the Type II fluid prior to fluid failure is not surprising as Type II fluids are not blown off the wing during the take-off run with low take-off speeds such as those used in the simulation. Due to this property, Type III fluids were developed as anti-icing fluids for commuter aircraft at Figure 6.2 indicates their effect on lift prior to fluid failure is similar to that of Type I fluids.



[Source: Oleskiw and Penna, NRC, 1997)

Figure 6.3 Lift Coefficient Versus Snowfall Duration for Four Fluid Types*

* Lift coefficient at 15% angle of attack and snowfall rate: light to moderate (10 $g/dm^2/hr$)

The large drop in the lift coefficient occurs when the fluid is completely contaminated and the percentage decrease in lift (at the 15° angle of attack) from a clean wing is similar to other contaminated wing tests, as discussed above. Photographs taken of the wing just prior to take-off confirm the failure of the fluid over the entire wing when the large reduction in lift occurs.

Prior to the large reduction in the lift at the 15° angle of attack, there are much smaller reductions for the fluids plotted with protection times of greater than 20 minutes. These small reductions in lift occur from 5 to 15 minutes prior to the large reduction, the latter corresponding to when the full wing is contaminated. One of the observations made by NRC and given in their conclusions was that the fluid failed on the leading and trailing edges of the wing first. Photographs of the wing for shorter snowfall durations indicate the fluid has started to fail, usually near the leading edge, and the surface is not particularly rough. Unfortunately, it is not possible to judge the extent or degree of the failure, or whether the trailing edge has failed from the photos. The small reductions in lift are very likely due to only partial failure of the fluid on only the leading and/or trailing edges, or to properties of initial fluid failure where the viscosity of the fluid is increased and any adhesion of ice to the surface is weak or localized. The initial stages of fluid failure are commonly associated with only small areas of failure and are therefore unlikely to pose a serious risk.

Table 6.2 summarizes the percentage reductions in lift at a 15% angle of attack for the four types of fluid for fluid failure during snowfall. Values are given for fluid failure of the full wing and prior to complete failure. For all but Type IB fluid, the percentage reductions are similar to the reductions in maximum lift with either only the leading edge, or all but the leading edge contaminated in NRC tests (see Table 6.1). For the Type IB fluid, the reduction in lift for the snowfall duration prior to the largest observed lift loss (see Figure 6.3) is only slightly less than that of the maximum (15 compared to 18 minutes) and photographs indicate that the fluid had failed on most or all of the wing by that time. Thus, the reductions in maximum lift associated with partial fluid failure, typically on the leading and trailing edges, appear to be consistent with the reductions in maximum lift with complete fluid failure on particular segments of the wing.

Table 6.2 Reduction in Lift* for Four Fluid Types with Snow Contamination for Fluid Failure of the Full Wing and Range for Partial Wing Fluid Failure

Contamination	Lift Coefficient*			% Reduction in Lift*		
	Full Wing	Partial Wing - Range		Full Wing	Partial Wing - Range	
		Lower	Upper		Lower	Upper
Clean wing	2.58					
Type 1A failed	1.87	2.40	2.50	28%	3%	7%
Type 1B failed	1.90	2.10	2.58	26%	0%	19%
Type IIA failed	1.87	2.25	2.35	28%	9%	13%
Type IIIB failed	1.92	2.40	2.45	26%	5%	7%

* Lift coefficient at 15% angle of attack.

6.3 Risks Associated with Degraded Performance

In order to assess the comparative risks of pre-take-off inspection based primarily on visual observation and on sensor systems, it is necessary to set, at least approximately, the accident risk associated with various levels of wing contamination typical of fluid failure at take-off. Since the major effect of wing contamination is the effect on lift, risks are determined based primarily on the reduction in lift. Where different data sources or approaches could be used, those giving the larger decrease in maximum lift were used so as to be conservative in estimating the risks.

Since the aircraft is assumed to be free of contamination, the risk calculations assume that the crew will use speeds for normal take-off (V_1, V_{LOF} and V_2) and not reduce weight to offset ice contamination effects. During take-off, at the 35-foot screen height the aircraft is supposed to have reached a speed of V_2 , with or without engine failure, and attain a climb gradient of 1.4% to 3.0%, depending on the number of engines. With wing contamination, as the pilot follows the climb out procedure from lift-off to V_2 speed, a number of changes in performance may occur, including (22):

- an aerodynamic buffet,
- a nose-up pitch increase even though the pilot is holding a constant pitch attitude on the artificial horizon,
- the climb rate may have been reduced by an increase in drag, and
- the aircraft may commence roll oscillations.

The interactions between these effects on performance are complex and are not considered here. A simplistic approach is used which captures the essential effects of the contamination on the risk and we believe this approach is sufficient for deriving the measures of comparative risk used in Section 9.

Aircraft take-off performance calculations of take-off weight, speeds, etc., include a safety margin to allow for unforeseen or random effects or incidents. The calculations include a 20% safety margin in the speed which the aircraft reaches by the 35-foot screen height, V_2, to reduce the risk of the aircraft stalling. That is,

$V_2 = 1.2\ V_s$

where V_2 is the speed at the 35-foot screen height, and
V_s is the stall speed.

V_s is determined in straight level flight, but the actual stall speed will occur at a higher speed in a turn or if the rate of climb increases. Two important benefits of this 20% margin are:

- it allows the aircraft to maneuver in emergency situations with virtually no risk of stalling; and
- with $V_2 = 1.2\ V_s$, the maximum lift can be reduced due to contamination of the wing by up to about 30% before there is insufficient lift to cause the aircraft to stall[8].

Thus, the 20% safety margin in speed translates into a safety margin of approximately 30% in the maximum attainable lift. Figure 6.4 illustrates the change in maximum lift with angle of attack and wing contamination. However, if the safety margin is reduced by

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[8] The lift required for the aircraft not to stall must be greater than:

$L_{stall} = c\ C_L\ (V_s)^2$ where C_L is the lift coefficient when aircraft is clean and c is a function of the air density and wing area.

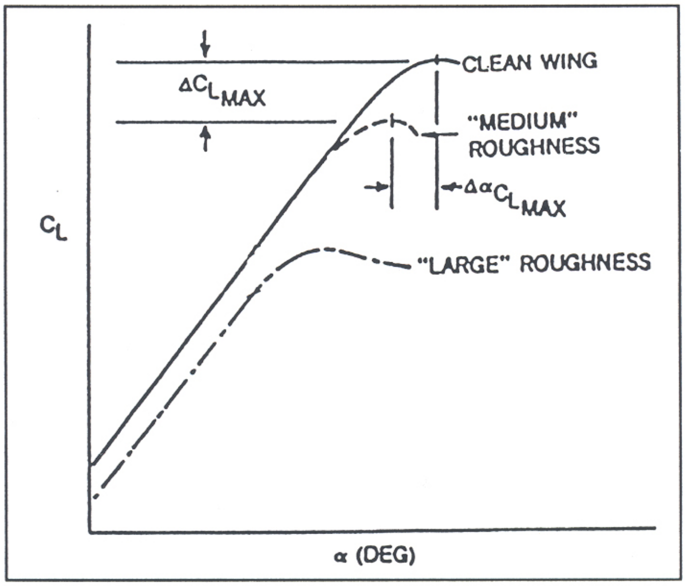
When aircraft is contaminated, the lift coefficient is reduced and the lift is given by:

$L_{contam}\ (v) = c\ C_{Lc}\ V^2$ where C_{Lc} is the lift coefficient when aircraft is contaminated.

To prevent the aircraft stalling at speed V_2 when the aircraft is contaminated, the lift must be greater than L_{stall}, that is: $L_{contam}\ (V_2) > L_{stall}$. Thus,

$c\ C_{Lc}\ V_2^2 > c\ C_L\ (V_s)^2$
$C_{Lc}\ (1.2\ V_s)^2 > C_L\ (V_s)^2$ thus $C_{Lc}/C_L > 1/(1.2)^2 \approx 0.70$

the reduction in lift due to the wing contamination, the aircraft will not be able to maneuver to get out of emergency situations. The effect of the reduced maneuvering capability on the risks was not considered in the analysis.



[Source: Reference (23) Figure 4]

Figure 6.4 Typical Effect of Surface Roughness at the Leading Edge on Aerodynamic Lift

As V_2 is set based on the take-off weight (calculated at the gate) and is attained even if an engine failure occurs (by adjusting the climb gradient), the risk of the aircraft stalling is essentially unaffected by the take-off weight (excluding weight of ice on aircraft which is minimal) or an engine failure. However, the pilot has more options for reducing the risks at low take-off weights and all engines operating.

The 30% safety margin is significant, especially when only part of the wing is contaminated, and could explain why accidents on take-off due to icing are infrequent.

Based on the relationships between reductions in maximum lift and level of contamination given in Section 6.2, approximate values of the probability of the decrease in maximum lift being greater than the 30% safety margin for a given level of contamination were estimated. These estimates are based on limited data, especially for partial wing contamination, and are useful only for determining the comparative risks. Estimates are calculated based on ranges of:

- four aircraft with chord lengths varying from 2.2 to 7.5 m
- five roughness levels (0.5, 1, 1.5, 2 and 3)

The effect of roughness on lift is dependent on the chord length of the wing. Table 6.3 gives the average chord length of common commercial aircraft types in use in Canada. Based on these average chord lengths, the analysis was repeated for the following four chord lengths: 2.2 m, 3.5 m, 6 m and 7.5 m.

Table 6.3 Average Chord Length of Common Commercial Aircraft Types in Use in Canada*

Aircraft	Span (m)	Area (m^2)	Average Chord (m)	Aircraft	Span (m)	Area (m^2)	Average Chord (m)
Metro23	17.37	28.7	1.65	MD80	32.87	115.1	3.50
EMM 202	11.69	19.9	1.71	A320	33.91	122.4	3.61
BAe Jetstrm	18.29	32.6	1.78	B737-600	34.31	125.0	3.64
DHC8-100	25.91	54.4	2.10	B737-300	28.88	105.4	3.65
ATR42	24.57	54.5	2.22	Gulfstream	23.72	88.3	3.72
DHC8-400	28.42	63.1	2.22	B757	38.05	185.3	4.87
F-50	29.00	70.0	2.41	A300-600	44.84	260.0	5.80
DH7	28.35	79.9	2.82	B767	47.57	283.3	5.96
BAe146	26.21	77.3	2.95	A340	60.30	393.1	6.52
F28	25.07	79.0	3.15	MD11	51.66	338.9	6.56
DC9-100	27.25	86.8	3.18	L1011	47.34	320.0	6.76
DC9-20,50	28.47	93.0	3.27	DC10-30,40	50.41	367.7	7.29
F100	28.08	93.5	3.33	DC10-10	47.34	358.7	7.58
				B747-400	64.44		7.85

* Wing span and areas from Janes Aircraft 1996 and 1972

The "Brumby Curves", shown in Figure 6.1, were used to estimate the percentage reduction in maximum lift for a given level of roughness when the entire wing was contaminated and when only the leading edge was contaminated. However, due to the larger reductions in maximum lift with only the leading edge contaminated found by Boer and van Hengst for the F28 wing, estimates for the leading edge contaminated were increased by 4% above the "Brumby curve"[9]. Note that the "Brumby Curves" gave higher estimates of the reduction in maximum lift than that found for failed fluid by NRC. For simplicity it was assumed that the slats are retracted and reduction in maximum lift was therefore over estimated for low roughness levels. The scatter in observed points around the "Brumby Curves" was reflected by assuming the actual reduction in maximum lift is distributed around a mean value estimated from the curve and has a standard deviation of 4%. The standard deviation used is slightly higher than that estimated from the observed points in Figure 6.1. Use of a higher value is

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[9] By increasing the expected percentage lift loss by 4%, the value found by Boer and van Hengst is within 3 standard deviations of the expected value and is therefore a possible, but unlikely value.

conservative in that it leads to a higher probability of exceeding the 30% safety margin when only part of the wing is contaminated.

The probability that the percentage reduction in maximum lift will be greater than the 30% safety margin was estimated for the various chord lengths and roughness levels and are summarized in Table 6.4. The risks are highest for small aircraft with short wing chord lengths as the roughness of the failed fluid is independent of the aircraft type (thus K/C increases as C decreases). The probabilities, although less than one in most cases, represent an intolerable risk due to contamination of the full wing. Similarly, for contamination of the leading edge risks are intolerable for all but possibly very low roughness on large aircraft.

Table 6.4 Estimated Probability that the Decrease in the Maximum Lift Coefficient is Greater Than 30% Safety Margin for the Various Chord Lengths and Roughness Levels

Contamination	Roughness (mm)	Chord Length (m)			
		2.2	3.5	6	7.5
Entire Wing	0.5	0.37	0.08	0.004	0.001
	1	0.90	0.58	0.14	0.057
	1.5	0.99	0.87	0.45	0.26
	2	1.0	0.97	0.71	0.51
	3	1.0	1.0	0.93	0.84
Leading Edge Only	0.5	0.00145	0.00006	0.00000	0.00000
	1	0.0446	0.00529	0.00019	0.00004
	1.5	0.171	0.0353	0.0025	0.0007
	2	0.34	0.101	0.012	0.0036
	3	0.63	0.30	0.06	0.026

The probability of exceeding the 30% safety margin in the reduction in maximum lift is clearly related to the amount and location of the contamination on the wing. Since these are highly variable for fluid failure, it is necessary to relate them to the probabilities of exceeding the 30% safety margin in the maximum lift. To do this, the location and area of fluid failure were combined into a single measure by weighting contamination on different sections of the wing according to their effect on maximum lift. The leading edge section was given a weight of one. Based on defined sections of the wing used in the TDC Winter Testing Program by APS (described in Section 7) and NRC, the leading edge, middle and trailing edge sections were assumed to comprise 16%, 54% and 30% of the total wing area, respectively. Based on the reductions in maximum lift when the middle and trailing edge was contaminated in the tests by NRC and Ljungstrom (4%, 11% and 21%), the weighting factor for each section was set to:

- leading edge section - criticality factor = 1.0
- middle section - criticality factor = 0.2
- trailing edge section - criticality factor = 0.2

With only the leading edge contaminated, the weighted percentage of the wing contaminated is about 16% and this corresponds to a decrease in maximum lift (on average) of about 20%, depending on the roughness. With just the middle and trailing edge sections contaminated, the weighted percentage of the wing contaminated is about 19%. Thus, using this weighting system, the reduction in maximum lift associated with contamination of both the middle and trailing edge sections is assumed to be similar to the reduction with just the leading edge contaminated. This weighting will therefore give reductions in maximum lift closer to the high value found by Ljungstrom for the wing with slats and flaps than the low value found by NRC (see Table 6.1) and may overestimate the reductions in maximum lift for some wing types.

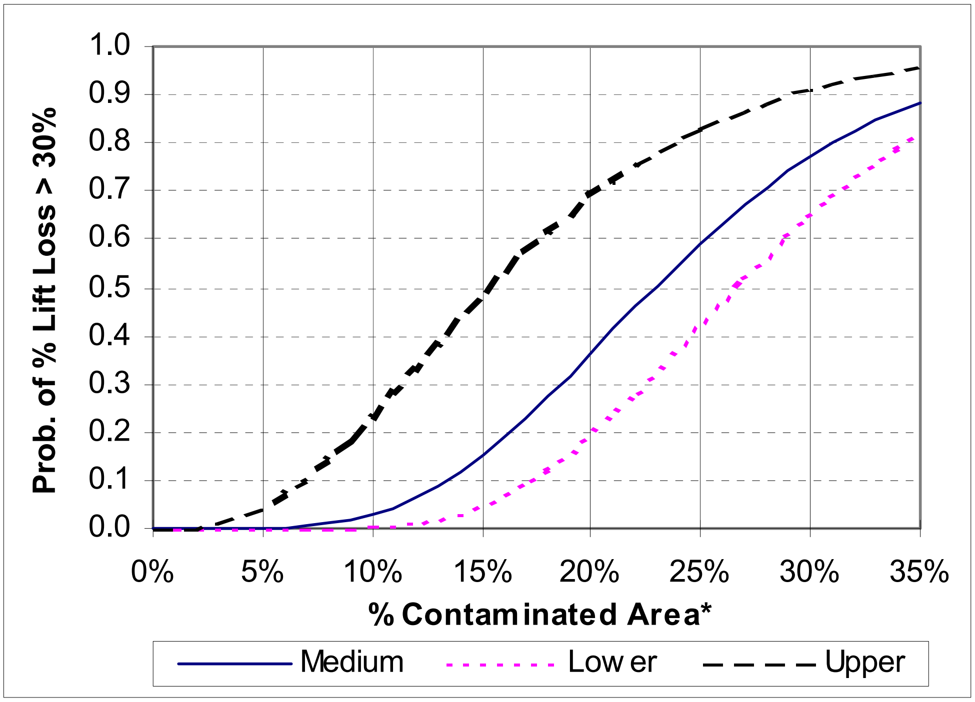
Combining the distribution of aircraft types (chord lengths) and the range of levels of roughness, the probability of the reduction in maximum lift exceeding the 30% safety margin for various percentage areas of the wing contaminated, weighted by criticality factor, was estimated and is shown in Figure 6.5. Due to the high degree of uncertainty in these estimates, low and high values were also estimated to reflect the possible range in values.

As the major factor contributing to accident risk is the reduction in maximum lift, the above probabilities were used for determining a risk measure for comparing sensor and visual based inspection. Other possible factors which could cause an accident, such as increased drag and reduced stability, are correlated with reductions in maximum lift. The overestimate of the variation in the decrease in maximum lift for given levels of contamination, which increases the probability of exceeding the safety margin, should offset the effects of these other factors to some extent.

Also not considered here is the possible activation of the stall warning devices. For small reductions in maximum lift, the stall warning devices would be more likely to kick in prior to the aircraft stalling because the reduction in the angle of attack at maximum lift would also be small. This would further reduce the possibility of an accident for small reductions in maximum lift. However, for reductions in maximum lift close to or greater than the 30% safety margin, the devices are unlikely to warn of approaching stall and would therefore not affect the risks.

The risks shown in Figure 6.5 may be overestimated if pilots are able to increase take-off speeds and reduce the climb rate and angle of incidence under conditions of freezing precipitation. These measures will significantly reduce the risk of the aircraft stalling, but should have little effect on the comparative risks of visual and sensor based inspection.

As the effect on maximum lift is the major factor, the probabilities shown in Figure 6.5 should reflect at least the correct order of magnitude of the risk for given levels of contamination and provide reasonable values for assessing the comparative risks of visual and sensor based inspection.



* Percentage of wing area where fluid has failed, weighted by criticality factor (maximum for wing = 35%)

Figure 6.5 Approximate Probability of the Decrease in the Maximum Lift Being Greater than 30% Versus Percentage of Wing Area Contaminated, Weighted by Criticality

7. IDENTIFICATION OF FLUID FAILURE BY POINT SENSORS

Currently, fluid failure is determined by visually observing the fluid and assessing whether set criteria are met. Point and area sensors have been calibrated to match the visually observed failures. Initial findings from wind tunnel tests conducted by NRC indicate that the point of fluid failure based on the current criteria corresponds closely to the point where aerodynamic performance is significantly affected.

The critical elements that were considered when assessing the identification of fluid failure by point sensors are:

- how well do point sensors identify fluid failure in comparison to visually observed fluid failure at the sensor under ideal conditions;
- how well do point detectors identify fluid failure outside in actual icing conditions, considering the accuracy of visual observations made in those conditions which are used for comparison;
- how does the time of fluid failure vary over the wing in actual conditions;
- how well can a small number of sensors predict fluid failure on any part of the wing; how many detectors are required and where should they be located;
- if fluid failure occurs before the sensors identify fluid failure, how much of the wing is affected, how critical are those areas and to what degree has the fluid failed?
- what is the probability of the sensor system not identifying first fluid failure prior to take-off, and
- how much of the critical area of the wing will be contaminated at the time of take-off if the fluid fails prior to take-off and the sensor system does not identify failure before take-off (what is the probability distribution of this critical area).

These questions are examined in detail in Appendices B and C and are summarized in the sections below.

In the following analysis of sensors, the time of fluid failure visually observed under ideal conditions is taken to be the basis for comparison. However, it is recognized that there is some degree of variation, or error, in this visually observed time, and that this variance/error is greater in less than ideal viewing conditions.

In setting the location of the sensors, this analysis considers the optimal location from the standpoint of the likely areas of fluid failure and the effect on aerodynamic performance of failure in those areas. The practicality of locating sensors in those locations is not considered. If the sensors are located in other positions, the risks associated with fluid failure at take-off will be greater. In this regard, the analysis may overstate the ability of sensors to identify fluid failure. However, this, will be offset to some extent by optimally locating sensors for each aircraft type.

7.1 Comparison of Visually Observed and Sensor Predicted Fluid Failure

The Université du Quebec à Chicoutimi (UQAC) conducted holdover time performance tests with de/anti-icing fluids to evaluate the consistency between visually observed failure times of the fluid on the sensor head and times indicated by the CWDS sensor (24). Data was collected with a sensor mounted on a flat plate inclined at 10° and an airfoil under simulated icing conditions with a range of precipitation rates. Figure 7.1 compares the sensor and visually observed times of fluid failure over the sensor head in flat plate tests conducted in a laboratory. The sensor and visually observed times correlate very well. As shown in Figure 7.2, there appears to be more variation between sensor and visually observed failure times when the sensor mounted is mounted on an airfoil.

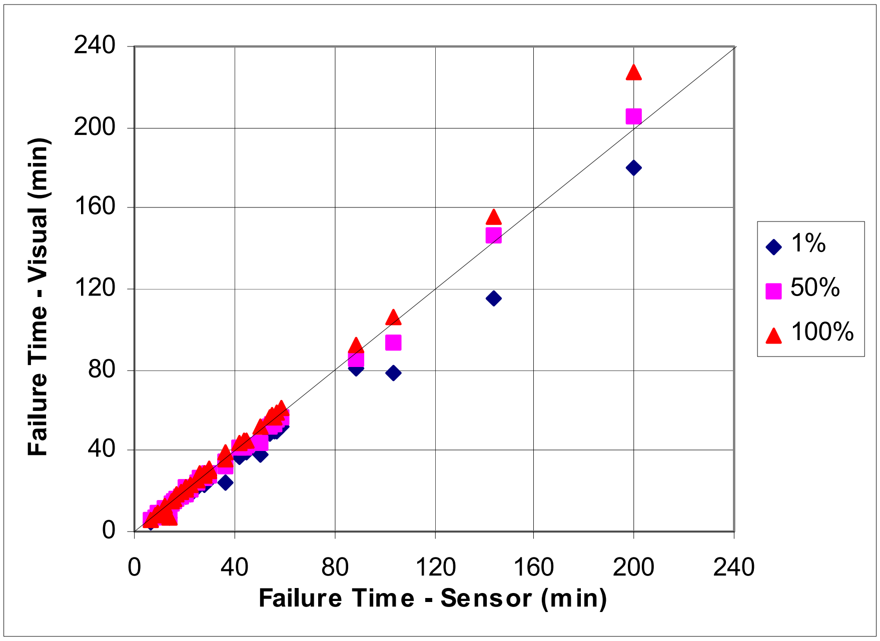


Figure 7.1 **Visually Observed Times to Failure Over 1%, 50% and 100% of the Sensor Head Versus CWDS Failure Time for Sensor Mounted on Flat Plate**

On average the sensor and visually observed fluid failure times are very close, differing by less than 0.3 minutes for the flat plate tests and by 1.3 minutes of the airfoil tests. However, there is a fair degree of variation between the sensor and visually observed times for the airfoil tests. Excluding an "outlyer", the sensor identified failure time was up to 4.0 minutes after the visually observed time on the flat plate tests, while for the airfoil tests, the sensor time was up to 12 minutes after the visually observed time. The outlying point occurred when slush formed on the sensor head prior to the ice front, which travels down the plate, reaching the sensor. The sensor was not activated by the slush formation and indicated ice formation 6.5 minutes after the visually observed failure. From these tests, it can be concluded that the fluid failure times of the CWDS sensor correlate well with visually observed failure on both flat plates and airfoils under ideal viewing conditions. However, even excluding the "outlyer", a safety margin of about 25% is required if the sensor is to reliably identify fluid failure at or before the visually observed failure at a particular point.

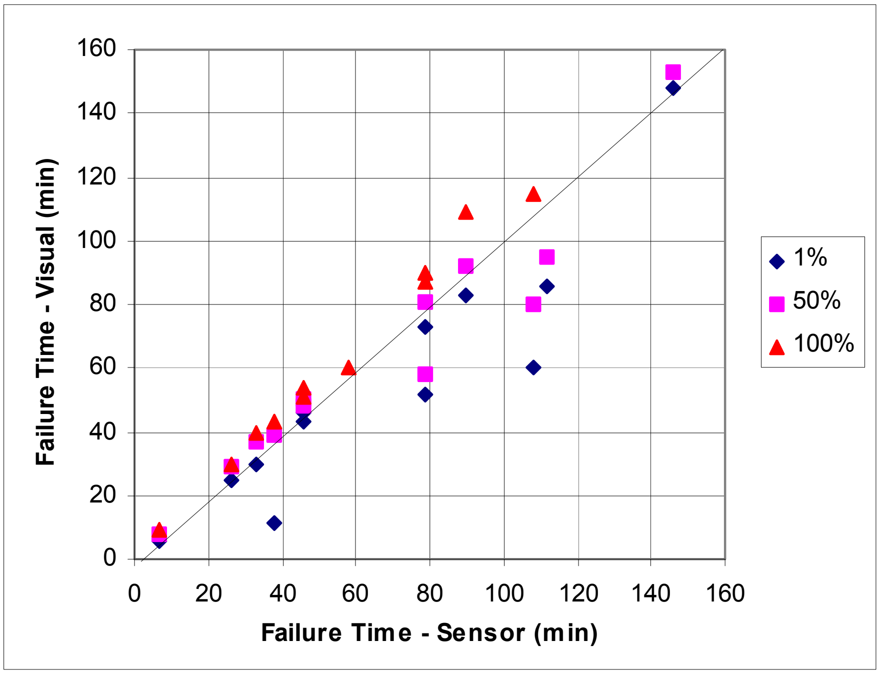


Figure 7.2 Visually Observed Times to Failure Over 1%, 50% and 100% of the Sensor Head Versus CWDS Failure Time for Sensor Mounted on Airfoil

It could be argued, however, that the sensor represents a more consistently accurate method of identifying fluid failure and that the safety margin should be applied to the visually identified failure times. Considered in this way, in 8% of tests first failure was visually identified after the fluid had failed (according to CWDS), and "50% failure" over the sensor head was identified after the fluid had failed in 69% of tests on the airfoil. A safety margin of about 20% would be required to reliably identify failure using visual observation before the sensor identifies failure. This corresponds roughly to the time between first failure and time when 75% of the sensor head was visually observed to fail.

An analysis of the differences between the sensor and visual observed failure times showed no relationship between them and the precipitation rate.

Instrumar conducted a series of tests in 1995 with the CWDS sensor system installed in a BAe 146 aircraft (12). During freezing precipitation (snow and blowing snow) with Type I fluid applied, the conditions of the leading and trailing edges of the inner and outer sections of each wing and the horizontal stabilizer were observed. Sensors were located near the wing tips and tail tips on both sides of the aircraft, however, the left tail sensor was out of service during the tests. Times when the fluid was visually observed to fail over the sensor head were also recorded and the corresponding outputs from the CWDS were recorded. The six sets of sensor and visually observed failure times at the sensor head varied significantly from each other and showed no consistent trends. Given the reasonable consistency in sensor and visually observed failure under ideal conditions in the UQAC tests, the lack of agreement between the sensor and visually observed failure times is likely indicative of the difficulty in visually assessing fluid failure on an aircraft in actual conditions. Other data collected by APS using the C/FIMS sensor in controlled conditions (37) confirm the accuracy of the point sensor in identifying fluid failure over the sensor.

Comparisons of the time the fluid was visually observed to fail on various parts of the wing or tail and the corresponding times the sensor identified fluid fail on that wing or tail using the Instrumar data (12) indicate that a single sensor located in the wing (or tail) cannot reliably predict when the fluid will fail in that wing (or tail). Despite the lack of agreement between sensor and visually observed failure in the same area, the use of three sensors (one on each wing and one on the right horizontal stabilizer) was effective in predicting the time of first visually identified fluid failure. In the three tests, the minimum sensor fluid failure time was similar to, or slightly less than, the visually identified time of first failure on the aircraft. Three tests are too few to base any conclusions on, but this indicates that reliability can be greatly increased by increasing the number of sensors.

7.2 Analysis of Fluid Thickness on Aircraft Wing

A primary influence on the time of failure of the protective fluid is the thickness of the fluid. Analysis of fluid thickness can therefore provide an indication of the likely distribution of early fluid failures over the wing and the most effective locations for locating sensors. Wing temperature is also an important determinant for fluids with short protection times, such as Type I fluids. For these fluids, fluid thickness and the amount of heat absorbed into the wing surface are the primary influences on the failure times.

Tests were conducted by APS on the Canadair RJ, DC-9 and A320 in early 1996 (25). For each of these aircraft, particular points on the leading edge consistently had thinner fluid than most other locations on the wing examined. In these tests, the leading edge on the inner side of the wing typically had the thinnest fluid. The fluid was consistently thinnest at the steepest part of the leading edge; this was true for all three aircraft and each cord tested. The further back from the leading edge in the leading edge wing sections, the thicker the fluid. From a practical standpoint, it is acknowledged that it may not be possible to locate sensors near the steepest part of the leading edge and locating the sensors back from the edge will likely increase the risks of take-off with wing contamination.

In the middle wing sections, there is more variation in locations of the thinnest fluid. Locations towards the trailing edge side of the middle section, on average, have thinner fluid than other locations along the cord, but this was not consistent. On the trailing edge wing sections, the locations of the thinnest fluid vary greatly along the wing span and between aircraft types due to the different flap configurations. Even at the points where, on average, the fluid is thinnest, depths at many other points in that section are sometimes thinner in particular tests. Thus, optimal sensor locations in the trailing edge wing sections are dependent on the aircraft type, and even on aircraft of the same type, fluid failures on the trailing edge do not consistently occur first at the same locations.

7.3 Analysis of Progression of Fluid Failure on Aircraft Wing

The variation in the locations of fluid failure on the wing and the number of sensors that would be required to provide an adequate margin of safety was investigated by considering the patterns of fluid failure observed during 37 holdover time field trials. It is assumed that the point sensors will accurately identify failure of the fluid in close proximity to the sensor. The main considerations in the analysis were:

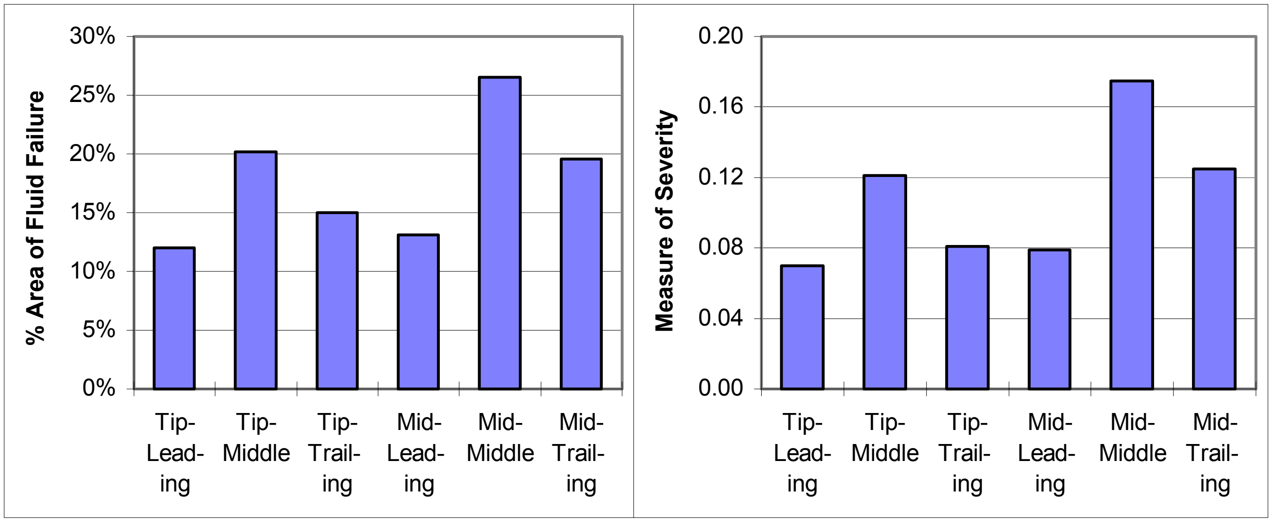
- at what time does the fluid fail on the very small area of the wing in close proximity of the sensor;
- at that time, over what areas of the wing had the fluid already failed, and how critical were those areas for safe flight; and
- in those areas of the wing where the fluid had already failed, for how long has the fluid been in the failed condition (measured by the average time since the fluid failed).

The procedure used to determine the likely extent of icing prior to fluid failure at the sensor is described in Appendix B. Fluid failure progression data was only available from 37 tests, including tests on a DC9, A320, B737, F28 and a BAe 146. Due to the small number of tests, the analysis was done using data on all aircraft types together. The data indicates that fluid failure progression may vary by aircraft type and the analysis should be repeated by aircraft type when sufficient data becomes available. **Use of data on all aircraft types combined will lead to conservative estimates of the risks** as optimizing the location of sensors for each aircraft type will increase the likelihood of early identification of fluid failure.

Results were initially calculated for use of a single sensor to warn of fluid failure using the following two measures of the severity of fluid failure over the whole wing at the time the sensor identifies fluid failure:

- the average percentage wing area with fluid failure, weighted by the criticality of failure in that location, and
- the average percentage weighted by both criticality and the duration of the fluid failure at the time the sensor identifies the failure.

Ideally, a perfect sensor system would give values of zero for these two measures. Figure 7.3 shows these two measures for six possible sensor locations. The leading edge near the wing tip appears to be the best location, based on these tests, especially taking into account the duration of failure. However, with a sensor in this location, on average 13% of the wing, weighted by the criticality factor (33% un-weighted) was contaminated at the time of failure at the sensor. For each of the sensor locations examined, the worst case of the 37 tests corresponded to almost all the wing being contaminated when the sensor indicated fluid failure. From these tests it is clear that the location of the sensor is important and that a significant warning period prior to failure at a sensor would be required to provide adequate safety using a single detector.



(a) Severity Measure: Percentage of Fluid Failure of Area*

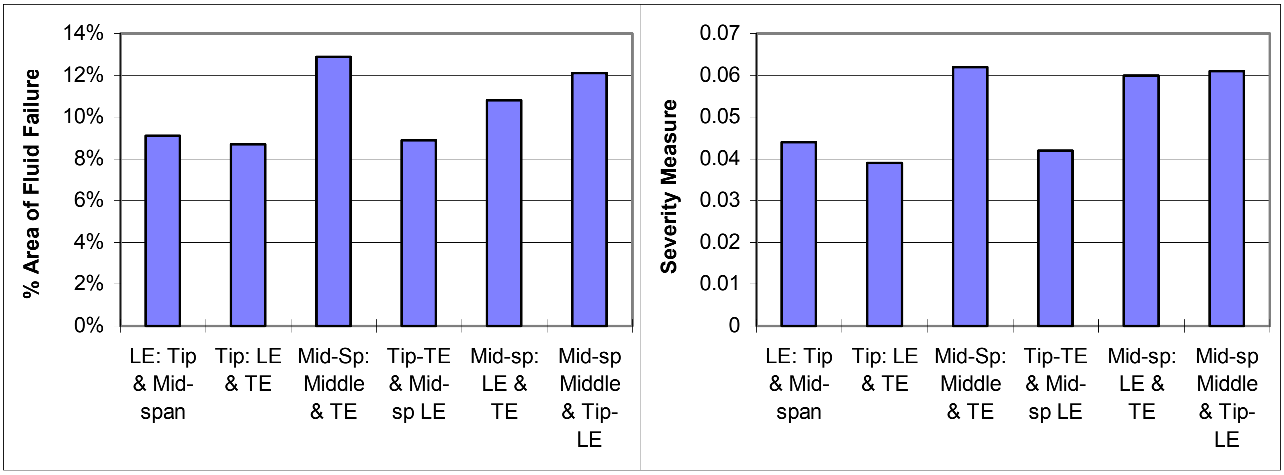
(b) Severity Measure: Percentage Area* Fluid Failure Weighted by Duration of Failure

Figure 7.3 Severity of Fluid Failure at Time of Sensor Identifying Failure for Six Sensor Locations - Single Sensor on Wing

* percentage area weighted by criticality factor

The effectiveness of locating sensors on specified representative surfaces was also investigated. A sensor located on either of the two representative surfaces for which data was collected gave significantly worse identification of critical conditions than the other locations.

The analysis was repeated for sensors at two locations on the wing and the results are summarized in Figure 7.4. The earliest time of fluid failure indicated by the two sensors was used for identifying fluid failure. With two sensors per wing, the best locations for the sensors are near the wing tip on the trailing edge and on the leading edge either near the wing tip or mid-span, or with the two sensors on the leading edge near the wing tip and mid-span. In these locations the fluid will have failed, on average, on 9% of the wing, weighted by the criticality factor (23% un-weighted), at the time the sensors would detect failure. The average time that any part of the failed fluid would have been in a failed state prior to the sensor identifying fluid failure is 5 minutes over all tests, and is less than 13 minutes in all but one test. In this test, Type IV fluid was used and the sensors would have detected failure 25 minutes after failure on the other sections. However, only a small area of the wing area failed prior to, or at the time the sensor would have identified fluid failure in that test.



(a) Severity Measure: Percentage of Fluid Failure of Area*

(b) Severity Measure: Percentage Area* Fluid Failure Weighted by Duration of Failure

Figure 7.4 Severity of Fluid Failure at Time of Sensor Identifying Failure for Six Sensor Locations - - Two Sensors per Wing

* percentage area weighted by criticality factor

Use of more sensors would increase the chance of the sensor system identifying fluid failure at the time of first failure on the wing. However, current applications of point sensors have used only one or two sensors per wing.

7.4 Contamination Levels at Take-off Using Sensor Based Inspection Only

Following the chain of events given in Figure 1.3, the following events could lead to an accident using a sensor based clean wing inspection system:

- fluid fails before take-off;
- sensor system fails to identify fluid failure prior to take-off; and
- sufficient contamination builds up on the wings to cause lift loss, increased drag and handling problems which result in the aircraft being unable to fly.

The probabilities of the latter two events are addressed in the analysis below. The first event, fluid failure prior to take-off, is common in the chain of events leading to an accident for both the visual and sensor based procedures for pre-take-off inspection. Estimates of the probability that a fluid fails prior to take-off found in Section 4.4 were:

- between 1% and 3% based on the frequency of times that HOTs are exceeded and aircraft are re-deiced; and
- 1.2% at large, busy airports using Type II fluid, 0.1% using Type IV fluid, and 2.4% to 5.5% at smaller airports, based on the distribution of delays times and the distribution of fluid failure times for departures.

It is assumed that the aircraft will be unable to fly if the contamination on either wing, not both, is beyond a threshold. This assumption is made because accident/incident data suggests that serious controllability problems can occur when the contamination is uneven on the two wings.

The analysis estimates the likelihood of a four point sensor system (two on each wing) not identifying fluid failure prior to take-off and the amount of contamination on the wing at take-off. The system is assumed to identify fluid failure at the time any one of the four sensors identifies the fluid as failed. No warning of imminent failure of the fluid is included in this analysis, although the approach could be extended to analyse this. It is assumed that:

- sensors are located on the leading edge near the wing tip and mid-span (Sections 2L and 4L), an alternative location on the leading and trailing edges near the wing tip (Sections 2L and 2T) was also analysed - example of wing sections for B737 is shown in Figure 7.5;
- sensors are placed in the location of most frequent fluid failure in those two areas; and
- sensors will accurately identify the failure fluid directly above the sensor.

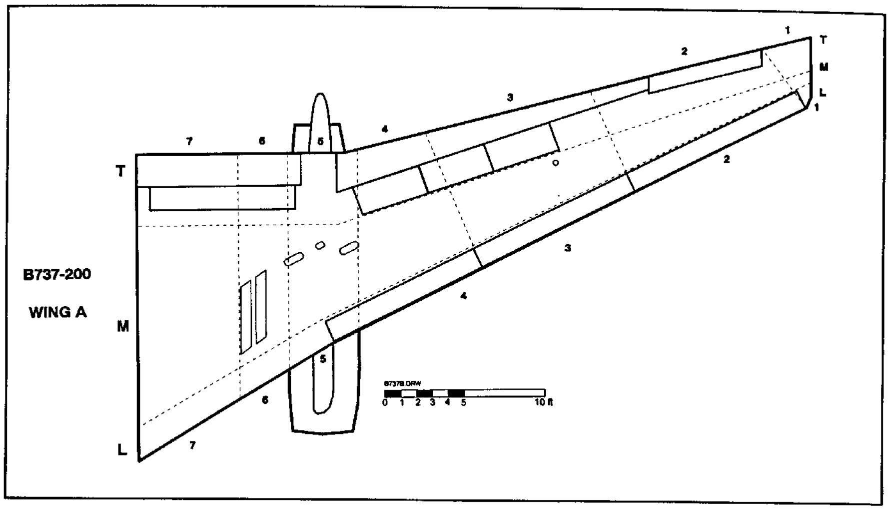
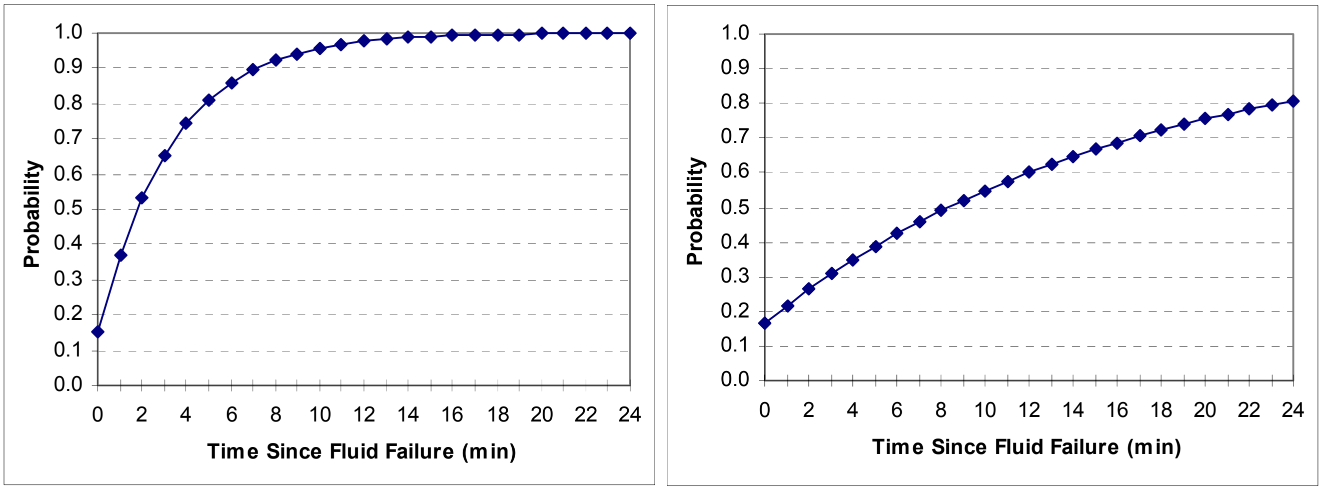


Figure 7.5. Diagram of B737 Wing with Wing Sections Marked

7.4.1 Failure to Identify Fluid Failure Prior to Take-off

Contamination of the wing caused by fluid failure rarely occurs simultaneously over the entire upper wing surface. Fluid failure usually occurs first in small areas near the leading and trailing edges and the actual locations depend on weather conditions, uniformity of fluid application and the aircraft type. The probability of the sensor system identifying the fluid failure within a given time since first fluid failure on the wing is shown in Figure 7.6. On a single wing, the sensor system will detect the fluid failure at the time of failure (within one minute) in about 15% of cases for Type I fluid and 17% for Type IV. In these cases, there is no risk of an accident associated with the fluid failure. Where the system does not detect the initial failure (i.e., time 1 or more on graph), there is a risk of an accident due to take-off with failed fluid, depending on the time of take-off. Figure 7.6 indicates that this risk drops quickly for Type I fluid as the time since first fluid failure increases.



(a) Type I Fluid **(b) Type IV Fluid**

Figure 7.6 Estimated Probability of Sensor System Identifying Fluid Failure by a Given Time Since First Fluid Failure on the Wing - 2 Sensor System (2L, 4L) on Single Wing

The mean time between fluid failure and take-off was estimated in Appendix A to be 3 minutes for Type I fluid and 5.2 minutes for Type IV fluid. From Figure 7.6 (considering only a single wing), at these average times the probability that the sensor system identifies a fluid that has failed prior to take-off is 0.65 for Type I fluid and 0.40 for Type IV fluid. The probability of identifying the failed fluid on either wing prior to take-off was found to be slighting higher when considering both wings. Allowing for the distribution of take-off times after a fluid failure, the probability of the sensor system *not* detecting the failure prior to take-off, given it fails prior to take-off, is estimated to be:

	Sensors at 2L & 2T	Sensors at 2L & 4L
• For Type I fluid:	0.36	0.41
• For Type IV fluid:	0.53	0.53

Thus, if the fluid fails prior to take-off, the 4 sensor system would only identify the failure prior to take-off in a little under two of three take-offs when Type I fluid is used and roughly half the take-offs if Type IV is used. The probability of not identifying the failure is greater for Type IV fluids because the failure spreads more rapidly with Type I, thus leading to a greater chance of the fluid over the sensor head failing prior to take-off with Type I fluid.

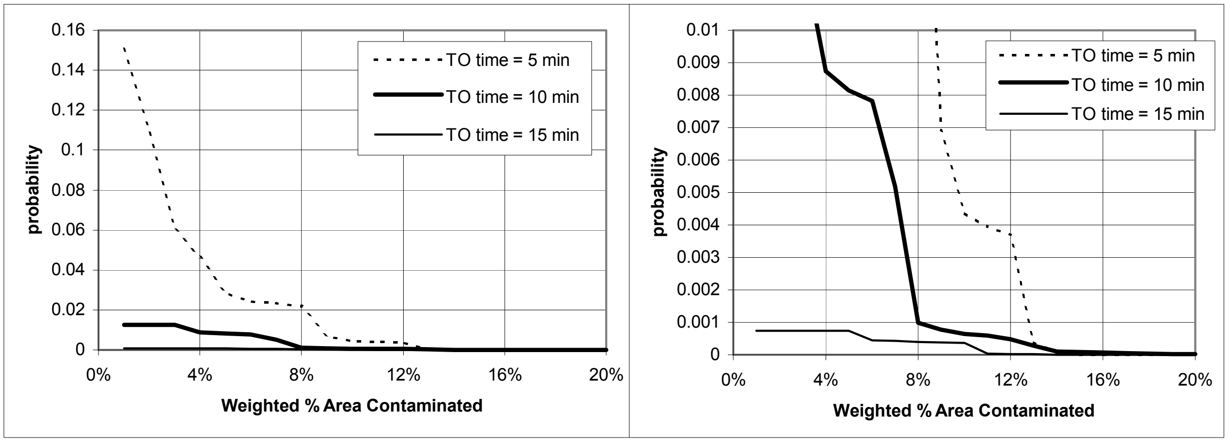
When considering risks, however, the extent and location of the fluid failure at take-off in cases where the sensor system does not identify the failure are critical.

7.4.2 Contamination of Wing at Take-off

As discussed in Section 6, failed fluid on a small section of the wing does not necessarily mean the aircraft will crash on take-off. The tolerance to contamination is dependent on the amount of roughness, the location of the contamination and the proportion of the wing that is contaminated. It is also dependent on the size and type of wing, which varies by aircraft type. The wing area contamination estimates are based on data from DC9, B737, F-100, BAe 146 and A320 aircraft. Performance degradation effects are based on a range of aerofoils and types of roughness as discussed in Section 6.

The extent and location of fluid failure at take-off, given the fluid fails prior to take-off, are very dependent on the time that the sensor would have detected the failure and the time interval between fluid failure and take-off. Using the methodology described in Appendix C, the probabilities of the percentage areas contaminated, weighted by their criticality, and the sensor system not identifying the failure prior to take-off, were estimated for a range of times of take-off. Estimates are shown in Figure 7.7 for the two leading edge sensors per wing system (2L and 4L) and Type I fluid. The discontinuities in this, and other, distributions are due to the use of limited data and discrete intervals in the analysis, rather than a property of the relationships being modelled.

As expected, probabilities decrease as the area contaminated increases for a given time of take-off after fluid failure. Similarly, the probabilities of a particular area being contaminated also decrease as the time of take-off increases due to the greater chance of the sensor system identifying the fluid failure prior to take-off. The leading edge section comprises between 10% and 20% of the area, weighted by the criticality factor, depending on the wing section definitions used in the field trials. The probabilities of areas of this order of magnitude being contaminated and the sensor not identifying the failure prior to take-off are less than 0.005 for Type I fluid. Thus, although the sensor system may not identify a third of the fluid failures prior to take-off, it is very unlikely that it will fail to detect a fluid failure where a significant critical area is contaminated.



(a) Showing full range of probabilities **(b) Blow-up for probabilities less than 0.01**

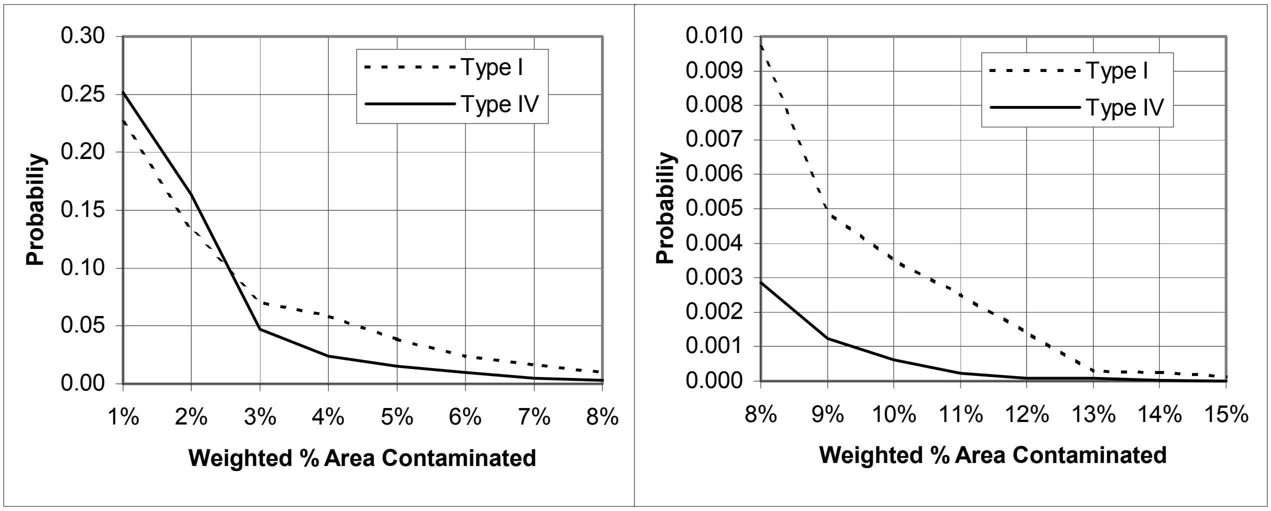
Figure 7.7 Estimated Probabilities of the Percentage Area Contaminated, Weighted by Criticality and Sensor System Not Identifying Fluid Failure Prior to Take-off, for Times of Take-off After Fluid Failure of 5, 10 and 15 minutes - 2 Sensors per Wing System (2L and 4L)

Using this distribution and allowing for the distribution of take-off times after fluid failure, the probability that more than a given percentage area, weighted by criticality, would be contaminated at the time of take-off was estimated. The probabilities for a range of critical areas contaminated are shown in Figure 7.8. Using the four point sensor system, the probability of take-off with the leading edge section, or equivalent area, contaminated <u>given the fluid failed prior to take-off</u>, is of the order of one in three hundred.

Major Assumptions

The major assumptions made in determining these estimates and the reasons for these assumptions and their likely effects are given below.

- Risks for a complete aircraft with a sensor system which also includes sensors mounted in the tail are assumed to be similar to risks for a system with two sensors on each wing considering only the consequences of lift loss due to contamination on wings.
    - ◊ Reason: No data available on fluid failure progression on tail sections
    - ◊ Effect: Effect is likely to be small given the difference in risks found between modelling one wing and both wings.



(a) For Weighted % areas of 1% to 8% **(b) For Weighted % areas of 8% to15%**

Figure 7.8 Estimated Probability of Take-off with More than Various Percentage Areas of Fluid Failure, Weighted by Criticality, Given Fluid Failure Prior to Take-off - 2 Sensor per Wing System (2L and 4L)

- Sensor will accurately identify fluid failure when the fluid over the sensor head fails.
  - ◊ Reason: data indicates that this is likely true, but the visual method of identifying fluid failure used for comparison does not appear to give consistently accurate failure times at sensor head in actual conditions.
  - ◊ Effect: may lead to over- or underestimates of the risks - effect likely small

- The test data used effectively represents the variation in the progression of fluid failure on aircraft wings.
  - ◊ Reason: no other data was available at the time of the analysis.
  - ◊ Effect: may lead to under- or overestimates of risks; the effect of small sample size was included in the estimated distribution of area contaminated at the time the sensor system identifies failure.

- Fluid failure progression patterns are similar over different aircraft types.
  - ◊ Reason: too little data available for individual aircraft types to conduct analyses separately for each aircraft type.
  - ◊ Effect: likely leads to overestimates of the risks as optimal sensor locations could be specified for each aircraft type. However, risks for some aircraft may be greater.

- The criticality factors of 1.0 for leading edge sections and 0.2 for middle and trailing edge sections reflect how critical contamination in each area is to safe flight.
  - ◊ Reason: Need to make distinction between how critical each area is to aerodynamic performance.

  - ◊ Effect: could change the choice for locating sensors and will affect the percentage of wing area with failed fluid, weighted by criticality and, thus, the estimated risks.

- If fluid fails prior to take-off, the average time of take-off after fluid failure has an exponential distribution with a mean of 3 minutes for Type 1 fluids and 5 minutes for anti-icing fluids.
  - ◊ Reason: Lack of data available for estimating a distribution, although estimates of 3 and 5 minutes were found from weather, application/taxi/delay time and protection time data for Types I and IV fluids, respectively.
  - ◊ Effect: not great as estimated risks are not highly sensitive to the mean value, especially if accident risks are low when less than 8% of the wing area, weighted by criticality, is contaminated.

7.5 Point Sensor Evaluation on Operational Aircraft

Little data has been collected on the reliability of sensors systems at identifying fluid failure on aircraft during normal flight operations. The Allied Signal/Instrumar point sensor system C/FIMS (previously CWDS) has been evaluated in two trials:

- a four sensor system (one on each wing and tail flap) was installed on a BAe 146 aircraft operated by Air Atlantic (12); and
- a two sensor system (one on each wing) was installed on an F-100 aircraft operated by Midway Airlines (11).

Air Atlantic BAe 146 Aircraft Evaluation

As discussed in Section 4.4.3, Instrumar conducted an evaluation of a CWDS system of four sensors (one on each wing and one on each tail) on a BAe 146 aircraft operated by Air Atlantic. Data was recorded for 312 flight legs, deicing was considered on 43 occasions and was deemed necessary on 20 of those occasions. The aircraft was re-deiced after one of these 20 deicings. Some of the results of the tests were:

- The CWDS system indicated “snow or ice” on the wing at the time of take-off on two of the 292 cases where deicing was not carried out, and on 23 occasions indicated other than “clean”. Thus, on 8.5% of take-offs the CWDS system indicated the wing was contaminated when the pilot’s inspection found no deicing was required.

- five detailed time plots of sensor reading when the aircraft was deiced were analysed and showed that:
  - ◊ the CWDS sensors indicated that deicing was required three times;
  - ◊ the sensors indicated that the fluid had failed prior to take-off on three occasions, the times to fluid failure were 7 & 10 minutes during freezing drizzle and 14 minutes during snowfall;

Thus, there were inconsistencies between the visual and sensor data, but there was no way of knowing for sure if the fluid had failed or not at the time of take-off. Visual inspections were carried out by the pilots, but, being a high wing aircraft, they did not have a good view of the upper surface of the wing. Thus, the data does not provide information on the accuracy of the sensor system at identifying fluid failure prior to take-off. However, the three fluid failures identified by the sensor system are likely correct given that the higher times in the HOT ranges were exceeded.

Midway F-100 Aircraft Evaluation

The F-100 evaluation had the advantage that tactile inspections were required during the pre-flight inspection, thus allowing an accurate assessment of the condition of the wing for comparison with the sensor outputs. However, the tactile inspections were not conducted during the pre-take-off contamination inspection where fluid failure is assessed.

In the Midway tests, the evaluation found that:

- The sensor system accurately predicted when deicing was required in all 15 occasions when the FAA Airworthiness Directive required that a tactile check be done. The good accuracy in these conditions indicates the high reliability of the sensor system at predicting the condition of the wing near the sensor. This high reliability is an important assumption in Sections 7.4.1 and 7.4.2 in determining the risks.

- In the 9 departures where the aircraft was deiced[10]:
    - ◊ The sensor system indicated fluid failure for the one departure where the aircraft had to be re-deiced. However, a single event provides little evidence about the reliability of the system[11].
    - ◊ The sensor system indicated fluid failure during one departure where the aircraft was not re-deiced. The actual condition is not known as no tactile inspection was conducted just prior to take-off, but the take-off proceeded without incident. Thus, either the sensor system incorrectly identified fluid failure, or the amount of contamination was insufficient to significantly affect the aircraft's take-off performance.

The infrequency of aircraft requiring re-deicing, thus fluid failing, means that the accuracy of the sensor system at identifying fluid failure prior to take-off cannot be determined with any certainty using operational data.

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[10] Includes eight deicing applications recorded in the engineer flight data collection and one deicing in pilot data set. Another from pilot data set was excluded due to C/FIMS operating improperly.

[11] The 95% confidence interval for the probability of identifying fluid failure prior to take-off, given the fluid has failed, based on this one case is [0.05 , 1.0]).

8. IDENTIFICATION OF FLUID FAILURE BY PILOT

8.1 Factors Affecting Visual Identification

The importance of factors affecting the visual assessment of fluid failure was investigated using the pilot survey. Pilot views were mixed on whether identification of fluid failure was easier for some fluid types than others. The pilots indicating that the type did make a difference often thought that the colours of the fluids helped. Many have had little experience with any but Type I fluid.

Pilots were asked to rate the importance of various factors on a scale of one to five. The average rating for each factor is shown in Figure 8.1. Lighting was identified as the most important factor affecting their assessment of the condition of the wing. The direction of external lighting and the availability of only wing or emergency exit lighting were the main two factors. These were followed by de/anti-icing fluid on the windows and the option to open the door on high wing aircraft or cockpit window. As shown in Table 8.1, the ranking of these factors did not vary greatly across categories of aircraft. Other factors included wing span, day/night, precipitation, wind/blowing snow, high/low wing, foaming of fluid and colour of wing.

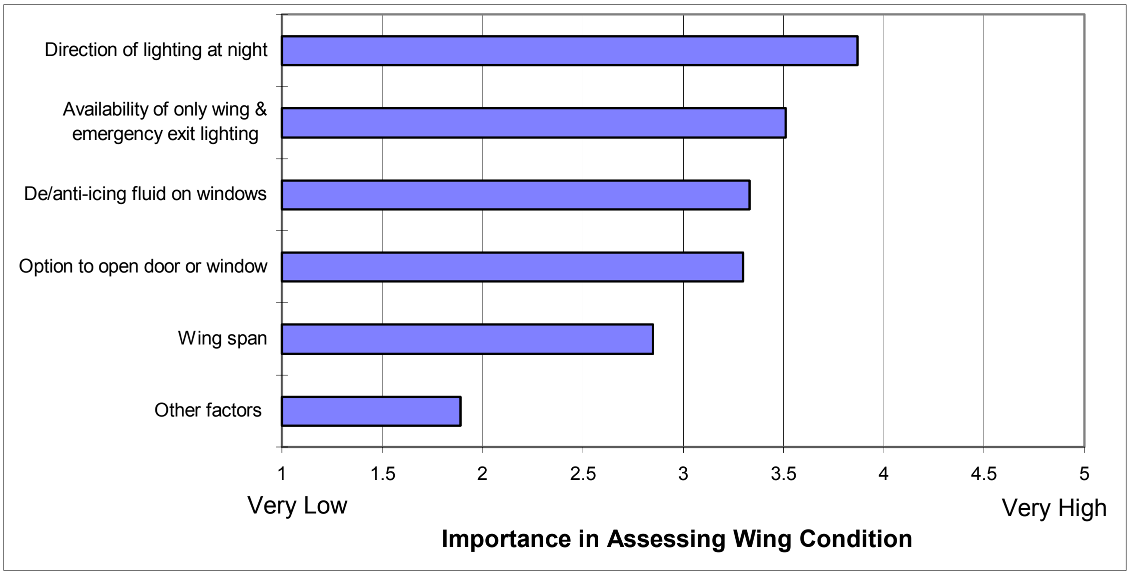

Figure 8.1 Average Rating on Scale 1 - 5 of Importance of Various Factors on Pilots' Assessment of the Condition of the Wing

Table 8.1 Average Ranking of Factors Across Categories of Aircraft and Number of Responses Used in Calculating Average

Type of aircraft you currently fly	Importance to ID FF - wing span	Importance to ID FF - avail. of only wing & emergency exit lights	Importance to ID FF - direction of lighting at night	Importance to ID FF - de/anti-icing fluid on windows	Importance to ID FF - option to open door or window	Importance to ID FF - other factors
Twin Turboprop High Wing	2.49	3.11	3.75	3.04	3.18	4.04
	114	112	114	114	114	45
Twin Turboprop Low Wing	3.06	3.53	3.94	3.06	3.53	3.50
	17	17	17	17	17	6
Twin Turbofan - Max 70 pax	3.14	3.57	3.84	3.50	4.05	3.86
	74	72	74	72	73	22
Twin Turbofan - Max 150 pax	2.81	3.66	3.92	3.46	3.32	3.90
	248	245	249	249	236	80
Twin Turbofan - Over 150 pax	2.94	3.67	3.92	3.54	2.98	3.69
	100	102	101	98	94	26
Three Turbofans	3.00	3.11	3.67	2.78	3.97	3.36
	30	28	27	27	29	14
Four Turbofans High Wing	3.20	3.47	4.00	2.73	3.38	4.20
	15	15	16	15	16	5
Four Turbofans Low Wing	2.93	3.47	3.88	3.22	2.65	3.16
	60	60	60	60	60	25
Total	2.85	3.51	3.87	3.33	3.30	3.79
	661	655	662	656	643	225

8.2 Accuracy and "When in doubt…."

8.2.1 Pilot's Confidence in Assessment of Fluid Failure

In the pilot survey, pilots were asked to rate their confidence in their assessment of fluid failure under various conditions on scale 1 - 5. Figure 8.2 shows the average ratings and also shows their confidence in the reliability of HOTs and identifying clear ice over fuel tanks. Most pilots (87%) have medium to high confidence that they can identify fluid failure during snowfall in daylight, irrespective of whether the snowfall is light or heavy. However, in freezing drizzle only 65% of pilots are as confident. Pilots were not as sure what to look for when identifying fluid failure during freezing drizzle and almost all agreed that the assessment was easier in snowfall. The majority have low or very low confidence in the accuracy of their assessment at night, especially with no external lighting and in freezing rain. For comparative purposes, confidence in their identifying clear ice over fuel tanks is higher than for identifying fluid failure at night in freezing rain.

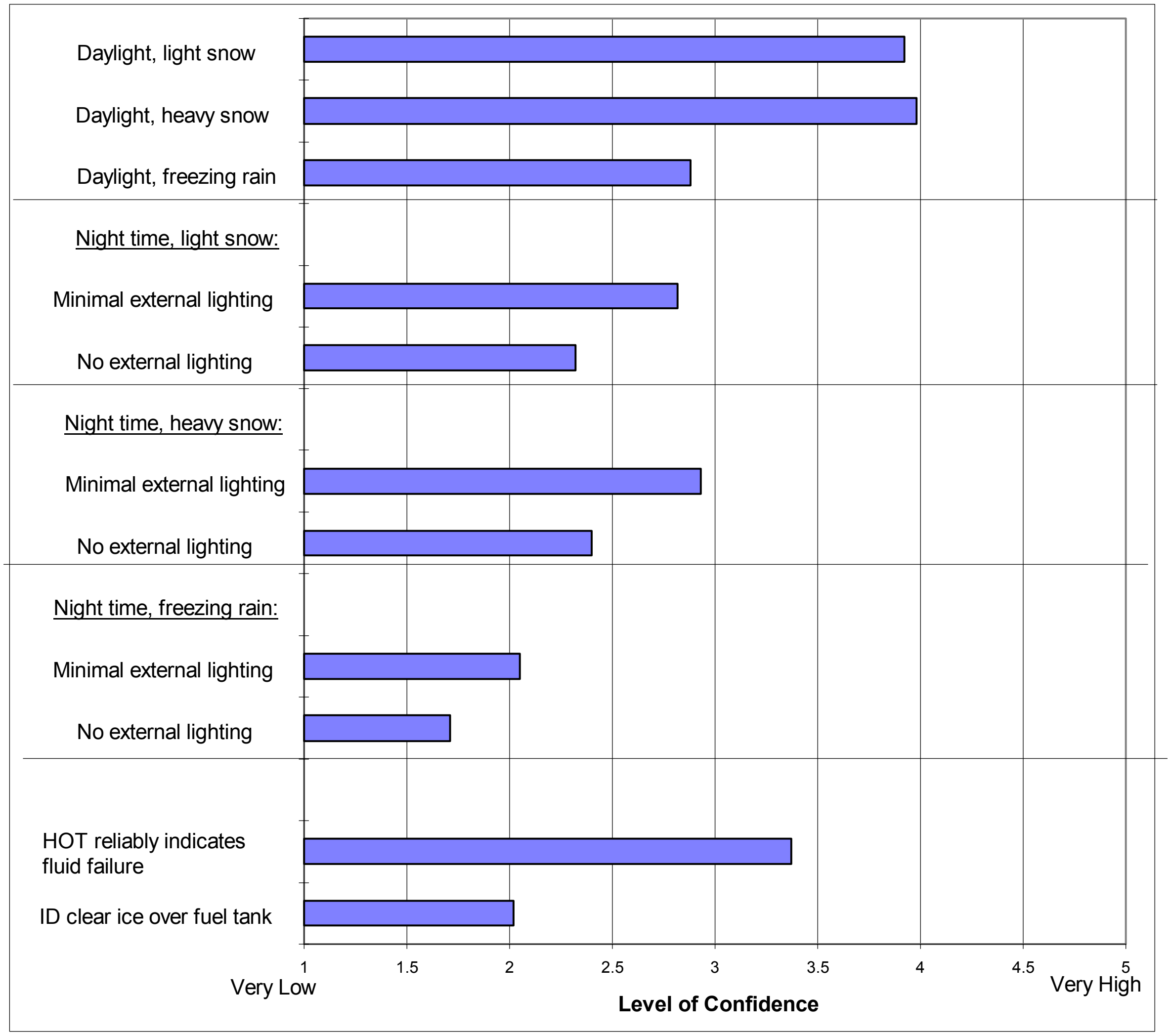

Figure 8.2 **Average Rating (on Scale 1 - 5) of Pilots' Confidence in Their Assessment of Fluid Failure Under Various Conditions and Confidence in the Reliability of HOTs and Identifying Clear Ice Over Fuel Tanks**

There is a strong reliance on the HOTs when deciding on the need to re-deice the aircraft, especially in poor visibility and/or in freezing rain/drizzle. Most pilots (82%) have medium to high confidence that the HOTs reliably indicate the earliest the fluid could fail. Given the low confidence in the accuracy of their assessment in poor visibility and/or in freezing rain/drizzle and their reliance on the HOTs, it is imperative that they understand the limitations of the HOTs, and the importance of consistent fluid application and the post-deice check on these conditions.

8.2.2 Tests With Assessment Made From Inside Cabin

Tests were conducted by APS (6) where fluid failure was assessed simultaneously from within the cabin and outside close to the wing. Eleven tests were conducted with a commercial pilot or trained observer in the aircraft cabin, nine on DC-9s, two on B737s. Type I XL54 fluid was used in seven tests and three other fluids used in the other four tests. All tests were conducted at night under good external lighting. Fluid failure times were identified by the inside observer and were compared with failure times determined using the standard method, i.e., outside observers positioned in optimal locations for observing fluid failure and equipped with flash lights (in addition to the flood lights). Both the inside and outside observers indicated when the first failure occurred and when 10% and 25% of the wing had failed. Sensor readings were not taken during these tests. The results are summarized in Table 8.2. Tests were conducted during snowfalls at rates varying from 2 to 21 g/dm^2/hr. The tests were not specifically designed to represent the conditions a pilot would experience during the pre-take-off inspection. The major differences were:

- very good external lighting of the wings in all tests;
- after the first test, fluid was cleaned off the windows;
- the wing was inspected continuously, not at specific time; and
- no passengers were present, thus allowing the observer easy access to the windows.

Table 8.2 Comparison of Failure Times Identified by Inside and Outside Observers

Test	HOT	1st Failure Time			10% Failure Time			25% Failure Time		
	(min)	Outside	Inside	% Diff.	Outside	Inside	% Diff.	Outside	Inside	% Diff.
L1	6-15	9	10	11%	12	12	0%	14	15	7%
L2	6-15	8			10	12	20%	12	21	75%
L3	15-60	9			12	17	42%	15	20	33%
L4	6-15	14	19	36%	23	21	-9%	25	22	-12%
L5	6-15	8	17	113%	12	18	50%	16	21	31%
L6	35-75	30	25	-17%	50	35	-30%	58	45	-22%
L7	15-60	20	24	20%	24	32	33%	48	45	-6%
L8	6-15	8	5	-38%	11	14	27%	13	16	23%
L9	6-15	10	8	-20%	12	12	0%	13		
Z1	6-15	8			10	11	10%	17		
Z2	6-15	12			24	50	108%	70		
Average % difference				15%			23%			16%
Standard dev. % difference				50%			37%			31%
Longest late identification error				113%			108%			75%
Longest early identification error				-38%			-30%			-22%

Test Z2 is unusual in that a Type I fluid was used and due to the relatively high temperature (+2°C) and low snowfall rate (2 g/dm^2/hr), the fluid failed well past the maximum of the HOT range and the inside observer had difficulty identifying the time of fluid failure. The results of the tests indicate that:

- The cabin observer usually observed the fluid as failing after the outside observed failure - 70% to 80% of the tests for each level of fluid failure.
- On average for 10% of wing failed, the cabin observer identified failure:
    - ◊ 3.1 minutes after outside observed failure, range was from 15 minutes before to 26 minutes after, the median being 2 minutes after; or expressed in percentage terms;
    - ◊ 23% later than the outside observed failure time, range was from 33% before to 108% after outside observed failure time.

In many cases it was noted that the observer completely missed a fluid failure patch when it occurred on the far half of the wing. Contributing factors identified by the observer were:

- glare and bad lighting;
- distance to aircraft wing - simply to far away;
- use of video camera with zoom not effective, partly due to precipitation; and
- representative surface tended to fail later (70% of tests) than other areas. This is despite a raised patch within representative surface on DC-9 which causes fluid thinning.

There is significant variation between tests with the inside observer identifying failure anywhere between the time of first failure (even prior to that) and the time of 25% failure of the wing.

The probability distribution of the amount of the wing with fluid failure at the time fluid failure is first identified by the inside observer was estimated, assuming that the outside observers correctly identified the failure progression. In several cases the inside observer indicated the fluid had failed before the it had actually failed, according to the outside observer, and these cases were excluded when determining the probability distribution. However, as it is not known for sure whether these cases were in fact errors, the distribution is also determined including these cases. The simplistic assumption is made that between the first and 10% failure times, the percentage failed increased linearly with time, and similarly between the 10% and 25% failure times. Also, in the four tests where times were only recorded by the inside observer when 10% of the wing had failed, the time when they would have identified first failure was estimated from their 10% failure time[12]. The cumulative probability distribution of the percentage of the wing

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[12] In the seven tests where both first and 10% failure times identified by the inside observer was given, the first failure was 26% prior to the 10% failure time. First failure times were therefore estimated by 0.76 x (10% failure time).

contaminated at the time fluid failure was first identified by the inside observer is shown in Figure 8.3 based on the seven tests for which full data are available, and on all 11 tests with and without the premature failure observations. Based on all tests, when the pilot first observes fluid failure, there is estimated to be:

- a 30% chance that there is no fluid failure, or first failure has just occurred (within the last minute),
- between a 45% and 60% chance that less than 5% of the fluid on the wing has failed;
- between a 60% and 70% chance that less than 10% has failed; and
- about a 90% chance that less than 20% has failed.

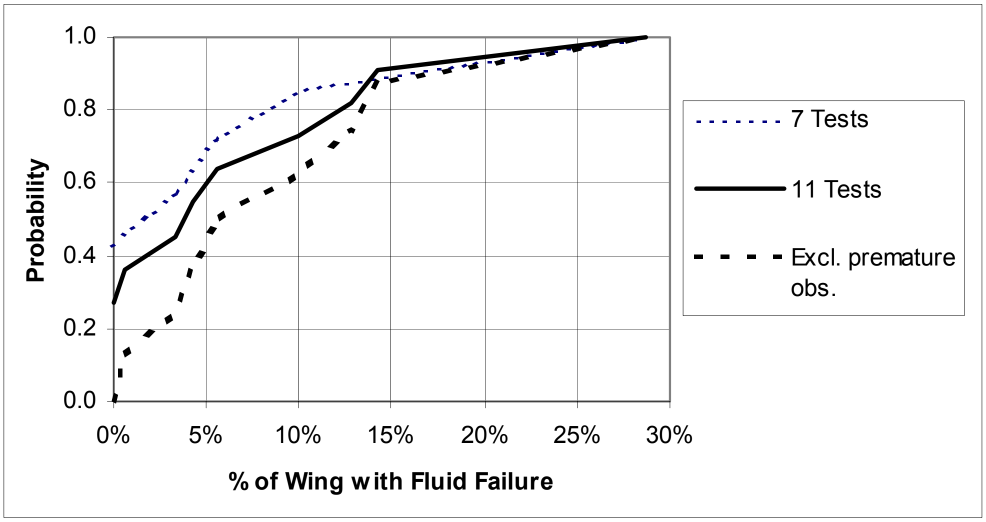

Figure 8.3 **Cumulative Probability Distribution of the Percentage of the Wing Contaminated at the Time Fluid Failure is First Identified by the Inside Observer**

As mentioned previously, the tests on which this distribution are based were conducted under very favourable conditions - very good external lighting, clean windows, no passengers in seats over windows and during snowfall (identification is more difficult during freezing drizzle). This probability distribution was therefore assumed to represent the distribution under "very good" viewing conditions.

The expected (average) percentage of the wing to have fluid failure at the time the pilot identified fluid failure is estimated to be about 8%. The relatively high proportion of the wing contaminated at the time the inside observer identifies the first fluid failure is indicative of the difficulty in assessing fluid failure from inside the cabin of the aircraft, even under very good viewing conditions

Due to the small number of tests, estimates of the amount of the wing contaminated shown in Figure 8.3 are only approximate. For example, based on the 11 tests there is estimated to be a 60% probability that less than 5% of the wing will be contaminated when the pilot first identifies fluid failure, but the 95% confidence interval for this probability is 30% to 90%. Thus, more data are required before any firm statements can be made concerning the likely area contaminated.

Data on the location of the failed fluid when first failure is observed from inside the aircraft was not reported and, thus, the effect of the location of the contamination on safe flight could not be analysed.

8.2.3 When in Doubt due to Poor Visibility

When it is difficult to identify whether the fluid has failed or not due to poor visibility, pilots do not rely solely on their visual inspection of the wing in reaching their decision whether to re-deice. Responses to the survey of pilots indicated that if the precipitation and HOTs indicate that the fluid has possibly failed and it is very difficult to see, 85% of pilots would return to re-deice even if they could not positively identify any fluid failure. This dropped to 63% returning to re-deice if it was somewhat difficult to see. Only 15% indicated that if they could not identify fluid failures (irrespective of visibility and available HOT), they would only return to re-deice if delayed and subsequent inspection revealed fluid failure.

8.3 Contamination Levels at Take-off Using Visual Based Inspection Only

As shown in Figure 1.3, there are two chains of events using visual based inspection procedures which could lead to an accident due to failure of the fluid. The two sequences are characterized by:

- fluid failure before the pre-take-off inspection and the pilot does not identify the failure at the inspection; and
- fluid failure after the pre-take-off inspection; the pilot correctly identifies the fluid as not failed and the fluid fails after the inspection but before take-off.

As discussed in Section 1.4, risks were not evaluated for the case where the aircraft could take-off within the minimum HOT and the pilot opted not to conduct a pre-take-off inspection. The likelihood of fluid failure either prior to the pre-take-off inspection or between the inspection and take-off is addressed in Section 4.4. The analysis below makes use of these probabilities and also estimates:

- the probability of the pilot not identifying a fluid failure at the pre-take-off inspection; and
- the amount of contamination built up on the critical parts of the wing by the time of take-off. This is characterized by the probability distribution of the critical areas with fluid failure at the time of take-off following failure to identify the fluid failure at the pre-take-off inspection.

Two different approaches were used to estimate the probabilities of the pilot visually identifying fluid failure at the pre-take-off inspection and the areas contaminated if the fluid failure is not identified. One approach, described in Appendix D, is based on the probability distribution given in Figure 8.3 and the areas of fluid failure in the fluid failure progression tests. The second approach, described below, is similar to that used in the analysis of sensor systems and allows the estimation of risks for combined sensor and visual inspection procedures. Also, use of a similar methodology should give better estimates of comparative risks. A detailed description of the statistical and data analysis used to estimate the probabilities is given in Appendix C. These probability distributions are then used in the comparative risk analysis in Section 9.

8.3.1 Probability of the Pilot Not Identifying Fluid Failure

The likelihood of the pilot identifying fluid failure depends on:

- the amount and location of the fluid failure on the wing; and
- the conditions under which the inspection is made.

The following steps were used to estimate the risks using visual inspection procedures:

- specify probabilities of the pilot being able to visually identify fluid failure on each section of the wing from within the aircraft for a given proportion of that section with fluid failure and given a viewing condition scenario (e.g., daylight poor view, nighttime, etc.);
- use fluid failure progression data to determine the area with fluid failure for each wing section in minute intervals after initial fluid failure, and use this area to estimate the probability of the pilot identifying the fluid failure at each of these time points;
- estimate the probability of fluid failure at specified times prior to take-off, given fluid failure prior to take-off;
- for given times between fluid failure and take-off and between pre-take-off inspection and take-off, estimate the probability of visually identifying the fluid failure at the pre-take-off inspection and the extent and criticality of fluid failure at take-off, given that the failure of the fluid is not identified at the pre-take-off inspection;
- given that extent and criticality of fluid failure at take-off, estimate the risk due to fluid failure; and
- repeat estimation of probabilities and risks for a range of possible times between de/anti-icing, pre-take-off inspection and take-off, and combine to give a single estimate of the risk for each viewing condition scenario.

To keep the analysis reasonably simple and easy to relate to actual situations, four viewing condition scenarios were considered - “very good”, “daytime-typical”, “daytime-poor” and “nighttime”. The viewing condition scenarios can also be used to test sensitivities of estimated risks to the visual identification of fluid failure probabilities used.

The analysis was further simplified by assuming that pre-take-off inspections were done 2 minutes prior to take-off for Type I fluid and 3 minutes for Type II and IV fluids[13].

The wing sections used in the analysis were those specified and used by APS in their aircraft tests (6), (8). An example of these sections was shown in Figure 7.5 for a B737.

The probabilities of the pilot visually identifying fluid failure on each wing section were determined based on:

- tests conducted by APS (described in Section 8.2.2);
- responses by the pilots in the surveys; and
- the views of the wing from within the aircraft based on photographs of the wing from the cockpit window (including through open window if it opens), several positions in the cabin.

Curves of the probability of visually identifying fluid failure versus the percentage area of the wing with fluid failure were specified for nine views of the wing ranging from extremely good to extremely poor using the curve shown in Figure 8.3 as a base. The curves are shown in Figure 8.4.

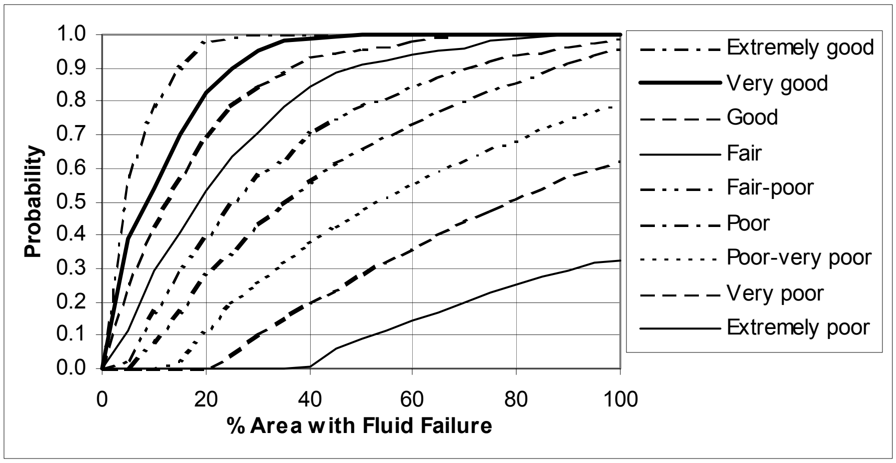

Figure 8.4. Hypothetical Probabilities of Visually Identifying Fluid Failure for Various View Ratings and Percentage Areas with Fluid Failure Used in the Analysis

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[13] Average times between inspection and take-off of around 2.5 and 3.5 minutes were found from the results of the US pilot survey after this analysis had been completed. Use of slightly lower values will offset the effect of a possible short delay between visually observed fluid failure and adherence to the wing and any significant effect on aerodynamic performance (discussed in Section 6.2). Delays between visually observed fluid failure and significant changes in performance will tend to reduce the impact of the pre-take-off inspection time on risk.

This report uses low wing aircraft to demonstrate the methodology for analysing the comparative risks using sensor and visual based inspection. The view of the wing from inside the aircraft is very different for high wing aircraft and the methodology below could also be applied to these aircraft.

The view of each wing section during typical daytime winter precipitation conditions was classified as one of the nine ratings assuming that pilots inspect each section from the best viewing point and will, if possible and appropriate:

- make the inspection from the cabin and will view the leading and trailing edges from different positions which offer the best view of each; and
- open the cockpit window to get a better view (avoids looking through contaminated window, improves angle and area that can be viewed).

The following factors were considered when assigning the view rating for each wing section:

- whether some or all of the wing section is visible; e.g., wing root area is not visible;
- the angle between the wing surface and the line-of-sight - view of wing is worse at low angles of incidence;
- the distance from the pilot's viewing point to the wing section;
- possible contamination of the window with snow, ice, and/or fluids obscuring the view of the wing section; and
- the conditions under which the inspection is made (e.g., "nighttime", "daytime-poor view", etc.).

Photographs of the wings from the cabin and cockpit for A320, B737 and F28 aircraft were used in rating the view of each section of the wing.

The view of the condition of the fluid on a typical low wing jet aircraft is shown in Figure 8.5 with the darker shading indicating a worse view. The wing root area is not visible from the cabin or cockpit. Beyond this area, the view of both the leading and trailing edges and the middle section are very good to excellent, depending on the clarity of view through the windows. When viewing sections closer to the wing tip, the view deteriorates due to the lower angle of incidence and the greater distance. The trailing edge sections are lower than the leading edge, giving a greater angle of incidence and thus a better view of the trailing edge than leading edge from the cabin. Also, the best views of the leading and trailing edges are from passenger windows near the front and back of the wing root. Due to the swept-back nature of the wing, distances along the line-of-sight increase, and angles of incidence decrease, more rapidly when viewing the leading than the trailing edge. This results in the view of the leading edge section being worse than the trailing edge section. These effects are evident in Figure 8.6 when comparing the view of the wing sections directly over the engine of a B737. The view of the wing tip is poor due to the very low angle of incidence.

The view ratings assigned to each wing section for typical daylight conditions for the three aircraft categories are given in Table 8.3. Note that where the view differs on the one section (for example, no view near wing root but very good view of outer part of section 7), the average rating of the whole section is used.

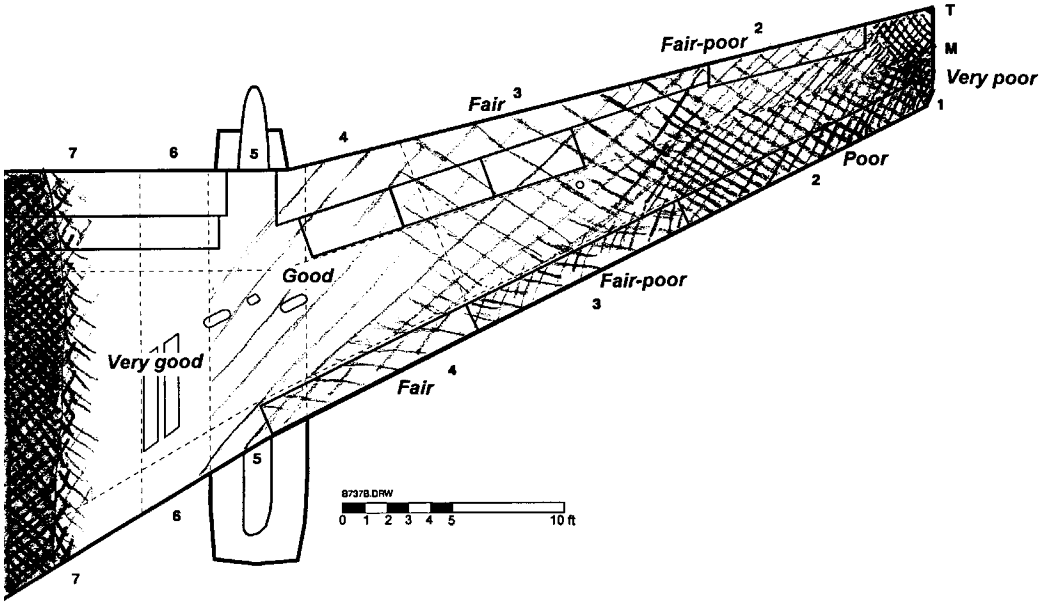


Figure 8.5 **Diagram of a Boeing 737 Wing with Shading Indicating the Quality of the View of the Fluid from the Cabin**

[Photos by Peter Dawson, APS]

Figure 8.6 **View of the Leading and Trailing Edge Sections of a Boeing 737 Wing From the Cabin**

The view ratings for nighttime were specified to represent conditions where:

- the aircraft is near the end of the runway with no lighting apart from that on the aircraft; and
- the pilot uses the emergency exit lighting, leading edge lighting and/or a flash light to get a view of the wing.

Table 8.3 View Ratings Assigned to Each Wing Section for Typical Daylight Conditions for the Three Aircraft Categories*

Wing Section			Rating of View
Wing Root	7	Leading	Fair-poor
		Middle	Fair-poor
		Trailing	Fair-poor
	6	Leading	Very good
		Middle	Very good
		Trailing	Very good
Over Engine	5	Leading	Good
		Middle	Good
		Trailing	Good
	4	Leading	Fair
		Middle	Fair
		Trailing	Fair
	3	Leading	Fair-poor
		Middle	Fair
		Trailing	Fair
	2	Leading	Poor
		Middle	Poor
		Trailing	Fair-poor
Wing Tip	1	Leading	Very poor
		Middle	Very poor
		Trailing	Poor-very poor

The rating of each section for inspections conducted at night or in poor daylight conditions were assumed to decrease uniformly over the wing; dropping by one in “daylight- poor” conditions and by two for “nighttime” conditions. The view ratings are assumed to increase by one when conditions improve from “typical” to “very good” during daylight. This gives, for example, the probabilities given in Table 8.4 of identifying fluid failure on the leading and trailing edge sections close to the window (Sections 6L and 6T shown on Figure 8.5) and approximately half to two-thirds of the way along the wing span (Sections 3L and 3T) when the fluid on 20% of the section has failed.

With these view ratings, probabilities shown in Figure 8.4 and the fluid failure progression data, the probabilities of the pilot visually identifying fluid failure under each of the viewing conditions were calculated using the above methodology for various areas of fluid failure. As shown in Figure 8.7, the distribution for "very good" viewing conditions corresponds, approximately, to the curve derived for correct visual observation from the cabin under good viewing conditions given in Figure 8.3.

Table 8.4 Probabilities of Identifying Fluid Failure on the Leading and Trailing Edge Sections 3 and 6 When the Fluid on 20% of the Section has Failed*

Section &	Leading Edge		Trailing Edge	
Viewing Condition	View Rating	Probability	View Rating	Probability
Section 6				
Very good	Extremely good	0.98	Extremely good	0.98
Typical daylight	Very good	0.83	Very good	0.83
Poor daylight	Good	0.69	Good	0.69
Nighttime	Fair	0.53	Fair	0.53
Section 3				
Very good	Fair	0.53	Good	0.69
Typical daylight	Fair-poor	0.39	Fair	0.53
Poor daylight	Poor	0.28	Fair-poor	0.39
Nighttime	Poor-very poor	0.11	Poor	0.28

* Section 6 is close to the window (in Figure 8.5) and Section 3 is approximately half to two-thirds of the way along the wing span. These probabilities do not take into account the different sizes of sections of the wing.

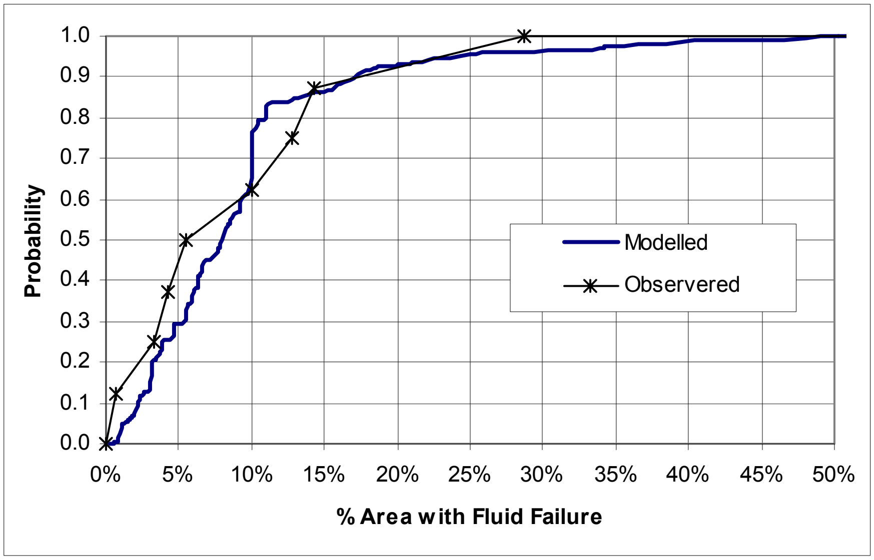


Figure 8.7 Comparison of Estimated Probabilities of the Pilot Visually Identifying Fluid Failure Under "Very Good" Viewing Conditions with Observed Probabilities Under Very Good Conditions

These probability distributions of the pilot visually identifying fluid failure on each wing section were then used with the fluid failure progression data as described in Appendix C to estimate the probability of identifying fluid failure on any part of the wing at given times after fluid failure.

Allowing for the distribution of times of take-off, the probability of the pilot not visually identifying fluid failure at the time of take-off in "typical daytime" viewing conditions, given fluid failure prior to take-off, was estimated to be:

- for Type I fluid: 0.41
- for Type IV fluid: 0.67

These probabilities relate to how well the pilot can identify a failed fluid and the probabilities are similar to those found using the two sensor per wing systems discussed in Section 7. However, the pilot conducts the visual check of the wing at the pre-take-off inspection which is typically several minutes prior to take-off. The probability of the pilot not identifying fluid failure at pre-take-off inspection, given fluid failure prior to take-off, is greater due to the possibility of the fluid failing after the inspection. Estimated values of this probability are given in Table 8.5 for Types I and IV fluids and the four viewing conditions analysed.

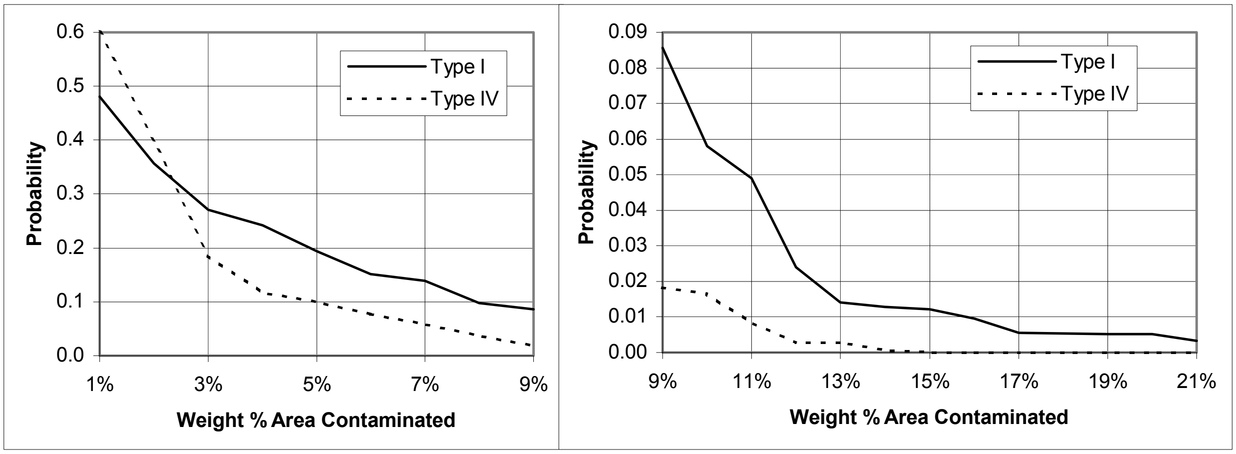
Table 8.5 Probabilities of the Pilot Not Identifying Fluid Failure at the Pre-take-off Inspection Given that it Would Have Failed By the Time of Take-off

Viewing Conditions	Type I	Type IV
Very good	0.63	0.76
Typical daylight	0.68	0.80
Poor daylight	0.72	0.83
Nighttime	0.76	0.86

These probabilities are estimated assuming the pre-take-off inspection is conducted two minutes prior to take-off for Type I fluid and three minutes prior to take-off for Type IV fluid. These are typical time intervals based on the survey of pilots. The analysis could be extended to include a distribution of times between pre-take-off inspection and take-off. The probabilities are greater for Type I than Type IV fluid because Type I fluid will, on average, have failed for a longer time period and the failure will spread more rapidly than with Type IV fluid, thus leading to a greater area of failed fluid and a greater chance of identifying the failure.

8.3.2 Critical Area Contaminated at Take-off Following Failure to Identify Fluid Failure at Pre-Take-off Inspection

The probabilities of the areas of fluid failure (weighted by criticality) at the time of take-off and of the pilot not visually identifying a fluid failure at the pre-take-off inspection, given the fluid fails prior to take-off, were estimated using the methodology described in Appendix C. Values for "typical daylight" viewing conditions are given in Figure 8.8.



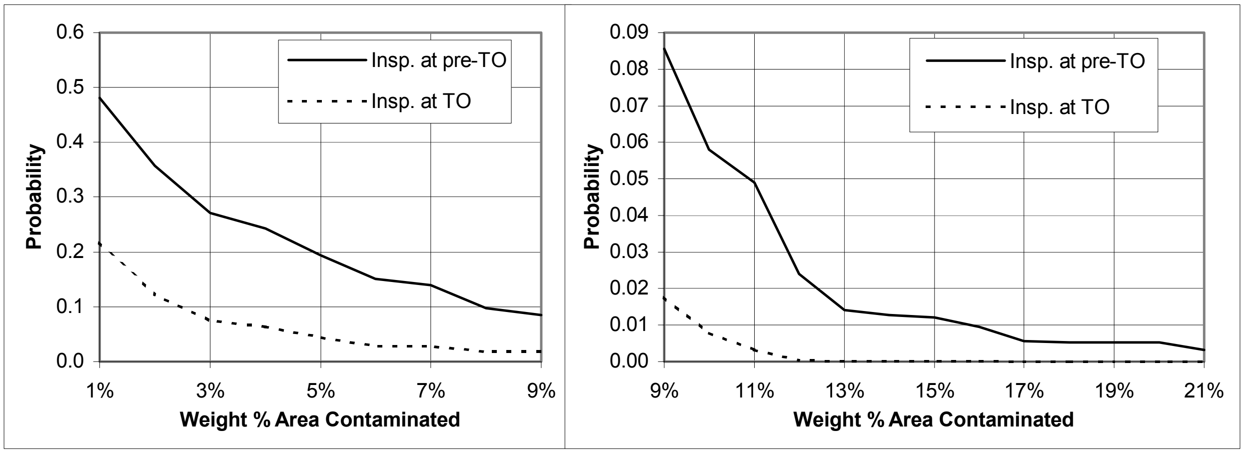
(a) For Weighted % areas of 1% to 9% **(b) For Weighted % areas of 9% to 21%**

Figure 8.8 Estimated Probability of Pilot Not Visually Identifying Fluid Failure at Pre-take-off Inspection and Take-off with More than Various Percentage Areas of Fluid Failure, Weighted by Criticality, Given Fluid Failure Prior to Take-off and "Typical Daytime" Viewing Conditions

The delay between pre-take-off inspection and take-off has a significant affect on the areas contaminated at take-off for two reasons:

- the fluid may fail after the inspection, but prior to take-off;
- for departures where a failed fluid at the time of the pre-take-off inspection was not identified at the inspection, the failure has more time to spread before take-off; and
- most importantly, cases where rapid failure occurs in the few minutes prior to take-off, which would likely be identified if a check could be made just prior to the commencement of the take-off run, could go undetected.

Figure 8.9 compares the probability distribution for Type I fluid shown in Figure 8.8 with the corresponding distribution had the pre-take-off inspection been made just prior to commencement of the take-off run. The likelihood of significant areas of contamination are greatly reduced. Unlike the visual inspection procedures where the pilot inspects the wing at the pre-take-off inspection, the sensor system continually monitors the condition of the wing right up to take-off. As shown in Figure 8.9, this would be a significant advantage of any inspection process.



(a) For Weighted % areas of 1% to 9% **(b) For Weighted % areas of 9% to 21%**

Figure 8.9 Estimated Probability for Visual Inspections Conducted at the Pre-take-off Inspection and Just Prior to Take-off - Type I fluid and "Typical Daytime" Viewing Conditions

The probability distributions of the areas contaminated at take-off are used in Section 9 to evaluate the comparative risks of visual and sensor based inspection.

Major Assumptions

The major assumptions made in determining these estimates and the reasons for these assumptions and their likely effects are given below.

- The ability of the pilot to correctly identify fluid failure from the cabin under very good viewing conditions is reflected by the probabilities shown in Figure 8.3 (curve excluding premature observations).
  - ◊ Reason: lack of good test data on visual identification of fluid failure from the cabin.
  - ◊ Effect: may lead to under- or overestimates of risks.
- The view ratings in Table 8.3 and hypothetical probabilities shown in Figure 8.4 provide good estimates of the probability of the pilot identifying fluid failure on specified sections of the wing in typical daytime viewing conditions.
  - ◊ Reason: Required to analyse risks of combined visual and sensor based systems.
  - ◊ Effect: may lead to under- or overestimates of risks.
- The ability of the pilot to correctly identify fluid failure on a given wing section from the cabin in various viewing conditions can be found by adjusting the view ratings on wing sections for typical daytime conditions by +1 for very good conditions, -1 for poor daylight conditions and -2 for nighttime conditions

  - ◊ Reason: lack of any test data on visual identification of fluid failure from the cabin under other than very good viewing conditions.
  - ◊ Effect: may lead to under- or overestimates of risks.

- There is little or no delay between when a patch of fluid on the wing is first visually observed to fail and when the failure will significantly affect aerodynamic performance (through adhesion and/or a thickening effect on the fluid).
  - ◊ Reason: As discussed in Sections 4.1 and 6.2 (Figure 6.3), the relationship between initial visual fluid failure and aerodynamic performance is uncertain.
  - ◊ Effect: Does not affect comparative risks if visual inspection is done just prior to commencement of take-off. A delay of several minutes between initial visual identification of fluid failure and a significant aerodynamic effect will reduce the risks associated with conducting the pre-take-off inspection 2 to 5 minutes prior to take-off. For Type I fluid the effect will likely be small, but for Type IV fluid, visual failure could be a number of minutes before adhesion commences due to the thickness of the fluid and the effect could be significant.

As with the analysis for point sensors, the following assumptions, given in Section 7.4.2, will also likely affect estimation of the risks.

- The test data used effectively represents the variation in the progression of fluid failure on aircraft wings.
- Fluid failure progression patterns are similar over different aircraft types.
- The criticality factors of 1.0 for leading edge sections and 0.2 for middle and trailing edge sections reflect how critical contamination in each area is to safe flight.
- If fluid fails prior to take-off, the average time of take-off after fluid failure has an exponential distribution with a mean of 3 minutes for Type 1 fluids and 5 minutes for anti-icing fluids.

Due to the lack of good test data on visual observation, tests of the sensitivity of the risk comparisons to these assumptions are very important.

9. COMPARISON OF ACCIDENT RISKS

The comparisons of risks given in this section are primarily for illustrative purposes only. The sensor system used in the comparison had two sensors on the leading edge of each wing (sections 2L and 4L shown in Figure 7.5) and notified the pilot of failure only when the fluid over the sensor failed, i.e., there was no warning of imminent failure. Due to the lack of good data on the accuracy of visual observation from inside the aircraft under a range of viewing conditions, the sensitivity of the comparative risks to the probabilities of visually identifying fluid failure used in the analysis was considered. As outlined in earlier sections, a number of assumptions were made in deriving these estimates of risk, and these should be considered when making any comparisons.

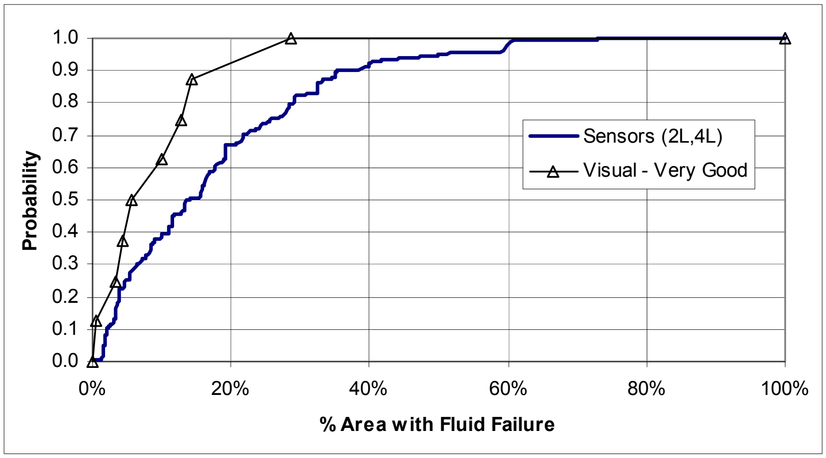
9.1 Comparison of Probabilities of Identifying Fluid Failure

The ability to identify fluid failure before it spreads too far and jeopardizes safety is critical in any inspection system. As discussed in Section 8, there is a lack of good data for estimating the probability of the pilot identifying the failure for various levels of contamination in different viewing conditions. The observed probabilities of the pilot correctly identifying fluid failure using visual inspection under good viewing conditions for various areas of the contamination (discussed in Section 8) are shown in Figure 9.1(a). The visual tests were conducted with low wing jet aircraft. The fluid failure progression data was analysed using the methodology as described in Section 6 and Appendix C to produce a similar relationship for the two-sensor per wing system. This distribution is included in Figure 9.1(a) for comparison. Under the very good viewing conditions prevailing during the visual observation tests, given the area of the wing with fluid failure, there was a greater chance of the inside observer identifying the failure than a two-sensor per wing system. This simple comparison can, however, be very misleading for two reasons:

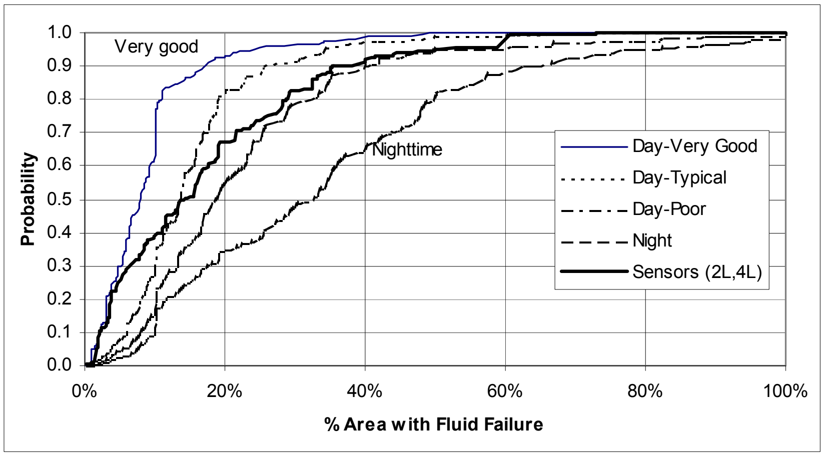
- under other viewing conditions the accuracy of visual inspection deteriorates while the sensor system is unaffected; and
- the curve is indicative of the ability to identify fluid failure at the time of the pre-take-off inspection for visual inspection, not at the commencement of take-off, as with the sensor system.

Figures 9.1(b) and (c) show the effect of these factors on the probability distributions.

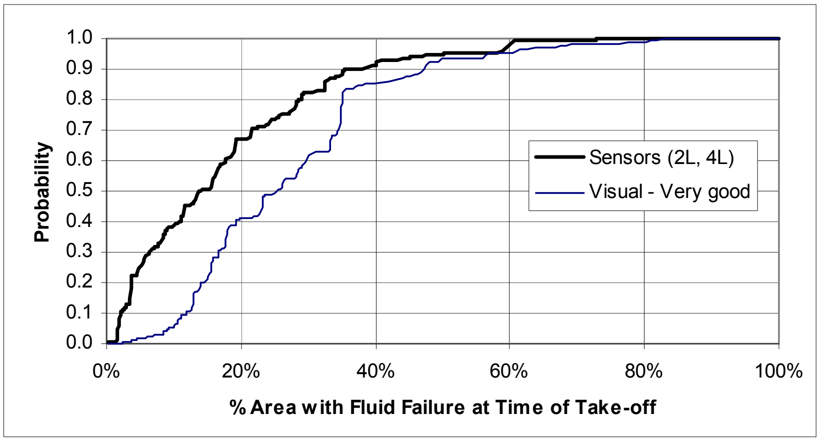
The estimated probabilities of identifying fluid failure under various viewing conditions are shown in Figure 9.1(b). Although the probabilities under viewing conditions other than “very good” are based on qualitative data and to some degree are hypothetical, the accuracy of visual based inspection deteriorates greatly in poor viewing conditions, and in nighttime conditions is almost certainly worse than a two sensor per wing system. A point sensor system offers the possibility of significantly improving the reliability of detecting contamination, especially during freezing drizzle/rain at night.



(a) Sensor and Observed Values for Visual Inspection in "Very Good" Viewing Conditions



(b) Sensor System and Visual Inspection Under Various Viewing Conditions



(c) Sensor System and Visual Inspection Under "Very Good" Viewing Conditions Verses Area of Contamination at the Time of Take-off - Type I Fluid

Figure 9.1 Comparison of Probabilities of Identifying Fluid Failure Versus Percentage of Wing Area Contaminated Using Visual Inspection and a Point Sensor System (2 per wing)

Figure 9.1(c) shows the probabilities of identifying fluid failure given the area of fluid failure at the time of take-off rather than at the time of the pre-take-off inspection. The curve for visual observation in the figure is for “very good” viewing conditions using Type I fluid. This allows a better comparison of the two inspection procedures since both relate to the amount of contamination at the same time and the risks are related to the extent of fluid failure at take-off, not at the pre-take-off inspection. Given that the fluid fails prior to take-off, the probability of identifying the failure is greatly reduced if the inspection is done several minutes prior to take-off.

The accuracy of visual and sensor based inspection systems will likely vary between aircraft types, especially for high wing aircraft and the accuracy of sensors could also be improved by optimizing the sensor systems for particular aircraft types. A more detailed comparison was not possible due to the lack of suitable test data.

Based on the probabilities shown in Figure 9.1(a) and assuming that additional sensors could be placed on the wing with similar probabilities of identifying fluid failure as the two sensors per wing examined, four sensors per wing would be required to given similar identification accuracy as the visual observation under these good viewing conditions. However, this many sensors may not be necessary to give similar risks, depending on the location of the sensors and the criticality to aerodynamic performance of contamination in those areas and the time of the pre-take-off inspection.

9.2 Comparison of Risks

The risks associated with identification of fluid failure were estimated using the relationship between risk and level of contamination described in Section 6 and the estimated probability distributions of the level of contamination. These were combined to give a single *risk measure* for use in the comparison. The sensitivity of the comparison of the *risk measures* to high and low values of the risk relationship given in Section 6 is also considered.

The *risk measures* were determined using the distributions of the critical areas contaminated at take-off (such as Figure 7.8 for sensor systems and Figure 8.8 for visual inspection). All comparisons are for visual inspection of low wing aircraft. *Risks measures* were also estimated for combined visual and sensor based inspection procedures assuming that:

- the pilot follows the current visual inspection procedure, but does not proceed with take-off if the sensor systems indicates fluid failure prior to commencement of the take-off run, and
- the pilot’s judgment of the condition of the wing is unaffected by the presence of the sensor system.

The *risk measures* for visual inspection procedures are based on the pilot’s visual observation of the condition of the wing and do not include any allowance for the use of HOTs, in conjunction with weather conditions and delay/taxi times, in deciding whether to proceed with the take-off. Use of HOTs could significantly reduce the risks associated with visual inspection, especially when visual observation is difficult.

The probability of the aircraft being deiced and at risk of fluid failure (i.e., continuing precipitation) was set at 0.02, as discussed in Section 4.4.1. The *risk measures* for each of the four airport-fluid type cases examined are given in Table 9.1 for the inspection systems and viewing condition scenarios examined.

Table 9.1 Risk Measures (per million departures) Due to the Inspection System Not Identifying Fluid Failure Prior to Take-off

Airport	Fluid Type	Inspection System*	Viewing Conditions			
			“Very Good”	“Day-Typical"	“Day-Poor”	“Night-time”
Large Busy	Type II	Sensor	0.033	0.033	0.033	0.033
		Visual	0.13	0.36	1.3	2.6
		Visual+Sensor	0.009	0.016	0.020	0.024
	Type IV	Sensor	0.003	0.003	0.003	0.003
		Visual	0.011	0.030	0.11	0.22
		Visual+Sensor	0.001	0.001	0.002	0.002
Small, Short taxi	Type I	Sensor	0.21	0.21	0.21	0.21
		Visual	1.1	3.8	7.7	13
		Visual+Sensor	0.055	0.063	0.074	0.099
Small, Long Taxi	Type I	Sensor	0.49	0.49	0.49	0.49
		Visual	2.6	8.6	18	30
		Visual+Sensor	0.13	0.14	0.17	0.23

* 2 leading edge sensors per wing, does not warn of imminent failure, not optimized for particular aircraft type

The *risk measures* for the sensor system are, of course, the same for the different viewing conditions. The *risk measures* for the visual based inspection procedure increase with deteriorating viewing conditions and in all cases, even under “very good” viewing conditions, are higher than using the sensor based system - the *risk measures* for Type I fluid and short taxi times are shown in Figure 9.2 for comparison. The *risk measures* shown in Table 9.1 indicate that use of Type IV fluid at large busy airports reduces the risks by a factor of 10 over those experienced with Type II fluid.

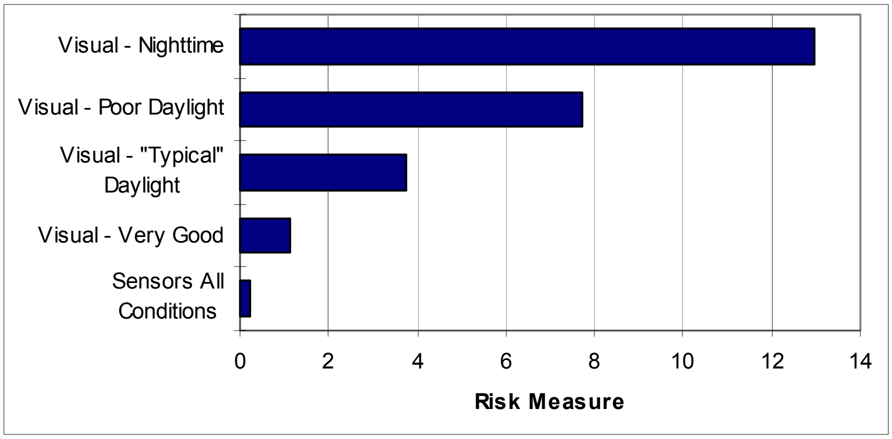


Figure 9.2 Comparison of Risk Measures for Point Sensor and Visual Based Inspection Under Various Viewing Conditions - Type I Fluid, Small Airport, Short Taxi Time Case

Use of visual inspection procedures in addition to the sensor based system reduced the *risk measures* by 30% to 75% from those using a sensor system alone. The risk measures are compared in Figure 9.3 for Type I fluid in the small airport-short taxi time case analysed. This significant reduction in the *risk measures* due to the use of visual inspection, despite the higher risks with visual inspection alone, appears to be due to the very different methods and procedures of the two systems which complement each other when used together. The sensors system inspects the wing right up to the time of take-off and has a high probability of detecting any significant amounts of contamination on the critical leading edge sections of the wing. Visual inspection covers all areas of the wing and has a good chance, depending on the viewing conditions, of identifying the few cases of widespread failure that are not identified by the sensors.

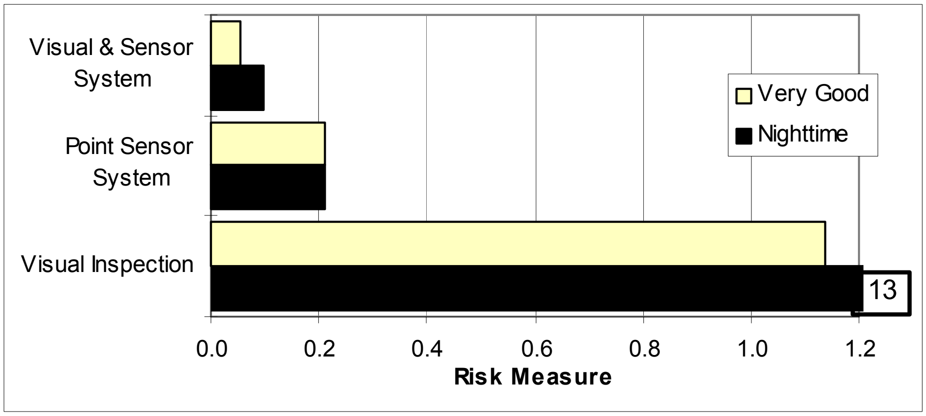


Figure 9.3 Comparison of Risk Measures for Point Sensor and Visual Based Inspection and for Combined Visual and Sensor Inspection for "Very Good" and "Nighttime" Viewing Conditions - Type I Fluid, Small Airport, Short Taxi Time Case

A number of assumptions were made in deriving these risk measures and the sensitivity of the comparative risks to these assumptions are an important consideration. The sensitivities of the comparative risks (given by the ratio of risks, sensor/visual) to a number of characteristics are given in Table 9.2 and discussed below.

- Ability of pilot to visually identify fluid failure - this characteristic is very important and its values are based on very limited data. The probability distribution for identifying fluid failure for "Day-typical" viewing conditions is used to represent the medium cases, the distributions for "Very good" and "Nighttime" viewing conditions are used for the high and low cases. The comparative risks are very sensitive to this assumption, but even for the high case, *risk measures* were 40% less using the sensor system.
- Delay/taxi times - significantly affects the likelihood of fluid failure and the amount of contamination on the wing at the time of take-off. For small airports using Type I fluid, the short and long taxi time distributions are used as the high and low cases. For busy airports using Type IV fluid, taxi/delay time distributions with means of 10, 13 and 18 minutes were used. The comparative risks were found to be insensitive to this parameter.
- Time interval between pre-take-off inspection and take-off - very important for visual inspection. In the low, or optimistic case, pre-take-off inspections were assumed to occur immediately prior to take-off, while in the pessimistic case, a four minute interval was used for both Type I and Type IV fluids. The comparative risks were found to be very sensitive to this assumption, but again, even in the most optimistic case where there is no delay between inspection and take-off, *risk measures* were less with the sensor system.
- Effect of amount of contamination on aerodynamic performance and risk - the low, medium and high curves for the relationship between the loss in maximum lift and the area contaminated shown in Figure 6.5 were used. The comparative risks are fairly sensitive to this assumption, changing the risk ratio by a factor of two.
- The time between fluid failure and take-off - values of 2.5 minutes for Type I and 5 minutes for Type IV fluid used in the analysis were estimated in Appendix A. The use of double these times had no effect on the comparative risks.
- Consistency of the location of initial fluid failure - with high consistency sensors can be located in areas which fail first and therefore have a high probability of detecting early fluid failure. Consistency on leading edge assumed to be "high" (e.g. with 20% of section contaminated sensor has 0.9 chance of identifying failure - see Figure C1 in Appendix C). For the low case, consistency on leading edge was reduced to "medium" (e.g., 0.4 probability of identifying failure with 20% of area contaminated - see Figure C1). The comparative risks are very sensitive to the assumed consistency of location, increasing the risk ratios by a factor of 3. However, the *risk measures* for the sensor system are still less than those for visual inspection, even under "very good" viewing conditions.

Table 9.2Sensitivity of Comparative Risk to Assumed Parameters Used in the Analysis*

Assumption regarding	Value used in Sensitivity Analysis			Risk Ratio: Sensor/Visual#		
	Low	Medium	High	Low	Medium*	High
Small Airport Type I Fluid Ability to visually ID fluid failure	"Nighttime"	"Day-typical"	"Very good"	0.02	0.06	0.19
Taxi/delay time (minutes)	Avg 5.5 min		Avg 8 min	0.06		0.06
Time between inspection & take-off	0 min	2 min	4 min	0.61	0.06	0.028
Effect of Contamination	Low	Medium	High	0.02	0.06	0.14
Time between fluid failure & take-off	2 min	3 min	5 min	0.06	0.06	0.06
Consistency of fluid failure location on sections with sensors	L.Edge Med.	L.Edge High		.16	.06	
Time between visually observed failure and adherence to wing		0-0.5 min	1-1.5 min		.06	0.08
Busy Airport Type IV Fluid Ability to visually ID fluid failure	"Nighttime"	"Day-typical"	"Very good"	0.013	0.09	0.25
Time between inspection & take-off	0 min	3 min	4 min	0.54	0.09	0.02
Effect of Contamination	Low	Medium	High	0.06	0.09	0.23
Time b/n fluid failure & take-off	3 min	5 min	10 min	0.05	0.09	0.12
Consistency of fluid failure location on sections with sensors	L.Edge Med.	L.Edge High		0.32	.09	
Time between visually observed failure and adherence to wing		0-0.5 min	5 min		.09	0.24

* "Daytime-typical" viewing condition used as base case for risks with visual inspection

\# Values of the ratio less than one indicate risks less with the sensor system

- Time interval between visually observed fluid failure and adherence to wing and/or significant effect on aerodynamic performance - longer times will significantly reduce the effect on risk associated with the delay between pre-take-off inspection and take-off. The medium values assume little or no time between visually observed failure and a significant effect on performance, while the upper values assume times of 1 to 1.5 minutes for Type I fluid and about 5 minutes for Type IV fluid. These higher times significantly reduced the *risk measures* for visual inspection, but also reduce the *risk measures* with sensor systems and the comparative risk ratio is still much less than one.
- Probability of fluid failure - the comparative risks, measured by the ratio of risks, are insensitive to the values used in the analysis and are not included in Table 9.2.
- Use of HOTs in deciding whether to proceed with take-off - allowance for the use of HOTs with visual inspection procedures was not included in the analysis. Use of HOTs varies between pilots and, at best, would be expected to give similar risks as visual inspection under "very good" viewing conditions since the HOTs are not directly related to the contamination in a particular situation. The risk measures would therefore not be expected to be reduced to below those for the sensor system.

- Methodology used to estimate the risks using visual inspection - a different methodology and different relationships for the accuracy of visual observation under different viewing conditions, described in Appendix D, was used to estimate the risk measures for visual inspection. Risk measures over all viewing conditions were found to be consistent with the values in Table 9.1[14]

Despite the higher values of the *risk measures* found for visual inspection procedures compared to the sensor system, the *risk measures* for visual inspection by the pilot under "very good" viewing conditions at the time of take-off (i.e., no delay between inspection and take-off) were found to be lower than for the sensor system.

The point sensor system analysed included two sensors on the leading edge of each wing optimally located to identify first fluid failure. The analysis is based on data from different aircraft types with fluid failure patterns and the accuracy of the sensors in identifying fluid failure could be improved by locating sensors optimally for each specific aircraft type.

As discussed in earlier sections, this comparison does not consider several other types of events for which sensors could further reduce the overall risks. These include:

- failure of the fluid prior to take-off and the pilot not conducting a pre-take-off inspection which, in Canada, may occur if the take-off can be completed within the HOT;
- poor de/anti-icing (e.g., inconsistent coverage of anti-icing fluid) or gross negligence (e.g., missed part of wing completely) causing very quick buildup of contamination well before the HOT expires; and
- buildup of ice on the aircraft in situations where the aircraft is not deiced.

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[14] *Risk measures* estimated to be between 3.1 and 5.9 for Type I fluid at small airport with short taxi times

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The following conclusions were drawn from the study:

- The risks of conducting pre-take-off inspection based primarily on visual observation and point sensor systems can be compared using the methodology specified in this report. Extensions to this methodology can be made to account for take-offs where no visual pre-take-off inspection is done, and for point sensor systems with three or more sensors per wing.
- The take-off accident rate where wing ice contamination has been a contributing factor of zero since 1993 is significantly (statistically) less than the non-zero rate from 1985 to 1992, and is likely due to the additional safety measures instituted since 1993.
- An accurate assessment of the relative risks associated with identifying fluid failure using visual and sensor based inspection is restricted by the amount of field data available, and sensitivity testing is necessary to draw any conclusions regarding the relative risks.
- The following additional data are required to complete the analysis:
  - ◊ fluid failure times and locations visually observed from inside the aircraft and actual fluid failure progression on aircraft over a range of conditions and aircraft types. The inside observations should be made, where possible by pilots, under conditions typical of those experienced by a pilot. The pilots should also indicate, if faced with an identical situation in a pre-take-off inspection and knowing the HOTs, whether they would have proceeded with the take-off.
  - ◊ fluid failure progression on high wing aircraft and small commuter jets;
  - ◊ times between pre-take-off inspection and take-off for a range of aircraft types;
  - ◊ taxi and delay times after deicing at a range of airports;
  - ◊ wind tunnel test data on the effect of small areas of fluid failure, and partial failure (slush formation on top of fluid) on the aerodynamic performance of low and high speed take-off aircraft, and
  - ◊ test data to determine whether contamination due to fluid failure present on the wing at the start of the take-off roll is still present at rotation and at lift-off.
- Based on the limited data currently available for low wing aircraft:
  - ◊ the use of Type IV rather than Type II fluids at large busy airports reduces the risks by a factor of 10;
  - ◊ risks with the visual inspection procedure associated with the delay between the pre-take-off inspection and take-off are significant, and the reduction of these risks would be an important benefit of sensor based systems;
  - ◊ the risks due to fluid failure using a point sensor system with two sensors on the leading edge of each wing are less than the risks using visual inspection from the cabin at the pre-take-off inspection; and

  - ◊ the risks using combined visual and sensor based inspection are significantly lower than using only a sensor based system.

- There is insufficient data to conduct a comparative analysis of the risks of conducting pre-take-off inspections based primarily on visual observation and on area sensors. The following types of data are required to conduct the analysis:
  - ◊ times of sensor indicated and visually observed fluid failure under a range of conditions in outdoor tests on aircraft;
  - ◊ the degree to which frozen contaminants are adhering to the wing surface when the sensors identify fluid failure;
  - ◊ the sensitivity of identification of fluid failure to localized or transient failures;
  - ◊ the view of the wing surface from the intended location of the sensor cameras; and
  - ◊ demonstrated use of system for identifying fluid failure in operational conditions.

- The following general conclusions were drawn from the results of the pilot survey:
  - ◊ pilots feel that recent changes in de/anti-icing procedures, standards and fluids have significantly improved safety;
  - ◊ pilots feel that the long HOTs provided by Type IV fluids have greatly improved the safety margin, and called for the greater availability of anti-icing fluids at small and medium sized airports;
  - ◊ pilots cannot make an accurate assessment of the condition of the critical surfaces using visual inspection at night or when visibility is poor, especially during freezing rain/drizzle;
  - ◊ the training of pilots for recognizing fluid failure is inadequate;
  - ◊ most pilots do not frequently make pre-take-off inspections and very rarely identify fluid failure, and will therefore not learn how to recognize fluid failure through experience;
  - ◊ pilots rely heavily on the HOTs and are reasonably confident in their accuracy;
  - ◊ pilots have confidence in the representative surfaces. Therefore, these surfaces must truly reflect the areas of early failure and/or areas critical to safe flight, or the concept of representative surfaces should be abandoned;
  - ◊ pilots feel that they and the ground crew are conservative in their decision on the need to deice and re-deice aircraft. In their view, this reduces the risk of take-off with contaminated surfaces, but leads to much unnecessary deicing of aircraft;
  - ◊ there is widespread agreement that sensors for identifying fluid failure would improve safety, but pilots indicated that the sensors must be accurate and reliable with no false warning, and must be used in conjunction with visual inspection;
  - ◊ a method for determining whether cold, dry snow is adhering to the wing would reduce the number of deicing operations and eliminate a source of uncertainty and conflict;
  - ◊ communication between the deicing crews and the pilot needs to be improved;
  - ◊ a range in HOTs, rather than a single value, is preferred, but some pilots do not clearly understand what the upper and lower values in the range represent;
  - ◊ few pilots make the link to the risks associated with airborne icing when considering the HOTs available in freezing rain/drizzle conditions;

- ◊ the de/anti-icing service at Vancouver Airport needs to be improved;
- ◊ pilots feel that major improvements in safety would be achieved by locating the deicing pad near the end of the active runway and by having ATC coordinate the timing of deicing and take-off. With the long holdover times offered by the new anti-icing fluids, all take-offs could then be completed well within the HOTs.

10.2 Recommendations

The following recommendations are made:

- TDC collect data on:
  - ◊ the accuracy of visual inspection by the pilot from inside the aircraft in various conditions and for both low and high wing aircraft,
  - ◊ fluid failure progression, especially on high wing aircraft, and
  - ◊ taxi and delay times, and times between pre-take-off inspection and take-off.
- The risk analysis be extended to:
  - ◊ evaluate three sensors per wing,
  - ◊ include the risks associated with not conducting a pre-take-off inspection,
  - ◊ include allowance for pilots to use HOT, in conjunction with weather conditions and taxi and delay time, in deciding whether to proceed with take-off, and
  - ◊ test the sensitivity of the comparative risks to other parameters and assumptions.
- The risk analysis be conducted for specific aircraft types where sufficient data is available; and
- The risk analysis be conducted for high wing aircraft.

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APPENDIX A

ESTIMATION OF PROBABILITY OF FLUID FAILURE PRIOR TO TAKE-OFF

ESTIMATION OF PROBABILITY OF FLUID FAILURE PRIOR TO TAKE-OFF

A1. Methodology

The probability of fluid failure before take-off is dependent on the time period between deicing and take-off and the protection time of the fluid. The variation in fluid application/taxi/delay times after deicing is critical in determining the likelihood of fluid failure, especially the frequency of longer times. The distributions of these times for large and small airports are discussed below.

Fluid protection times vary depending on fluid type and dilution and the weather conditions, especially the precipitation rate. Other conditions such as wind, wind blown snow, ambient and wing surface temperature and humidity can be important. Given the large number of combinations of fluids, dilutions, airports and weather conditions, it was not feasible to estimate a single probability of fluid failure prior to take-off for all departures in Canada. Instead, estimates were obtained for a number of typical cases. The following approach was used:

- the fluid application/taxi/delay time distributions for a large busy airport and for typical small airports with short and long taxi times were estimated;
- expected protection times of fluids for given precipitation rates and types and ambient temperatures were estimated;
- the variation in protection times around this expected value to allow for other factors (type of precipitation, wind, humidity, etc.) was estimated;
- the joint probability distributions of precipitation rate and type and temperature (distribution for Ottawa used) was estimated;
- variation in flight frequency and temperature distribution by time of day was allowed for;
- the fluid failure time for particular values of each of these factors and the probability of that combination of factors were estimated, and for each combination:
    - ◊ fluid failure time with each value of the range of possible fluid application/taxi/delay times were compared,
    - ◊ the joint probabilities of that fluid failure time and fluid application/taxi/delay time were summed over values of fluid failure times less than the fluid application/taxi/delay time; and
- the calculations were repeated to determine the frequency fluid failure times are less than the application/taxi/delay times for the large airport using Types II fluid and Type IV fluid, and for the small airports using Type I fluid (Types II and IV fluids are assumed to be at 100% concentration);

Expressed in mathematical terms, the probabilities were calculated for a given fluid type and airport as described below. Using the probability relationship that for any events A and B:

$$P[A] = \Sigma_n\ P[\,A\ \&\ B = n\,] = \Sigma_n\ P[\,A \mid B = n\,] \times P[\,B = n\,] \qquad \text{(A1)}$$

The probability of fluid failure can be written:

$$\begin{aligned}
&P[\,TFF < TDT \mid \text{Deiced}] = \\
&= \sum_{r\ \&\ t_m} P[TFF < TDT \mid \text{Deiced}\ \&\ R = r\ \&\ TM = t_m\,] \times P[R = r\ \&\ TM = t_m \mid \text{Deiced}] \\
&= \sum_{r\ \&\ t_m} P[TFF < TDT \mid \text{Deiced}\ \&\ R = r\ \&\ TM = t_m\,] \times P[R = r\ \&\ TM = t_m\ \&\ \text{Deiced}] \,/\, P[\,\text{Deiced}\,] \\
&= \sum_{r\ \&\ t_m} \sum_{t_d > 0} \sum_{t_f < t_d} P[\,TDT = t_d\ \&\ TFF = t_f \mid \text{Deiced}\ \&\ R = r\ \&\ TM = t_m\,] \times P[R = r\ \&\ TM = t_m\ \&\ \text{Deiced}] \,/\, P[\,\text{Deiced}\,] \\
&= \sum_{\substack{r\ \&\ t_m \text{ such that} \\ \text{aircraft Deiced}}} \sum_{t_d > 0} \sum_{t_f < t_d} P[\,TDT = t_d\ \&\ TFF = t_f \mid \text{Deiced}\ \&\ R = r\ \&\ TM = t_m\,] \times P[R = r\ \&\ TM = t_m\ \&\ \text{Deiced}] \,/\, P[\,\text{Deiced}\,] \qquad \text{(A2)}
\end{aligned}$$

where TFF is the time to fluid failure;
TDT is the time between fluid application and take-off;
R is the precipitation rate;
TM is the temperature;
P[X] denotes the probability of event X; and
Deiced indicates the aircraft was deiced due to precipitation.

The probability of the aircraft being deiced due to precipitation is estimated by summing over weather conditions where deicing would be necessary:

$$P[\,\text{Deiced}\,] = \sum_{\substack{r\ \&\ t_m \text{ such that} \\ \text{aircraft Deiced}}} P[\,R = r\ \&\ TM = t_m\,] \qquad \text{(A3)}$$

In this section, only aircraft that are deiced due to continued icing conditions are considered as it is these aircraft that are at risk of fluid failure. Thus, aircraft that are deiced due to overnight frost buildup are excluded. It is assumed that deicing will be required if snow, freezing rain, freezing drizzle or ice pellets are falling and temperatures are not very low (greater than -20°C). At the very low temperatures the snow is very dry and blows off the aircraft on take-off and aircraft are not usually deiced in these conditions.

Each of the factors affecting the fluid failure probability are considered in the Sections A2 to A4 and the probabilities calculated from these distributions and the relationships given by Equations A2 and A3 are given in Section A5. The probabilities that the fluid will fail either prior to, or after, the pre-take-off inspection are then considered in Section A6.

A2. Taxi/Delay Time Distributions

Taxi/delay time data were obtained for Lester B. Pearson International Airport in Toronto and Dorval Airport in Montreal from a short study conducted by ARC[1]. These data should represent conditions at large busy airports reasonably well. Type II or Type IV fluids are typically used at these airports when precipitation is falling and protection is required for any length of time. No data could be found for smaller airports and estimates are obtained for hypothetical cases of fluid application/taxi/delay time distributions. Only Type I fluid is used at the smaller airports and estimates were only found for that fluid at those airports.

ARC estimated the frequency distributions of times between aircraft leaving the gate or deicing pad and take-off. Separate distributions were estimated for when there was no precipitation (aircraft not deiced), when the aircraft were deiced at the gate, and when the aircraft were deiced at the deicing pad. Times were estimated by the difference in the time of second taxi clearance issued by air traffic control (ATC) and the time of take-off clearance. ARC notes that this method likely underestimates the taxi/delay times by 1 to 3 minutes. Taxi times from the gate and deicing pad to the start of the runway vary by runway and between airports. The average taxi/delay times for each of the data sets are given in Table A1.

At Dorval, both the average time and variation in times increased for deiced aircraft, while at Toronto the average times decreased slightly, but the variation for deicing at the pad increased. The distributions for aircraft deiced at the pad, shown in Figure A1, appear to best represent the taxi/delays that could be expected under deicing conditions. Also shown on the figure are gamma distributions fitted to the observed distributions. The distributions at the two airports are fairly similar with slightly longer taxi/delay times being expected at Toronto. However, several aircraft deiced at the gate at Dorval experienced waiting times over 20 minutes indicating that the Toronto distribution, with the longer times, may be more representative of deiced aircraft at these types of airports. The distribution for Toronto was therefore used in the subsequent analysis.

Table A1 Average and Standard Deviation of Taxi/Delay Times With and Without Deicing at Dorval and Toronto Airport

		No Precipitation	Deiced at Gate	Deiced at Pad
Dorval				
	Average	5.4	8.4	6.7
	SD	2.6	7.6	4.4
Toronto				
	Average	10.0	8.7	9.2
	SD	4.6	4.4	6.0

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[1] Aircraft Ground Operations in Canadian Winter Weather: Taxi Times, Wing Temperature & Hot De-icing, by ARC for TDC, report: TP 12735E, 1996

To better represent large airports in general and to remove the effects of small sample size, the smoothed distribution for Toronto Airport, represented by the gamma distribution, was used in the subsequent analyses.

The fluid must protect the aircraft from the start of the final fluid application until take-off. For aircraft that are anti-iced, the protection time starts from the beginning of application of the anti-icing fluid. Type I fluid application on a small jet aircraft typically takes between 3 and 8 minutes[2]. Type II and IV fluids usually take less time to apply than Type I fluid which is often used to clean the aircraft. This is offset, to some extent, by the larger size of aircraft typically receiving anti-icing fluids. Also, since the risk analysis is considering the amount of fluid failure on all parts of the wing and this is predicted from the time since application, its is not necessary to use the full application time in the analysis. Allowing for communication delays after deicing, about 70% of the application time is likely more appropriate. Thus, an allowance of between 3 and 7 minutes, with a mean of 5 minutes, was added to the taxi/delay times to account for final fluid application. In addition, one minute was added to the taxi/delay times to account for the bias in the procedure for estimating taxi and delay time.

For small airports, estimates were obtained for two distributions of the total fluid application, taxi and delay times. They have been termed short and long taxi time small airports and are assumed to have the following characteristics:

- Short taxi time airport: average = 5.5 min., SD = 2 min.
- Long taxi time airport: average = 8 min., SD = 2.5 min.

These distributions include an allowance for the time to deice the aircraft. The distributions are shown in Figure A2.

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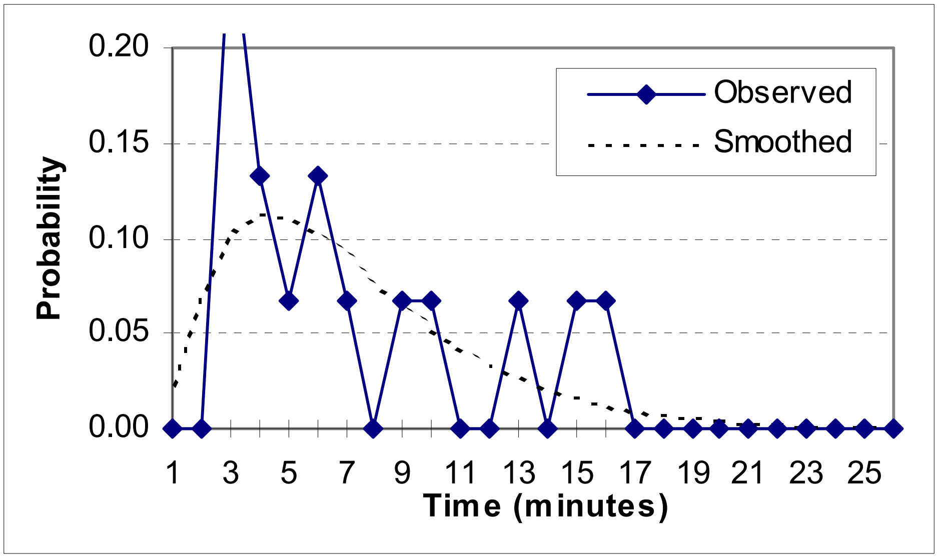
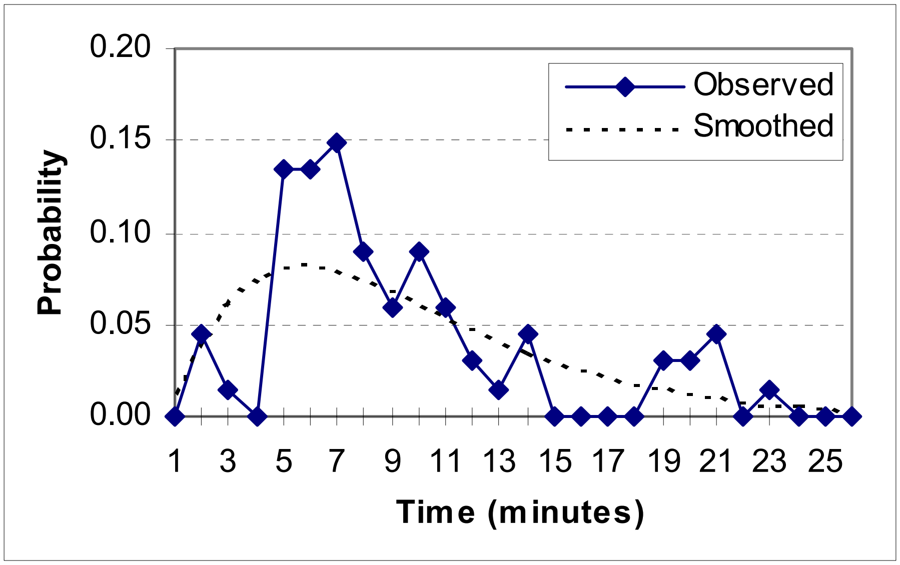
[2] Based on data on BAe 146 collected by Instrumar in eastern Canada in 1995/96 and documented in the report TP12425E to TC: “Study for the Evaluation of Flight Crew Requirements and Human Factors Related to a Cockpit Display of Aircraft Surface During Periods of Freezing Precipitation”, Nov. 1994.



(a) Dorval



(b) Toronto

Figure A1 Frequency Distributions of Taxi/Delay Times for Aircraft Deiced at the Deicing Pad for Dorval and Toronto Airports*

[Source: ARC report to TDC: TP 12735E, 1996]

* Smooth distributions estimated by gamma distribution

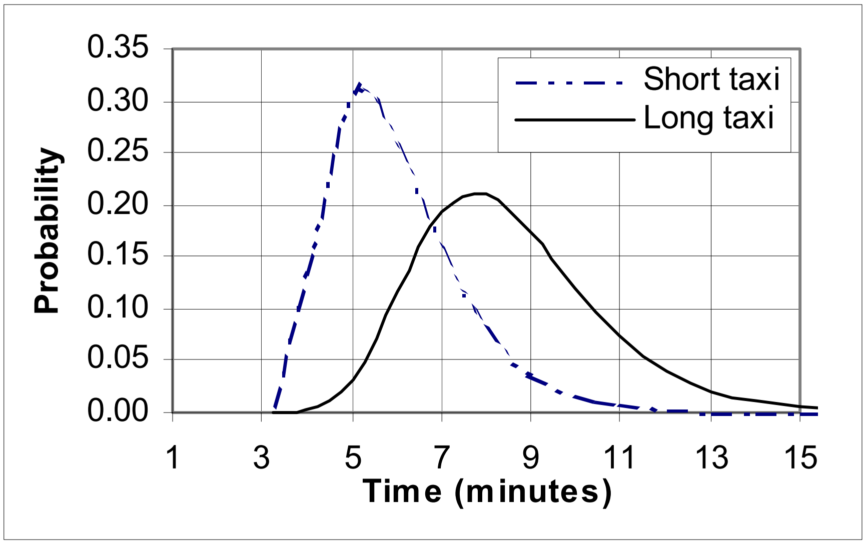


Figure A2 Hypothetical Frequency Distributions of Fluid Application/Taxi/Delay Times for Aircraft Deiced at Small Airports Used in Analysis

A3. Fluid Failure Time Distributions

HOT tables provide a guide to the protection times that could reasonably be expected in a range of fairly weather typical conditions. At very high precipitation rates or with wind blown snow or ice pellets, protection times may be less than the minimum values of the HOT range. Conversely, in many conditions, protection times will be greater than those given in the tables.

Actual test data were used, where available, to determine the fluid failure time distributions. Figure A3 summarizes fluid failure time data analysed by Instrumar[3] for Type II fluids (100% concentration) during snowfall obtained from both field and laboratory tests. Their analysis of the data found that precipitation rate and ambient temperature improved the prediction of fluid failure time and gave the following function for predicting fluid failure time:

$$TFF = (1.368/R^{0.560} + 0.01227\ TM + 0.423) \times 60 \qquad (A4)$$

where TFF is the time to fluid failure (minutes);
R is the precipitation rate ($g/dm^2/hr$); and
TM is the ambient temperature (°C)

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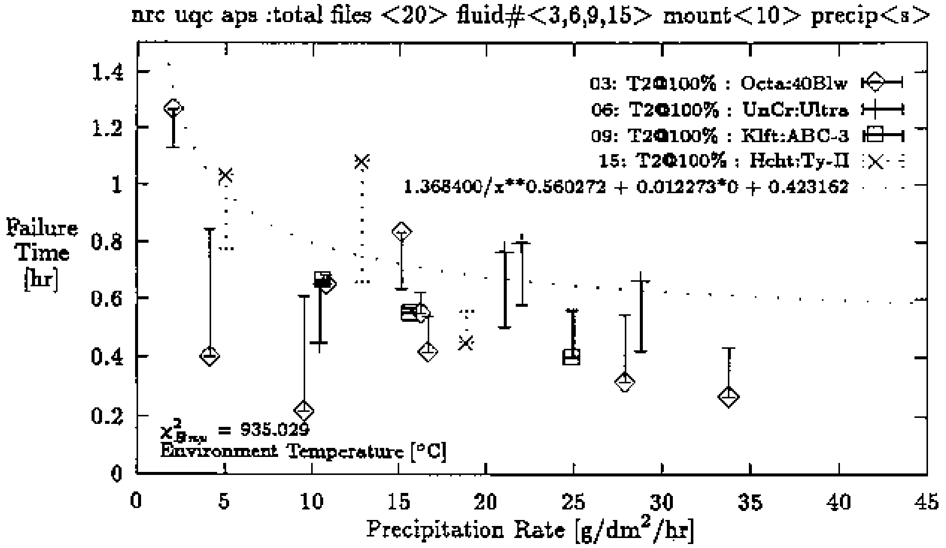
[3] Laboratory and Field Testing of De/Anti-icing Technologies, report prepared by Instrumar Limited for TDC, report TP12424E, Feb. 1995.



[Source: *Laboratory and Field Testing of De/Anti-icing Technologies*, Instrumar, Figure 3, pp. 21]

Figure A3 Fluid Failure Times for Type II Fluids at 100% Concentration during Snowfall - Field and Laboratory Tests

Actual failure times could fall anywhere around the expected value predicted using Equation A4 with the spread in points caused by the effect of other factors (e.g., wind speed, humidity, etc.). The spread in points around the expected value increases with increasing fluid failure time (this is even more evident with Type IV fluids discussed below). The variation for a particular fluid failure time was therefore expressed as a percentage of fluid failure time. The standard deviation of the percentage errors was calculated to be 30%. Thus, for a given precipitation rate and temperature, Equation A4 gives the expected failure time and the 95% confidence interval is approximately ±60% of that value. It is assumed that this distribution of failure times adequately represents the distribution over the different types of frozen precipitation, not just snow. (Note, the precipitation rate is g/dm^2/hr and allows for the difference in water content of the different types of precipitation). One exception was fluid failure times during ice pellet precipitation. These were reduced by 20% due to the possibility of ice pellets penetrating the fluid and causing local dilution of the fluid (due to their significant mass) and rapid failure.[4]

The distribution of fluid failure times for Type IV fluid was estimated from data given in a report by APS[5]. The data are plotted in Figure A4. The data did not include temperatures specifically, but the tests were conducted over a range of temperatures and the effect of temperature will therefore be included in the spread of points. The following function for predicting fluid failure time was derived from this data:

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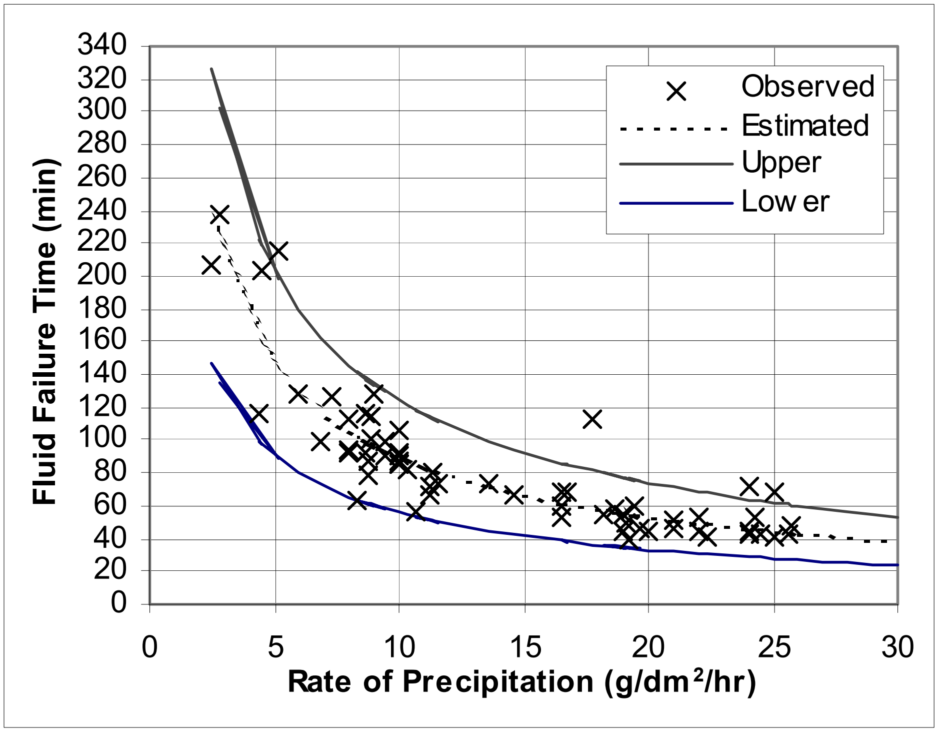
[4] Transport Canada Air Carrier Advisory Circular No. 0092, pages 6 and 7.

[5] *Aircraft Full-Scale Test Program for the 1995-1996 Winter* by APS Aviation, prepared for TDC, TC report TP 12901E, October 1996

$$TFF = 447 / R^{0.647} - 10.8 \qquad (A5)$$

Variation was again found to be related to the fluid failure time and the standard deviation in percentage errors was estimated to be 20%. The estimated failure time from Equation A5 and the 95% confidence interval of the failure time for given precipitation rates (given by ±40% of the estimated value) are also shown in Figure A4.



[Source: *Aircraft Full-Scale Test Program for the 1995-1996 Winter,* APS, Figure 3.4, pp. 28]

Figure A4 Fluid Failure Times for Type IV Fluids (100% concentration) for Simulated Freezing Drizzle and Light Freezing Rain - Flat Plate and Airfoil Tests

The effect of precipitation type for a given precipitation rate should be reflected in the distribution of failure times. However, few tests were conducted by APS in natural snow conditions during the 1995/96 winter due to unusual weather patterns. During the previous winter, tests conducted in natural snow conditions had a greater spread in fluid failure times for a given precipitation rate. The spread for a given precipitation rate was estimated to be 30%[6]. However, several problems were identified with the tests using Type IV fluids which may have caused premature failure in some tests. The results of tests conducted in the 1996/97 winter (not published early enough to be incorporated here) may provide better estimates of the distribution of failure times, in particular the

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[6] From Figure 2.12, pp. 44, of *Aircraft Full-Scale Test Program for the 1994-1995 Winter* by APS Aviation, prepared for TDC, TC report TP 12595E, December 1996

spread. The published HOT ranges indicate the standard deviation, reflecting the spread in times, varies between 18% and 29%, depending on the precipitation type and temperature[7]. Given this and the higher spread found for Type II fluids, a value of 25% for the standard deviation was used in the analysis. This value falls midway between the values for Type II (30%) and Type IV based on freezing rain (20%).

The distribution of fluid failure times for Type I fluid was estimated from the HOT tables. Table A2 gives the suggested ranges of HOTs for light, medium and heavy snowfall rates[8] and for freezing drizzle and light freezing rain[9]. Typical precipitation rates in g/dm^2.hr were assigned to these snowfall rates and are included in the table. The lower value of the HOT range represents, approximately, the shortest protection time that can be expected in these conditions. It is therefore equated to the lower end of the 95% confidence interval. Flat plate test results in natural snow and freezing drizzle conditions shown in Figures A5 and A6 were also used for predicting the protection time distributions.

Table A2 Fluid Failure Times for Type I Fluid Given in HOT Tables and Estimated Values

Precipitation		HOT* Range (min.)	Precipitation Rate (g/dm^2/hr)	Estimated Fluid Failure Times & 95% Confidence Interval (min.)		
				Expected	Lower	Upper
Snow	Light	12 - 15	5	30.0	12.0	48.0
	Moderate	9 - 12	15	18.8	7.5	30.0
	Heavy	6 - 9	25	15.0	6.0	24.1
	Very light		2	44.2	17.7	70.7
	Very heavy		35	13.0	5.2	20.7
Freezing	Drizzle	5 - 8	7	9.4	4.8	13.9
Freezing	Rain - light	2 - 5	25	5.1	2.3	8.0

* TC Air Carrier Advisory Circulars No. 0092 (Dec. 1995) and 0113 (March 1997)

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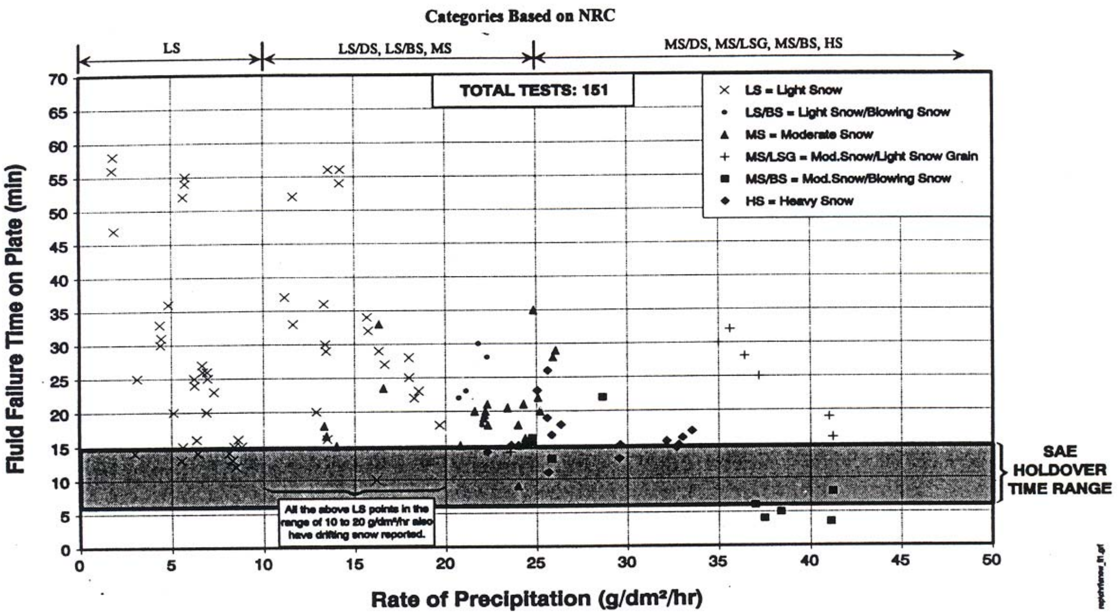
[7] HOTs in *Air Carrier Advisory Circular,* ACAC No. 0113, March 10, 1997, standard deviation (SD) found assuming lower value is 2 SDs below expected value, and upper value is 1 SD above expected value.

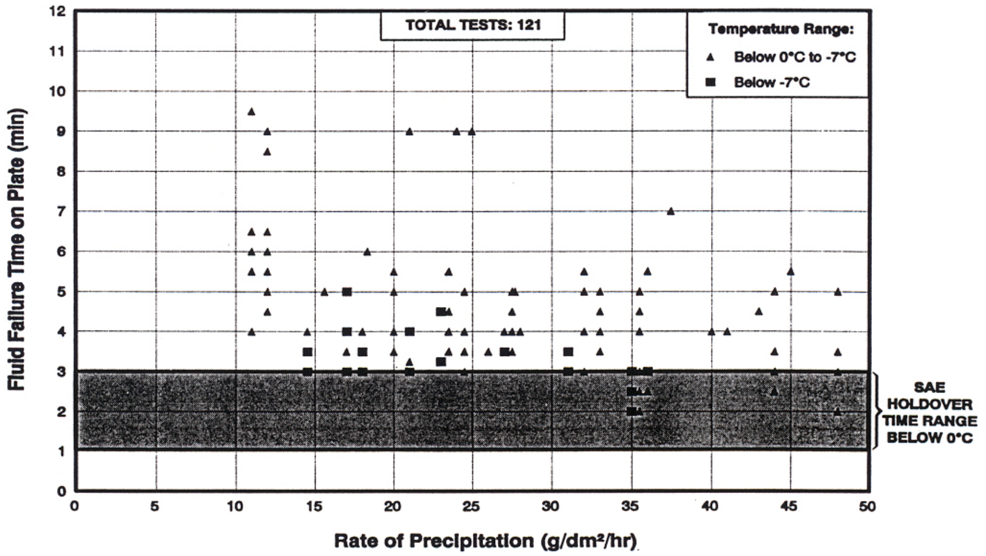
[8] TC Air Carrier Advisory Circular No. 0092

[9] TC Air Carrier Advisory Circular No. 0113, March 10th 1997.



[Source: APS report TP 11836E, Figure 5.3, pp. 62]

Figure A5 Fluid Failure Times for Type I Fluids (standard dilutions) in Flat Plate Tests in Natural Snow Conditions



[Source: APS report TP 11836E, Figure 5.3, pp. 62]

Figure A6 Fluid Failure Times for Type I Fluids (standard dilutions) in Flat Plate Tests in Simulated Freezing Drizzle

The holdover times of snow and freezing drizzle/rain appear to be related to both the precipitation rate and type of precipitation, and separate functions were therefore derived for the two types. In addition, for the low holdover times found with heavy freezing drizzle, the variation (spread in points) stabilized at low times. Thus, the standard deviation was estimated as a percentage of the expected holdover time plus a constant. For snow, the variation in fluid failure times for a given precipitation rate was assumed to be 30% (i.e., standard deviation of 30%), similar to that for Type II fluid. The following functions were derived from this data for predicting the mean and standard deviation of the failure time for Type I fluids:

For snow:

$$\mathrm{TFF} = 60 / R^{0.41} - 1.0 \tag{A6a}$$

$$\mathrm{SD} = 30\%\ \mathrm{TFF}$$

For freezing drizzle/rain:

$$\mathrm{TFF} = 23 / R^{0.41} - 1.0 \tag{A6b}$$

$$\mathrm{SD} = 20\%\ \mathrm{TFF} + 0.4$$

where SD is the standard deviation of the fluid failure time for a given precipitation rate.

The estimated failure times from Equation A6 and the 95% confidence interval of the failure time for given precipitation rates (given by ±2SD) are also given in Table A2. Estimates for very light and very heavy snowfalls are also given. This range of failure times compares well with values shown in Figures A5 and A6, and with the ranges in values from eleven tests given by Instrumar:

	Snowfall	Freezing Rain
Type I fluid failure times (minutes):	6 to 42	8.5 to 11
Precipitation rates (g/dm^2/hr):	27.9 to 3.8	31.8 to 9.1

As for Type II fluids, the fluid failure times during ice pellet precipitation were reduced by 20%.

A4. Precipitation Rate and Temperature Distribution

The precipitation rate and temperature distribution was derived from hourly weather data for Ottawa obtained from Environment Canada. The frequency of precipitation types at given ambient temperatures was determined for each month. The results, using the classifications used by Environment Canada and aggregated to an annual basis, are given in Table A3. The density of snow varies with temperature, the snow being usually slush when temperatures are above freezing, wet snow at temperatures of zero or just below freezing and dry snow when temperatures are well below freezing. Approximately 25% of the time that the temperature is in the critical range of 1 to -5°C, precipitation occurs which could lead to icing. Temperatures are in this range for about 16% of the time over the year in Ottawa.

Table A3 Frequency Distribution of Precipitation Types for Given Temperatures for Ottawa*

Temp. °C	Percentage of Time at Given Temperature Precipitation is: Snow			Snow	Freezing Rain		Freeze.	Rain & Showers			Drizzle	Ice	Dry	% at Temp.
	Low	Mod.	High	Showers	Low	Mod.	Drizzle	Low	Mod.	High		Pellets		
10-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	0.5	0.5	1.6	0.0	88.2	3.0%
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.3	0.4	0.3	1.1	0.0	86.1	2.4%
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8	0.8	0.3	2.7	0.0	84.1	2.4%
7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	15.9	0.4	0.0	4.4	0.0	80.6	2.4%
6	0.0	0.0	0.0	0.4	0.0	0.0	0.0	15.6	0.4	0.1	3.0	0.0	81.8	2.3%
5	0.1	0.0	0.0	0.5	0.0	0.0	0.0	15.5	0.8	0.0	2.9	0.1	81.3	2.4%
4	0.1	0.0	0.0	0.6	0.0	0.0	0.0	13.9	0.2	0.0	3.0	0.2	82.6	2.6%
3	1.0	0.0	0.0	1.8	0.0	0.0	0.0	11.6	0.1	0.1	4.1	0.2	84.4	2.6%
2	4.4	0.0	0.0	2.8	0.0	0.0	0.0	11.5	0.6	0.0	3.0	0.5	81.0	3.0%
1	12.4	0.0	0.0	4.6	0.0	0.0	0.0	8.1	0.1	0.0	4.1	1.0	73.6	3.1%
0	16.9	0.6	0.0	4.5	2.0	0.4	1.6	2.8	0.1	0.0	2.1	1.6	69.8	2.9%
-1	15.4	0.5	0.2	5.2	3.0	0.3	2.5	0.0	0.0	0.0	0.0	1.7	73.8	2.5%
-2	12.6	0.8	0.1	4.0	2.6	0.0	3.6	0.0	0.0	0.0	0.0	1.3	77.2	1.9%
-3	20.9	0.6	0.0	4.3	1.8	0.0	1.5	0.0	0.0	0.0	0.0	1.5	70.5	2.1%
-4	16.7	1.0	0.1	3.7	1.3	0.1	2.2	0.0	0.0	0.0	0.0	2.1	74.9	2.0%
-5	21.7	1.0	0.0	3.6	1.3	0.1	1.2	0.0	0.0	0.0	0.0	1.3	71.3	2.1%
-6	20.3	1.9	0.1	5.5	1.0	0.0	1.3	0.0	0.0	0.0	0.0	1.3	69.9	1.9%
-7	24.5	1.1	0.1	4.9	0.7	0.0	0.3	0.0	0.0	0.0	0.0	0.7	68.6	1.7%
-8	20.0	0.4	0.3	5.5	1.2	0.0	0.4	0.0	0.0	0.0	0.0	1.6	72.7	1.6%
-9	20.6	0.4	0.0	3.1	0.4	0.0	1.2	0.0	0.0	0.0	0.0	1.2	73.6	1.5%
-10	21.3	0.6	0.0	4.1	0.6	0.0	0.2	0.0	0.0	0.0	0.0	1.4	73.2	1.5%
-11	21.0	0.6	0.0	2.5	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2	75.7	1.4%
-12	23.0	0.4	0.0	3.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.7	73.2	1.3%
-13	19.6	0.2	0.0	3.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.9	76.4	1.2%
-14	21.2	0.5	0.2	1.6	0.0	0.0	0.2	0.0	0.0	0.0	0.0	1.2	75.5	1.0%
-15	16.2	0.5	0.5	2.8	0.0	0.0	0.8	0.0	0.0	0.0	0.0	1.0	79.7	0.9%
-16	13.4	0.9	0.0	1.5	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.9	83.4	0.8%
-17	12.7	0.3	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	83.4	0.8%
-18	9.2	0.0	0.0	3.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	1.5	86.3	0.7%
-19	4.3	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.0	0.6%
-24	5.6	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	91.7	0.6%
Total	6.3	0.2	0.0	1.6	0.4	0.0	0.4	3.6	0.2	0.1	2.9	0.0		100%

Notes:

- Distribution over full year (separate distributions over each month used in analysis).
- Based on data from Environment Canada over period 1983 to 1988 (approximately 50,000 hours).
- Precipitation categories used by Environment Canada.
- Care should be taken when interpreting percentages for the one precipitation type; percentages are for a given temperature and probabilities of temperatures differ (distribution given on right of table).

Precipitation rates, in units of g/dm^2/hr, were estimated from this distribution using the procedure used in a previous study by Sypher[10]. The method allowed for a range in

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[10] *An Analysis of Aircraft Take-off Risks in Icing Conditions*, by Sypher:Mueller International for TDC, Report No. TP 11683E, 1994

precipitation rates for each of the precipitation categories and allowed for the greater density of snow at higher temperatures. The estimated cumulative distribution of precipitation rates for Ottawa in icing conditions, given that it is precipitating, is given in Figure A7. Icing conditions were taken to be when precipitation occurs at temperatures of between zero and -20°C, or frozen precipitation occurs at above zero temperatures. From the figure it is evident that precipitation rates are usually low in icing type conditions. For example there is only about a 10% chance that the rate will be greater than 15 g/dm^2/hr in icing type conditions.

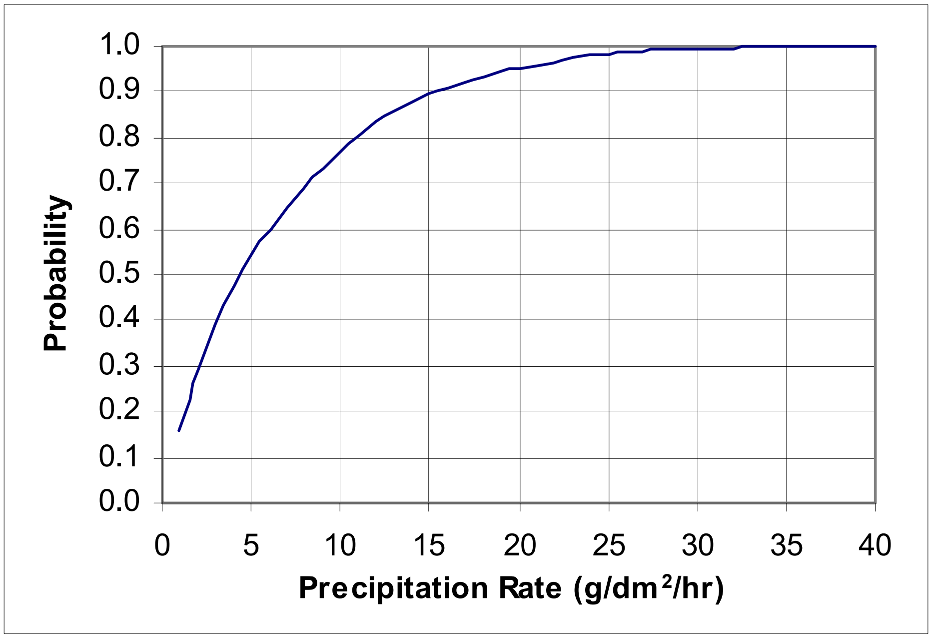

Figure A7 Estimated Cumulative Distribution of Precipitation Rates For Ottawa in Icing Conditions

Using the joint distributions of precipitation rates and temperatures derived from the Ottawa data and the distributions of fluid failure times for given precipitation rates and temperatures given previously, the distributions of times to fluid failure for Type I, II and IV fluids (Types II and IV at 100% concentration) were estimated. The three distributions are plotted in Figure A8. The non-smooth nature of the curve is due to it being estimated from points with different types of precipitation and ranges of discrete rates of precipitation and temperatures.

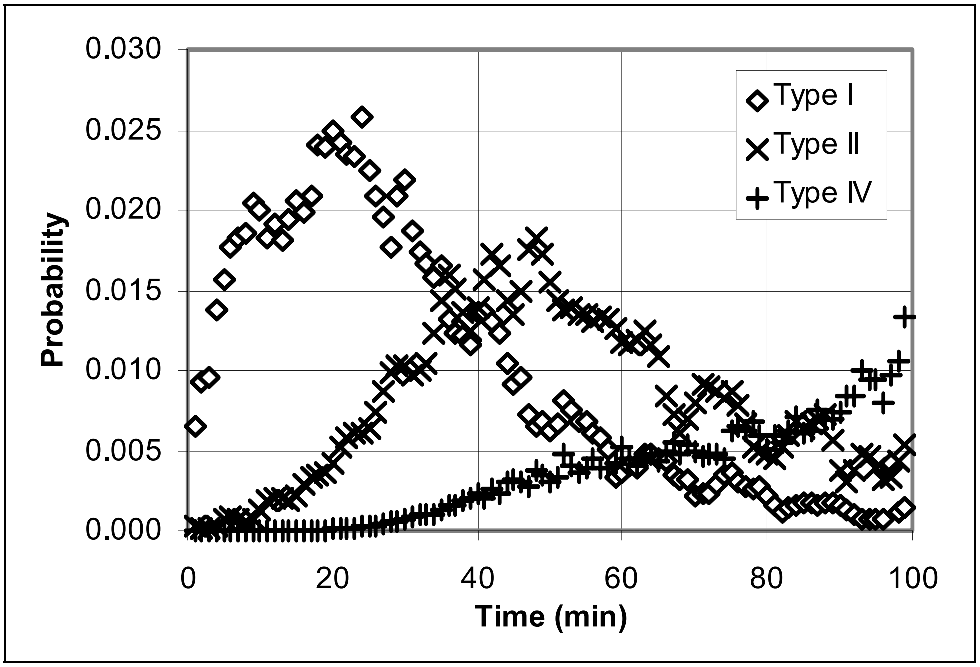

Figure A8 **Estimated Distributions of Times to Fluid Failure for Type I, II and IV Fluids (Types II and IV at 100% Concentration) For Weather Conditions at Ottawa Airport**

The estimated fluid failure probabilities and the major assumption made in determining these estimates, the reason for the assumption and their likely effect are given in Section 4.4.2.

A5. Frequency of Fluid Failure Prior to and After Pre-Take-off Inspection

The probability that the fluid will fail after the pre-take-off inspection and before take-off, given that it has not failed at the time of pre-take-off inspection, can also be estimated using the departure delay and weather data as follows:

$$P[\, TFF < TDT \mid TFF > TDT\text{-}TI \;\&\; \text{Deiced}] =$$

$$= \sum_{r \,\&\, t_m} P[TFF < TDT \mid TFF > TDT\text{-}TI \;\&\; \text{Deiced} \;\&\; R = r \;\&\; TM = t_m\,] \text{ x } P[\, R = r \;\&\; TM = t_m \mid \text{Deiced}]$$

$$\begin{aligned} = \sum_{r \,\&\, t_m} & P[TFF < TDT \;\&\; TFF > TDT\text{-}TI \mid \text{Deiced} \;\&\; R = r \;\&\; TM = t_m\,] \,/ \\ & P[\, TFF > TDT\text{-}TI \mid \text{Deiced} \;\&\; R = r \;\&\; TM = t_m\,] \text{ x} \\ & P[\, R = r \;\&\; TM = t_m \;\&\; \text{Deiced}] \,/\, P[\,\text{Deiced}\,] \end{aligned}$$

$$\begin{aligned} = \sum_{r \,\&\, t_m} \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_d-t_i<t_f<t_d} & P[TDT = t_d \;\&\; TFF = t_f \;\&\; TI = t_i \mid \text{Deiced} \;\&\; R = r \;\&\; TM = t_m] \text{ x} \\ & P[\, TI = t_i \mid \text{Deiced} \;\&\; R = r \;\&\; TM = t_m\,] \,/\, P_{PI} \text{ x} \\ & P[\, R = r \;\&\; TM = t_m \;\&\; \text{Deiced}\,] \,/\, P[\,\text{Deiced}\,] \end{aligned} \qquad \text{(A7)}$$

where TI is the time interval between pre-take-off inspection and take-off;

P_{PI} is the probability that fluid fails after pre-take-off inspection, and is calculated in a similar way to the above probability (Equation A7), but without the condition TFF > TDT-TI, and with the summation of t_f restricted to after the time of the pre-take-off inspection:

$$P_{PI} = \sum_{r\ \&\ t_m} \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_f>t_d-t_i} P[TDT = t_d\ \&\ TFF = t_f\ \&\ TI = t_i \mid Deiced\ \&\ R = r\ \&\ TM = t_m] \text{ x } P[\,TI = t_i \mid Deiced\ \&\ R = r\ \&\ TM = t_m\,] \text{ x } P[\,R = r\ \&\ TM = t_m\ \&\ Deiced\,] / P[\,Deiced\,] \qquad (A8)$$

(Note that other variables defined with Equation A2.)

The sum over r & t_m in Equations A7 and A8 can be restricted to the sum over r & t_m such that the aircraft is deiced since otherwise $P[R = r\ \&\ TM = t_m\ \&\ Deiced] = 0$. The probability aircraft is deiced is calculated using Equation A3

The probability that the fluid will fail prior to the pre-take-off inspection can then be found by subtracting the probability of it failing between the inspection and take-off from the probability of it failing before take-off.

The distribution of the time interval between pre-take-off inspection and take-off used in the analysis is given in Figure 4.5 and the probabilities of fluid failure prior to the pre-take-off inspection and between this inspection and take-off are given in Section 4.4.3.

APPENDIX B

ANALYSIS OF IDENTIFICATION OF FLUID FAILURE BY POINT SENSORS

ANALYSIS OF IDENTIFICATION OF FLUID FAILURE BY POINT SENSORS

Currently, fluid failure is determined by visually observing the fluid and assessing whether set criteria are met. Point and area sensors have been calibrated to match the visually observed failures. Initial findings from wind tunnel tests conducted by the Canadian National Research Council (NRC) indicate that the point of fluid failure based on the current criteria corresponds closely to the point where aerodynamic performance is significantly affected. In the following analysis of sensors, the time of fluid failure visually observed under ideal conditions is taken to be the basis for comparison. However, it is recognized that there is some degree of variation, or error, in this visually observed time, and that this variance/error is greater in less than ideal viewing conditions.

The critical elements that were considered when assessing the identification of fluid failure by point sensors are:

- how well do point sensors identify fluid failure in comparison to visually observed fluid failure at the sensor under ideal conditions;
- how well do point detectors identify fluid failure outside in actual icing conditions, considering the accuracy of visual observations made in those conditions which are used for comparison;
- how does the time of fluid failure vary over the wing in actual conditions;
- how well can a small number of sensors predict fluid failure on any part of the wing, how many detectors are required and where should they be located;
- if fluid failure occurs before the sensors identify fluid failure, how much of the wing is affected, how critical are those areas and to what degree has the fluid failed?
- what is the probability of the sensor system not identifying first fluid failure prior to take-off, and
- how much of the critical area of the wing will be contaminated at the time of take-off if the fluid fails prior to take-off and the sensor system does not identify failure before take-off (what is the probability distribution of this critical area).

In setting the location of the sensors, this analysis considers the optimal location from the standpoint of the likely areas of fluid failure and the effect on aerodynamic performance of failure in those areas. The practicality of locating sensors in those locations are not considered. If the sensors are located in other positions, the risks will be greater. In this regard, the analysis may over state the ability of sensors to identify fluid failure. However, this, will be offset too some extent by optimally locating sensors for each aircraft type.

These questions are examined in the sections below.

B.1 Comparison of Visually Observed and Sensor Predicted Fluid Failure

B.1.1 Université du Quebec à Chicoutimi Tests

The Université du Quebec à Chicoutimi (UQAC) conducted holdover time performance tests[1] with de/anti-icing fluids to evaluate the consistency between visually observed failure times of the fluid on the sensor head and times indicated by the CWDS sensor. Readings from a sensor mounted on an airfoil were compared with visually observed failure times at the sensor location under simulated icing conditions with a range of precipitation rates. Similar comparisons were made with the sensor mounted on a flat plate inclined at 10°. Visual time of failure of fluid over the sensor head was recorded for when 1%, 50% and 100% of the fluid on the sensor head had failed. These are compared with a single time of fluid failure predicted by CWDS. The comparisons are shown Figures B1 and B2 for the sensor on the flat plate, and in Figure B3 for the sensor mounted on the airfoil. A line is shown indicating where the visual and CWDS fluid failure times are equal. Points below the line correspond to where the sensor indicated fluid failure after visual observation.

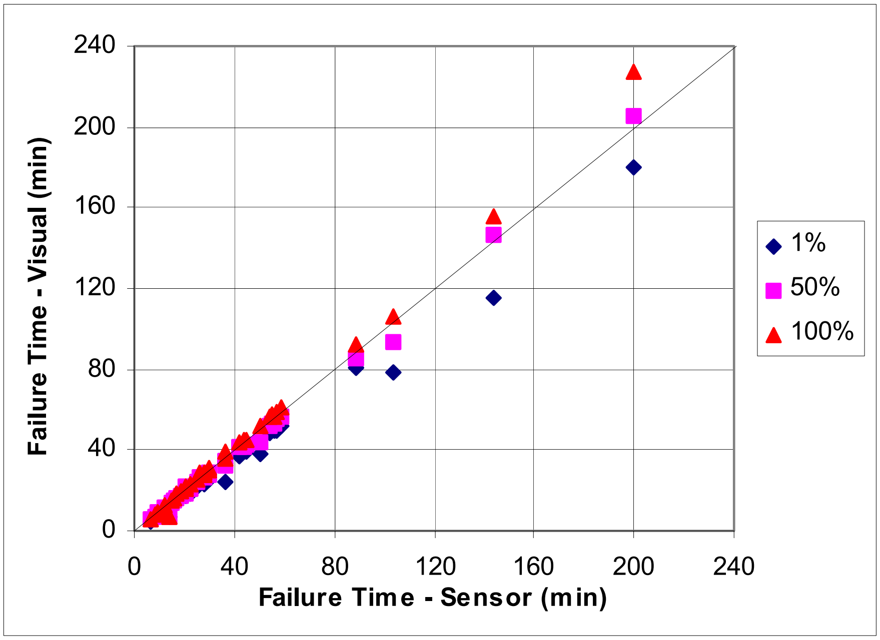

Figure B1. **Visually Observed Times to Failure Over 1%, 50% and 100% of the Sensor Head Versus CWDS Failure Time for Sensor Mounted on Flat Plate**

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[1] "Holdover Time Performance of De/Anti-icing Fluids: UQAC Tests Using CDWS Sensor", report by UQAC for TDC, Report No. TP12599E, Dec. 1995

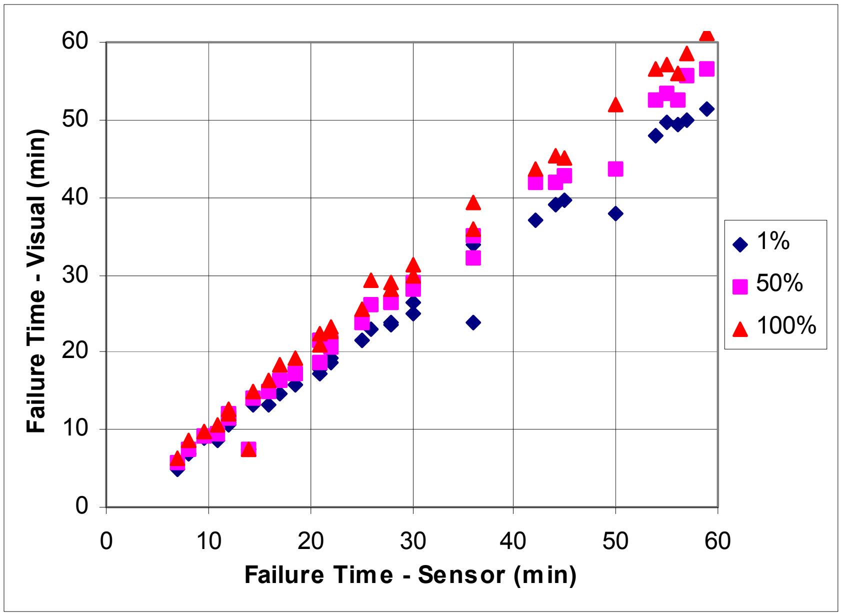

Figure B2. **Visually Observed Times to Failure Over 1%, 50% and 100% of the Sensor Head Versus CWDS Failure Time for Sensor Mounted on Flat Plate - Subset of Failure Times Less Than 60 Minutes**

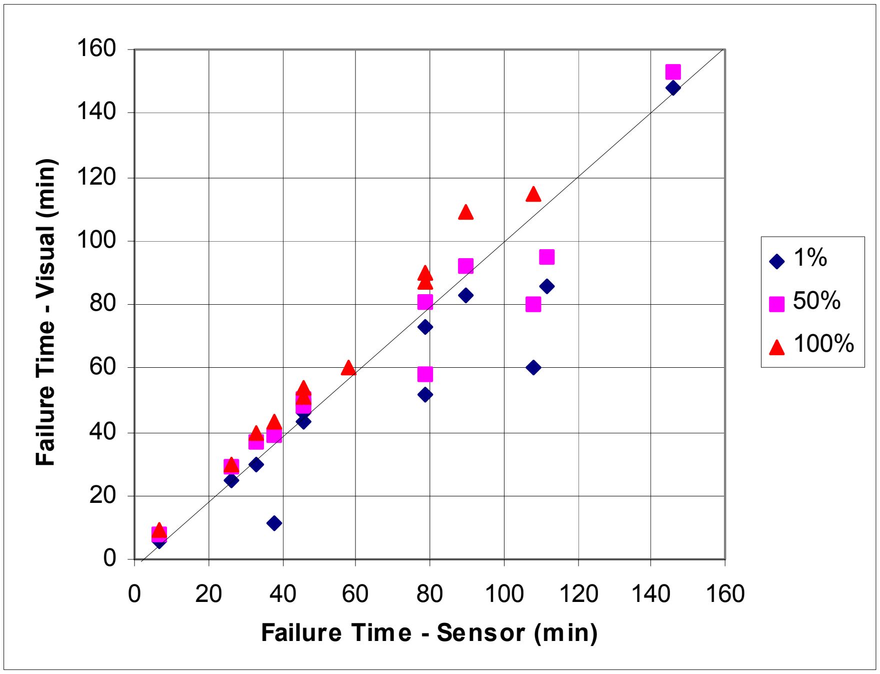

Figure B3. **Visually Observed Times to Failure Over 1%, 50% and 100% of the Sensor Head Versus CWDS Failure Time for Sensor Mounted on Airfoil**

The three figures indicate that:

- the CWDS and visually observed failure times of fluid on the sensor head are generally similar;
- the CWDS failure time is consistently after the time of first failure, and typically between the visually observed 50% and 100% failure times;
- the differences between the CWDS and visual observations tend to vary more as the failure time increases; and
- there appears to be more variation between the times when the sensor is mounted on the airfoil.

Comparisons of the visually observed failure times over 50% and 100% of the sensor head with the CDWS times indicates that the CDWS values correspond <u>on average</u> with failure of fluid over 75% of the sensor head, based on visual observation. Summary statistics of the difference between the sensor fluid failure time and the estimated visual 75% failure time (average of 50% and 100% values) are given in Table B1. The flat plate tests include one test where slush was observed to form over the sensor head after 7.5 minutes and the sensor did not identify fluid failure until the 14 minute mark - a 6.5 minutes (89%) difference. Since this point was far outside the distribution of all other data, statistics are given with and without this point included. The implications of outlying points such as this are discussed below. In addition, as the variation of the difference increases with increasing failure time, statistics are also given for percent differences.

Table B1. Summary Statistics for Difference* Between Sensor and Visual (of 75% of Sensor Head) Fluid Failure Times

Summary Statistic	Sensor Located on:		
	Flat Plate		Airfoil
	All Points	Exclude Outlyer	
No. of Observations		31	13
Average difference (min)	-0.1	-0.3	-1.3
Maximum difference (min)	6.5	4.0	12.0
Standard error of estimate (min)	3.4	3.2	7.6
95% Confidence Intervals of difference	6.8	6.5	16.6
Average % difference	3.3%	0.9%	-4.3%
Maximum % difference	87%	16%	12%
Standard error of estimate	16%	4%	11%
95% Confidence Intervals of difference	32%	9%	24%

* Difference: (Sensor time) - (Average of Visually Observed failure over 50% and 100% of sensor head)

On average the sensor and visually observed fluid failure times are very close, differing by less than 0.3 minutes for the flat plate tests and by 1.3 minutes of the airfoil tests. In

14% of tests the sensor identified fluid failure after 100% of the sensor head was visually observed to fail. Excluding an “outlyer”, the sensor identified failure time was up to 4.0 minutes after the visually observed time on the flat plate tests, while for the airfoil tests, the sensor time was up to 12 minutes after the visually observed time. These maximum differences were 16% and 12% of the failure time, respectively. Allowing for the variation in the differences and the sample size, the 95% confidence intervals indicate the sensors could be as much as 9% greater than the visually observed failure time (of 75% of the sensor head) on the flat plate, or 24% greater on the airfoil.

An analysis of the differences between the sensor and visual observed failure times showed no relationship between them and the precipitation rate.

The outlying point occurred when slush formed on the sensor head prior to the ice front travelling down the plate reaching the sensor. This phenomenon was observed to occur occasionally during periods of high precipitation, but only once on the sensor head. Slush formation was typically observed to occur well before the ice front on both the flat plate and airfoil tests. It is not clear from the data provided whether the formation of slush on the surface in these cases represents actual ice formation which would be detrimental flight. This is critical if sensor observations are to be used with confidence. The consistency of the CDWS readings in identifying ice formation in the other tests and the wide difference in this case indicates that the slush formation in this test may not represent the onset of ice formation.

Thus, it can be concluded that the fluid failure times of the CWDS sensor correlate well with visually observed failure on both flat plates and airfoils under ideal viewing conditions. However, even excluding the “outlyer”, a safety margin of about 25% is required if the sensor is to reliably identify fluid failure before the visually observed failure at a particular point.

It could be argued, however, that the sensor represents a more consistently accurate method of identifying fluid failure and that the safety margin should be applied to the visually identified failure times. Considered in this way, in 8% of tests first failure was identified after the fluid had failed (according to CWDS), and “50% failure” was identified after the fluid had failed in 69% of tests on the airfoil. If the time when 75% of the fluid on the sensor head is visually observed to fail is used to determine fluid failure (the percentage where visual and sensor correlate best), a safety margin of about 20% would be required to reliably identify failure before the sensor. This corresponds roughly to the time between first failure and time when 75% of sensor head was visually observed to fail.

B.1.2 Instrumar Tests on BAe 146 Aircraft

Instrumar conducted a series of tests in 1995 with the CWDS sensor system installed in a BAe 146 aircraft[2]. During freezing precipitation (snow and blowing snow) with Type I fluid applied, the condition of the leading and trailing edges of the inner and outer sections of each wing and the horizontal stabilizer were observed. Sensors were located near the wing tips and horizontal stabilizer tips on both sides of the aircraft, however, the left tail sensor was out of service during the tests. Times when the fluid was visually observed to fail over the sensors were also recorded and the corresponding outputs from the CWDS were recorded.

Comparison of Visual Observation and Sensor Prediction at Sensor Location

From the three tests, six sets of observations were made and the results are summarized in Table B2.

Table B2. Comparison of Visual Observation and Sensor Prediction at Sensor Location

Side of Aircraft	Test	Visual Observed (min)		Sensor Fail (min)	Difference from 1st	% Difference
		1st failure	100% fail			
Right	B	18.8	20.5	15.2	-3.6	-19%
	C	void	8.7	3.6		
	D	5.8	void	11.0	5.2	90%
Left	B	12.6	16.2	6.3	-6.3	-50%
	C	6.7	7.7	11.6	4.9	73%
	D	4.6	6.5	2.4	-2.2	-48%

The sensor and visually observed failure times varied significantly from each other and showed no consistent trends. Lack of agreement in the two methods of identifying time of failure is in contrast with the results of the UQAC tests. Possible causes of the differences are:

- The visual observation is based on fluid properties at the surface of the fluid, but the sensor measures fluid integrity at 3 levels in the fluid;
- Visual observation of failure on top of the sensor head was noted as being difficult in flat plate tests. In the aircraft tests, observers were positioned at the sensor, but tests were conducted at night with observers equipped with a flash light. It was noted by Instrumar that this “allowed the complete area on and around the sensor to be monitored effectively”. Given the results, this may not have been the case; and

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[2] “Flight Crew Information Requirements & Human Factors Supplemental Report’, by Instrumar for TDC, TP 12574E, Aug. 1995.

- The inherent difficulty in assessing fluid failure in actual conditions on an aircraft wing at night. If this is the case, identification by the pilot from inside the cabin with little lighting would be even more difficult.

The sensor failure times are, on average, closer to the time of first failure at the sensor identified visually. In the UQAC tests, the sensor times matched the visually observed failure time of about 75% of the sensor head. If the sensor failure times more closely represent the actual failure time, the first visually observed failure times offer no margin of safety as was the case in the UQAC tests.

Given the reasonable consistency in sensor and visually observed failure under ideal conditions in the UQAC tests, the lack of agreement between the sensor and visually observed failure times is likely indicative of the difficulty of visually assessing fluid failure on an aircraft in actual conditions.

Comparison of Visual Observations and Sensor Prediction on Same Wing/Tail

The times the fluid was visually observed to fail on various parts of the wing or tail and the corresponding times the sensor identified fluid fail on that wing or tail are given in Table B3. The shaded areas indicate the percentages of those sections where the fluid had failed prior to the sensor on that wing or tail. In two tests the wing was visually observed to be 100% failed before the sensor identified fluid failure (C-left and D-right). Similarly, when the sensor identified fluid failure, the outer right wing was visually 100% failed in test B and the right tail was visually 75% failed in test C. For the other tests and locations the sensors did not disagree significantly from the visual observations. Of the 15 cases considered, in 6 (40%) the wing was at least 25% failed (by visual observation) when the sensor identified fluid failure. In those 6 cases, the sensor failure time was on average 2.9 minutes after the 25% visual failure time (range 0.6 to 5.5 min.).

It can be concluded that a single sensor located in the wing or tail cannot reliably predict when the fluid will fail in that wing.

Despite the lack of agreement between sensor and visually observed failure in the same area, the use of three sensors (one on each wing and one on the right tail) was effective in predicting the time of first visually identified fluid failure. In the three tests, the minimum sensor fluid failure time was similar to, or slightly less than, the visually identified time of first failure on the aircraft. Three tests are too few to base any conclusions on, but this indicates that reliability can be greatly increased by increasing the number of sensors.

Table B3. Comparison of Times fluid was Visually Observed to Fail and Times Sensor Identified Fluid Fail on Same Wing or Tail

Test	Location		Visually Observed Failure Time (min)*						Sensor
	Side	Wing/Tail	1st	1 sq ft	25%	50%	75%	100%	Failure
B	Right	Outer wing	7.3	11	11.9	12.3	13.3	15.1	15.2
		Inner wing	12	16.7	18.5	20.9	23.8	27	
		Tail	8.1	9.4	11.1	13.9	15.5	void	11.7
	Left	Outer wing	11	void	void	void	13.7	14.5	6.3
		Inner wing	10.6	11.6	13.1	14.2	14.2	14.2	
C	Right	Outer wing	3.5	4.8	5.3	5.8	void	8.1	3.6
		Inner wing	void	void	5.5	6	6.8	8.3	
		Tail	4.3	5.6	6.3	7.3	7.8	9	8.5
	Left	Outer wing	4.9	5.5	void	void	6.3	7.2	9.4
		Inner wing	5.9	6.1	6.9	7.8	void	8.3	
D	Right	Outer wing	3.5	4.8	5.4	7.4	8.1	9.6	10.9
		Inner wing	5	7.3	7.8	8.3	8.7	10.2	
		Tail	6.6	void	void	10.2	13.3	14.1	7.5
	Left	Outer wing	void	3.7	4.7			5.7	2.4
		Inner wing	void	3.9	6.4	7.3	8.1	8.7	

* Minimum of the failure times at the leading and trailing edges.
Shaded cells represent cases where visually observed failure occurs before sensor identifies failure

B.2 Analysis of Fluid Thickness on Aircraft Wing

A primary influence on the time of failure of a de/anti-icing fluid is the thickness of the fluid. An analysis of fluid thickness can therefore provide an indication of the likely distribution of early fluid failures over the wing and the most effective locations for locating sensors. Wing temperature is also an important determinant for fluids with short protection times, such as Type I fluids. For these fluids, fluid thickness and the amount of heat absorbed into the wing surface are the primary influences on the failure times.

Tests were conducted by APS on the Canadair RJ, DC-9 and A320 in early 1996[3]. The thickness of the fluid was measured at 12 to 15 points across two or three cords of the wing at a number of time points after fluid application. Between 4 and 6 tests were conducted on each aircraft type using two or three fluid combinations. The stabilized fluid thickness were analysed to determine:

- The consistency of the fluid thickness at points along the cord within each wing section. If the same points consistently have the thinnest fluid, they will likely consistently fail first at those points. If no point is consistently the thinnest, how much variation is there. [These results are of use in Section B.3 below.]

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[3] "Evaluation of Fluid Thickness to Locate Representative Surfaces", by APS Aviation to TDC, TP 12900E, Oct. 1996.

- The consistency with which particular points have the thinnest fluid over the cords examined.

In the first analysis, the wing was divided into sections - leading edge, middle and trailing edge, and the fluid thickness at each point on a wing section was ranked (1 for thinnest, 2 for second thinnest, etc.). The average and maximum rank over the tests for each aircraft type were calculated for each test point on each cord, and are given in Table B4. A low average (close to 1) for a point indicates that if a sensor was placed at a distance from the leading edge similar to that point, it would likely fail before points at other distances from the leading edge in that wing section. The maximum is an indication of how many other points along the cord in that section could fail first.

As expected, the location of the steepest part of the leading edge consistently has the thinnest fluid of those points on the leading edge wing sections - true for all 3 aircraft and each cord tested. Optimally, sensors should be located in that area. The further back from the leading edge in the leading edge wing sections, the thicker the fluid. From a practical standpoint it is acknowledged that it may not be possible to locate the sensors near the steepest part of the leading edge and location of the sensors back from the edge will likely increase the risks.

In the middle wing sections, there is more variation in the locations of the smallest fluid depths. Locations towards the trailing edge side of the middle section, on average, have thinner fluid than other distances along the cord. This is consistent across the three aircraft types and the cords examined. However, the maximum rank indicates that several other points along the cord sometimes have thinner fluid. On these occasions, the fluid would likely fail first at these points.

In the trailing edge wing sections, the locations of the thinnest fluid vary greatly along the wing span and between aircraft types due to the different flap configurations. Even at the points where, on average, the fluid is thinnest, the maximum rank indicates that depths at many other points in that section are sometimes thinner. Thus, optimal sensor locations in the trailing edge wing sections are very dependent on the aircraft type and, even for aircraft of the same type, fluid failures on the trailing edge section will not consistently occur first at those locations.

The same sets of thickness measurements were analysed to determine the consistency of locations where the fluid was thinness, or close to the thinnest, over the whole wing. Locations where the fluid was thinnest were given a weighting of one, while locations where the fluid was within 0.2 mm of the smallest depth, were given a weighting one half. The weighted proportion of tests where the thickness of the fluid was close to lowest over all locations examined are given for each point on the cords tests in Table B5.

Table B4. Average and Maximum Rank Order of Thickness of Fluid at Points in Each Wing Section Along Each Cord

Aircraft		Cord 1 (Section T6) Fuselage Side										No. of Tests
		L1	L2	L3	M1	M2	M3	T1	T2	T3	T4	
RJ	Average	1.0	1.8	3.0	1.5	3.0	1.5	2.0	2.8	1.3	2.0	4
	Maximum	1	2	3	2	3	2	3	3	2	4	
DC9	Average	1.0	2.2	2.8	1.8	2.2	1.4	2	1.8	1.5	1.2	6
	Maximum	1	3	3	3	3	2	4	3	2	2	
Both	Average	1.0	2	2.9	1.7	2.6	1.4	2	2.2	1.4	1.5	10
	Maximum	1	3	3	3	3	2	4	3	2	4	

		CORD 2 (Section T4/5) Mid-Wing											
		L1	L2	L3	M1	M2	M3	T1	T2	T3	T4	T5	T6
RJ	Average	1.0	1.8	3.0	2.8	2.3	1.0	3.0		2.8	2.0		1.0
	Maximum	1	2	3	3	3	1	3		3	3		1
DC9	Average	1.0	1.7	2.0	1.8	2.3	1.5	3.3	2.8	3.3	3.0	1.7	1.7
	Maximum	1	2	3	2	3	3	6	5	4	3	3	3
Both	Average	1.0	1.7	2.4	2.2	2.3	1.3	3.2	2.8	3.1	2.6	1.7	1.4
	Maximum	1	2	3	3	3	3	6	5	4	3	3	3

		CORD 3 (Section T3) Wing Tip Side														
		L1	L2	L3	L4	M1	M2	M3	T0	T1	T2	T3	T4	T5	T6	T7	T8
RJ	Average	1.0	1.7	3.0	3.7	2.3	2.3	1.7		6.5	7.5	4.0	3.8	3.3	2.3	1.3	2.3
	Maximum	1	2	3	4	3	3	2		7	8	6	5	4	3	2	6
DC9	Average	1.0	1.7	2.2		1.7	2.2	1.0	7.7	8.3	1.5	1.8	3.5	3.2	4.0	3.8	5.8
	Maximum	1	2	3		2	3	1	8	9	4	4	6	6	6	6	8
Both	Average	1.0	1.7	2.4	3.7	1.9	2.2	1.2	7.7	7.6	3.9	2.7	3.6	3.2	3.3	2.8	4.4
	Maximum	1	2	3	4	3	3	2	8	9	8	6	6	6	6	6	8

		Cord 1 (Section T6) Between Engine & Fuselage													No. of Tests
		L1	L2	L3	L3a	M1	M2	M3	M4	T1	T2	T3	T4	T5	
A320	Average	1.0	1.8	2.4	4.0	2.4	2.2	2.0	2.0	3.6	2.0	3.2	1.4	1.8	5
	Maximum	1	2	3	4	4	4	3	4	5	5	4	2	3	

		CORD 3 (Section T2) Wing Tip Side															
		L1	L2	L3	L4	L5	M1	M2	M3	M4	T1	T2	T3	T4	T5	T6	T7
A320	Average	1.0	2.2	3.2	3.6	3.4	3.2	1.6	1.4	1.2	1.0	1.2	2.2	4.4	4.0	4.2	6.4
	Maximum	1	3	5	5	5	4	3	2	2	1	2	3	6	6	6	7

For each aircraft particular points on the leading edge consistently had thinner fluid than most other locations on the wing examined. In these tests, the leading edge on the inner side of the wing typically had the thinnest fluid.

Table B5. Proportion of Tests where Thickness of Fluid at Location was Either the Thinnest or Close to the Thinnest of All Locations Examined

A/C	Cord 1 (Section T6) Fuselage Side										No. of Tests
	L1	L2	L3	M1	M2	M3	T1	T2	T3	T4	
RJ	0.9	0.5	0	0	0	0	0	0	0	0	4
DC9	0.3	0	0	0	0	0	0	0	0	0	6

	CORD 2 (Section T4/5) Mid-Wing											
	L1	L2	L3	M1	M2	M3	T1	T2	T3	T4	T5	T6
RJ	0.4	0.1	0	0	0	0	0	0	0.1	0	0	0.3
DC9	0.9	0.3	0.3	0.2	0.3	0	0	0	0	0	0	0

	CORD 3 (Section T3) Wing Tip Side															
	L1	L2	L3	L4	M1	M2	M3	T0	T1	T2	T3	T4	T5	T6	T7	T8
RJ	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DC9	0.4	0	0	0	0	0	0	0	0	0.6	0.4	0.2	0.3	0	0.3	0

	Cord 1 (Section T6) Between Engine & Fuselage													No. of Tests
	L1	L2	L3	L3a	M1	M2	M3	M4	T1	T2	T3	T4	T5	
A320	1.0	0.3	0.2	0.1	0.1	0.1	0	0	0	1	0	0.1	0	5

	CORD 3 (Section T2) Wing Tip Side															
	L1	L2	L3	L4	L5	M1	M2	M3	M4	T1	T2	T3	T4	T5	T6	T7
A320	0.7	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0	0	0.1	0.1

B.3 Analysis of Progression of Fluid Failure on Aircraft Wing

The variation in the locations of fluid failure on the wing and the number of sensors that would be required to provide an adequate margin of safety was investigated by considering the patterns of fluid failure observed during 37 holdover time field trials (the tests used are listed at the end of this Appendix). It is assumed that the point sensors will accurately identify failure of the fluid is in close proximity to the sensor. The main considerations in the analysis were:

- at what time does the fluid fail on the very small area of the wing in close proximity of the sensor;
- at that time, over what areas of the wing had the fluid already failed, and how critical were those areas for safe flight; and
- in those areas of the wing where the fluid had already failed, for how long had the fluid been in the failed condition (measured by the average time since the fluid failed).

The procedure used to determine the likely extent of icing prior to fluid failure at the sensor is illustrated below. The case of one sensor at a given location based on data from one test is described.

- For each wing section, the percentage of the section where the fluid had failed was recorded for discrete time points (see example in Table B6);
- For a detector located on a given section, the probability of the sensor being under (or close proximity to) the failed fluid on that section was estimated for each time point (equivalently, the probability the sensor identified fluid failure at that time point);
- For each time point, the proportions of each of the other sections that failed prior to that time was calculated;
- Combining the probability that the sensor was under the failed section at each time point with the proportion of other sections failed at that time, the proportion of other sections to fail prior to the sensor was estimated;
- By weighting each wing section by its area, the expected proportion of the area of the wing where the fluid would fail prior to the fluid on the sensor was estimated;
- Since the location of ice on some parts of the wing is more critical than others, a weighted expected proportion was also calculated. The criticality factors given in Section 6 were used:

◊ leading edge	1.0
◊ middle section	0.2
◊ trailing edge	0.2

- For those areas were the fluid failed prior to failure on sensor, the average time interval between the two, weighted by the area failed, was estimated;
- Since the most hazardous conditions occur when:
    - ◊ fluid fails prior to sensor on a high proportion of the area of the wing;
    - ◊ the fluid failures occur on the most critical parts of the wing; and
    - ◊ the length of time between fluid failure and sensor warning is large;

  the measure of severity used was the product of the proportion of wing area failed prior to the sensor warning, weighted by criticality factor, and the mean time the fluid failed first.

These probabilities and measures were estimated for each of the 37 tests where sufficiently detailed failure time data was available. Probabilities of fluid failure on other parts of the wing prior to failure on the sensor were estimated based on all these tests. The expected time interval between fluid failure and failure at the sensor was not calculated over all tests as the tests involved Type I, II and VI fluids under varying conditions and had very difference times to failure. Since the spread of the failure times is approximately proportional to the time of first failure, the expected value of the following ratio was estimated based on the 37 tests:

$$\text{Ratio} = \frac{\text{Average time between failure at sensor and other fluid failures}}{\text{Time to first fluid failure.}}$$

In estimating the probability that a sensor, located on a given section of wing, will be able to identify fluid failure when the fluid has failed on only part of that section, it is assumed that:

- the probability is proportional to the proportion of the section on which the fluid has failed;
- the detector is of a finite size and thus the smaller the section, the higher the probability of the sensor identifying the failed fluid - an effective size of 0.2% of the wing area is used implying that 500 detectors would effectively cover the compete wing;
- the probability is related to the consistency of the location of the thinnest fluid over that particular section; previous experience has shown that the fluid will likely fail in some areas earlier than others (such as on steep sloping sections, near joints, discontinuities, etc.).

Table B6. Fluid Failure Time Progression on Various Sections of the Wing for Test L2

Location*	Time and % of Section where Fluid has Failed					
	8 min	11 min	13 min	16 min	20 min	25 min
T1L	70	80	100	100	100	100
T1M	20	20	100	100	100	100
T1T	10	75	100	100	100	100
T2L	0	20	50	90	100	100
T2M	0	0	5	80	80	100
T2T	5	25	60	90	90	100
T3L	0	20	50	75	95	100
T3M	0	0	0	50	50	100
T3T	5	20	50	85	85	100
T4L	0	12	40	65	85	100
T4M	0	0	0	40	40	100
T4T	0	40	75	85	85	100
T5L	0	12	30	60	75	100
T5M	0	0	0	75	75	100
T5T	0	30	70	75	75	100
T6L	0	12	30	50	70	100
T6M	0	10	10	100	100	100
T6T	0	15	30	75	75	100
T7L	0	10	35	50	70	100
T7M	0	35	35	100	100	100
T7T	65	68	75	90	100	100

* Notation for wing section - length of wing broken into 7 sections, T1 near wing tip to T7 near fuselage, and wing cord broken into 3 sections:

L leading edge "where the curvature of the upper wing surface begins to taper off and round out towards the under wing surface" typically there is a visible seem in the aluminium skin,
M middle section (between leading and trailing edge sections), and
T trailing edge "between the inner edge of the aileron and flap hinges and the trailing edge of the wing".

In some tests, results were not recorded for all sections, but were recorded for T2 and T4 and often for the representative sections.

Fluid failure progression data was only available from 37 tests, including tests on a DC9, A320, B737, F28 and a BAe 146. Due to the small number of tests, the analysis was done using data on all aircraft types together. The data indicates that fluid failure progression may vary by aircraft type and the analysis should be repeated by aircraft type when sufficient data becomes available. **Use of data on all aircraft types combined will lead to conservative estimates of the risks** as optimizing the location of sensors for each aircraft type will increase the likelihood of early identification of fluid failure.

B.3.1 Single Sensor on Wing

The results for use of a single sensor to warn of fluid failure are given in Table B7 for two possible sensor locations. The table illustrates that there is considerable variation in how well a sensor at a particular location will warning of fluid failure over the whole wing. In five tests the fluid had failed on less than 10% of the wing when a sensor in section T4L indicated fluid failure (i.e., fluid at sensor location failed). However, in eight tests over 50% of the wing was contaminated when a sensor, located in the same section, indicated fluid failure. The average time these sections had been contaminated prior failure at the sensor was significant - over 15 minutes in a quarter of the tests.

The results for a single sensor to warn of fluid failure averaged over a number of tests are given in Table B8 for various locations of the sensor. The leading edge in Section 2 (near wing tip) appears to be the best location, based on these tests, especially taking into account the duration of failure and criticality of the location of failure. However, with a sensor in this location, on average 30% of the wing was contaminated at the time of failure at the sensor. From these tests it is clear that the location of the sensor is important and that a significant warning period prior to failure at a sensor would be required to provide adequate safety using a single detector.

A sensor located on either of the two representative surfaces gave significantly worse identification of critical conditions that the other locations.

Table B7. Estimated Percentage of Wing with Fluid Failure at Time of Failure at Sensor for Each Test for Sensor Located on Middle Leading Edge Section

Test	% Area Fluid Fail 1st		Average*	Measure of	Time 1st
	Unweighted	Critical	Time (min)	Severity#	Fluid Failure
L1	28%	12%	2.0	0.25	9
L2	28%	11%	2.9	0.31	8
L7	26%	10%	9.6	0.91	20
L8	15%	7%	2.1	0.15	5
L9	28%	12%	2.0	0.25	8
Q1	17%	12%	10.0	1.24	50
Q2	23%	15%	6.7	0.99	50
Q3	22%	12%	2.8	0.33	3
L5	29%	11%	9.9	1.10	20
B4A	19%	7%	1.5	0.09	47
B4B	26%	8%	1.8	0.13	10
A5C	33%	10%	2.8	0.28	9
ID1	3%	3%	2.2	0.07	36
ID5	10%	6%	1.2	0.08	4
ID6	6%	3%	1.7	0.05	7
ID7	14%	8%	2.1	0.17	7
ID8	27%	12%	3.2	0.40	11
ID13	14%	7%	26.4	1.88	36
ID14	27%	11%	2.1	0.23	4
ID15	8%	3%	3.5	0.11	5
ID16	6%	3%	2.0	0.06	3
ID17	7%	3%	10.3	0.31	21
ID18	38%	14%	12.5	1.77	24
ID19	71%	25%	15.0	3.71	9
ID20	46%	19%	5.3	0.98	4
ID21	92%	34%	3.2	1.11	6
ID22	76%	22%	5.2	1.12	7
ID23	90%	34%	2.2	0.73	6
ID25	16%	12%	5.2	0.62	8
ID26	16%	10%	5.8	0.60	12
ID29	54%	19%	12.4	2.38	27
ID30	20%	12%	15.2	1.82	11
ID31	56%	23%	10.8	2.44	6
ID32	50%	18%	7.3	1.34	4
ID33	87%	27%	3.6	0.96	9
ID34	31%	12%	11.8	1.46	12
ID35	54%	19%	13.1	2.48	15
Avg	33%	13%			
sd	25%	8%			

* Average time for those parts where fluid failed prior to failure at sensor

\# Proportion to fail prior to sensor multiplied by average time failed

Table B8. Estimated Percentage of Wing where Fluid Fails Prior to Failure at Sensor for a Sensor at Various Locations - Average Over Tests

Sensor Location	% Area Fluid Fail Prior to Sensor			Avg Ratio Time/1st Failure*	Measure of Severity#
	No Weighting	Critical areas weighted			
		Average	Maximum		
T2L	30%	12%	34%	0.59	0.07
T2M	53%	20%	35%	0.60	0.121
T2T	40%	15%	36%	0.54	0.081
T4L	33%	13%	34%	0.60	0.079
T4M	72%	27%	34%	0.66	0.175
T4T	52%	20%	36%	0.64	0.125

* Average of ratios of time for those parts where fluid failed prior to failure at sensor to time of first failure

\# Proportion to fail prior to sensor multiplied by ratio of failure times

B.3.2 Two Sensors on Wing

The above analysis was repeated for sensors at two locations on the wing. The earliest time of fluid failure indicated by the two sensors was used for identifying fluid failure. Table B9 gives the percentage of contaminated areas at time of first failure at the sensors for various pairs of sensor locations averaged over the 37 tests. The results indicate that the best location for a pair of sensors is on sections T2L and T2T, especially in the most critical areas. A breakdown of the results for each test with sensors at T2L and T2T are given in Table B10. In these locations the fluid will have failed, on average, on 9% of the wing, weighted by the criticality factor (23% un-weighted), at the time the sensors detect failure. The average time failure occurs prior to the sensor identifying failure is less than 13 minutes in all but one test, ID13 where the sensors would have identified failure 25 minutes after the other sections. In this test the first failure occurred 20 minutes after application, but took another 110 minutes for the wing to fail completely and only 13% of the wing area (6.8% weighted by the criticality factor) failed prior to, or at the time the sensor would have identified failure.

Use of more sensors would increase the chance of the sensor system identifying fluid failure at the time of first failure on the wing. However, current applications of point sensors have used only one or two sensors per wing. The above procedures could be used to analyse the best locations for 3 or more sensors.

Table B9. Estimated Percentages of the Wing to Failure Before Fluid Failure at Either Sensor for Sensors Various Locations - Average over Tests

Sensor Location	% Area Fluid Fail Prior to Sensor			Avg Ratio Time/1st Failure*	Measure of Severity#
	No Weighting	Critical areas weighted			
		Average	Maximum		
T4L T2L	24%	9.1%	36%	0.49	0.044
T2L T2T	23%	8.7%	22%	0.45	0.039
T2M T2T	34%	12.9%	27%	0.48	0.062
T2T T4L	24%	8.9%	19%	0.47	0.042
T4L T4T	28%	10.8%	22%	0.55	0.06
T4M T2L	31%	12.1%	32%	0.50	0.061

* Average of ratios of time for those parts where fluid failed prior to failure at sensor to time of first failure

\# Proportion to fail prior to sensor multiplied by ratio of failure times

B.4 Data on the Progression of Fluid Failure

Data on the progression of fluid failure from the following tests were used in the analysis in Section B.3 and Appendix C:

- Tests L1, L2, L5, L7, L8 and L9 *Aircraft Full-Scale Test Program for the 1994-1995 Winter* by APS Aviation, prepared for TDC, TC report TP 12595E, December 1995
- Tests 4A - left, 4B-Left & Right on BAe 146 given on pages C-30, C-32, C-33, and Test 5C-Left on A320 given on page C-38 of *Aircraft Full-Scale Test Program for the 1994-1995 Winter* by APS Aviation, prepared for TDC, TC report TP 12595E, December 1995
- Tests on DC9 conducted on Feb. 28, 1996 Runs 1 and 2 (labeled in this report Q1 and Q2, respectively) given in Figures 3.5 & 3.6 of *Aircraft Full-Scale Test Program for the 1995-1996 Winter* by APS Aviation, prepared for TDC, TC report TP 12901E, October 1996
- Tests on B737 conducted Jan. 28, 1997 by APS labeled in this report labeled Q3 in this report) and tests by APS in Jan. to Mar. 1997 (ID1, 5, 6, 7, 8, 13, 14, 15, 16, 17, 25, 26)
- Tests on Fokker F-100 conducted by APS in Jan. to Mar. 1997 (ID18, 19, 20, 21, 22, 23, 29, 30, 31, 32, 33, 34, 35)

Table B10. Estimated Percentages of the Wing to Failure Before Fluid Failure at Either Sensor for Sensors at Leading and Trailing Edges Near Outer Wing (T2L & T2T)

Test	% Area Fluid Fail 1st		Average	Measure of	Time 1st
	Unweighted	Critical	Time (min)*	Severity#	Fluid Failure
L1	13.3%	5.6%	2.0	0.112	9
L2	19.2%	6.8%	2.6	0.177	8
L7	17.4%	6.8%	7.8	0.531	20
L8	14.6%	6.9%	2.0	0.137	5
L9	11.5%	5.3%	2.0	0.107	8
Q1	14.5%	10.8%	9.4	1.016	50
Q2	4.0%	3.1%	3.4	0.103	50
Q3	9.2%	1.9%	0.1	0.001	3
L5	20.3%	7.9%	7.8	0.614	20
B4A	14.5%	4.7%	1.2	0.055	47
B4B	17.8%	5.2%	1.6	0.083	10
A5C	8.2%	2.2%	2.0	0.044	9
ID1	7.8%	7.7%	1.3	0.103	36
ID5	15.5%	8.8%	1.0	0.084	4
ID6	19.9%	5.8%	0.3	0.019	7
ID7	6.1%	2.7%	1.5	0.042	7
ID8	20.6%	8.7%	2.8	0.241	11
ID13	13.4%	6.8%	25.0	1.704	36
ID14	6.1%	1.4%	1.1	0.015	4
ID15	5.9%	1.9%	2.5	0.049	5
ID16	14.0%	6.7%	2.0	0.133	3
ID17	38.1%	14.5%	3.6	0.528	21
ID18	35.1%	12.7%	10.3	1.304	24
ID19	5.7%	1.9%	12.7	0.245	9
ID20	37.1%	13.6%	4.9	0.660	4
ID21	46.3%	15.3%	2.7	0.419	6
ID22	25.9%	6.1%	2.0	0.120	7
ID23	25.0%	5.7%	2.4	0.138	6
ID25	13.9%	10.3%	5.0	0.512	8
ID26	3.7%	3.7%	0.1	0.003	12
ID29	54.4%	19.4%	11.9	2.316	27
ID30	46.9%	19.0%	7.3	1.378	11
ID31	52.3%	19.2%	9.7	1.863	6
ID32	57.8%	16.8%	5.7	0.961	4
ID33	39.5%	9.3%	3.8	0.354	9
ID34	39.2%	14.5%	8.2	1.189	12
ID35	60.5%	21.5%	12.1	2.606	15
Avg	23.1%	8.7%			
sd	16.7%	5.6%			

* Average time for those parts where fluid failed prior to failure at sensor

\# Proportion to fail prior to sensor multiplied by average time failed

APPENDIX C

ESTIMATION OF TAKE-OFF RISKS USING SENSOR BASED INSPECTION ONLY

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX D

ALTERNATIVE METHODOLOGY FOR ESTIMATION OF TAKE-OFF RISKS USING VISUAL INSPECTION ONLY

ESTIMATION OF TAKE-OFF RISKS USING VISUAL INSPECTION ONLY

As shown in Figure 1.3, there are two chains of events using visual based inspection procedures which could lead to an accident due to failure of the fluid. The two sequences are characterized by:

- fluid failure before the pre-take-off inspection and the pilot does not identify the failure at the inspection; and
- fluid failure after the pre-take-off inspection, the pilot correctly identifies the fluid as not failed and the fluid fails after the inspection but before take-off.

As discussed in Section 1.4, risks were not evaluated for the case where the aircraft could take-off within the minimum HOT and the pilot opted not to conduct a pre-take-off inspection. The likelihood of fluid failure either prior to the pre-take-off inspection or between the inspection and take-off are addressed in Section 4.4. The analysis below makes use of these probabilities and also estimates:

- the probability of the pilot not identifying a fluid failure at the pre-take-off inspection; and
- the amount of contamination built up on the critical parts of the wing by the time of take-off. This is characterized by the probability distribution of the critical areas with fluid failure at the time of take-off following failure to identify the fluid failure at the pre-take-off inspection.

These are then used to estimated the accident risk.

D1. Probability of the Pilot Not Identifying Fluid Failure

Let $P_{pt}(t_p,t_f)$ be the probability of the pilot not identifying fluid failure at time t_p given it fails at time $t_{f:}$

$$P_{pt}(t_p,t_f) = P[\ TP > t_p \mid TFF = t_f\ ] \qquad \text{(D1)}$$

where TP is the time at which the pilot first identifies fluid failure;

The likelihood of the pilot identifying fluid failure depends on:

- the amount and location of the fluid failure on the wing; and
- the conditions, denote by {C}, under which the inspection is made.

Thus, using the probability relationship given in Equation C2,

$$P_{pt}(t_p,t_f) = \sum_{a_f>0} \sum_{f_t} \sum_{\{C\}} P[TP > t_p \mid TFF = t_f \ \& \ AFF(t_p) = a_f \ \& \ \{C\} \ \& \ FT = f_t\,] \times P[\,AFF(t_p) = a_f \mid TFF = t_f \ \& \ FT = f_t \ \& \ \{C\}] \times P[FT = f_t \mid \{C\}] \times P[\{C\}] \tag{D2}$$

where AFF(t_p) is the percentage of the wing that has failed at time t_p; and
FT is the fluid type (I, II, III or IV).

Assuming that the likelihood of the pilot identifying fluid failure, given the area of failed fluid, is independent of the time interval between the fluid failure and the time it is inspected, then:

$$P_{pt}(t_p,t_f) = \sum_{a_f>0} \sum_{f_t} \sum_{\{C\}} P[TP > t_p \mid AFF(t_p) = a_f \ \& \ \{C\}] \times P[\,AFF(t_p) = a_f \mid TFF = t_f \ \& \ FT = f_t \ \& \ \{C\}] \times P[FT = f_t \mid \{C\}] \times P[\{C\}] \tag{D3}$$

The probabilities of the pilot identifying fluid failure, given the percentage area of the wing that has fluid failure, were estimated from the test data giving the times an inside observed identified fluid failure. The data only included eleven tests conducted at night in light to moderate snow conditions with good external lighting. The probabilities of identifying the fluid failure for these conditions are shown in Figure D1. In these conditions, a significant portion of the wing must have had fluid failure before the pilot is very likely to identify the fluid failure.

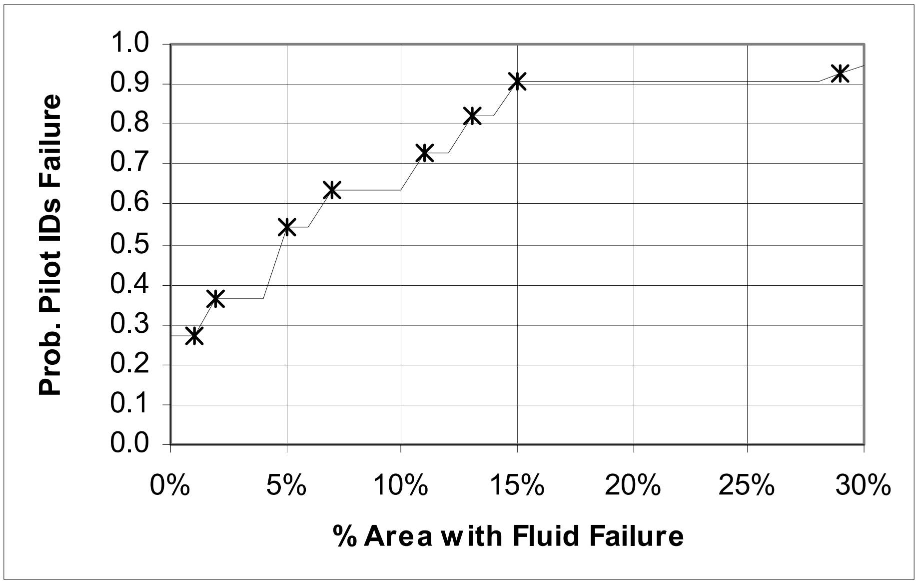


Figure D1. Probabilities of Inside Observer Identifying Fluid Failure at Night with Good Lighting During Light to Moderate Snowfall, Given Percentage Area of Wing With Fluid Failure

The tests were not specifically designed to represent the conditions a pilot would experience during the pre-take-off inspection. The major differences were:

- very good external lighting was available;
- after the first test, fluid was cleaned off the windows;
- the wing was inspected continuously, not at specific time;
- no passengers were present, thus allowing the observer easy access to the windows;
- the observer made their best judgment of the state of the fluid and were not conservative in their assessment as a pilot would be.

The data were all collected under similar viewing conditions and were far from optimal for determining the required probability distribution. Thus, they only provide a rough indication of the possible relationship between the probability of identifying fluid failure and the area contaminated. Due to the great uncertainty associated with estimates based on this data, two possible probability relationships were developed for use in demonstrating the risk analysis methodology.

Case 1: A major penalty due to poor viewing conditions is applied for all levels of wing contamination and may represent the situation where pilots base their decision solely on their visual assessment of the wing and do not take into account the viewing conditions or HOTs in deciding whether to re-deice.

Case 2: The major penalty for poor viewing conditions is applied when the area contaminated is small, although a small probability of the pilot not identifying fluid failure with large areas of the wing contaminated is included. This case accounts, to some extent, for pilots being conservative in their decision to re-deice when viewing conditions are poor.

The pilot survey indicated that in poor viewing conditions and, when the precipitation and HOTs indicate that the fluid may have failed, most pilots would return to deice. When it was “very difficult” to see, 85% indicated they would return, while 63% indicated they would return if it was “difficult” to see. Assuming that large areas of contamination will usually be associated with precipitation and HOTs indicating the fluid may have failed, this conservatism will lead to low probabilities of continuing take-off in poor viewing conditions with large areas contaminated. Accident experience in those conditions is consistent with this assumption.

The two cases should, however, be treated as hypothetical and do not necessarily represent upper and lower, or optimistic and pessimistic cases, as there is insufficient data to put likely bounds on the probability relationship. The approach used to determine the two cases from the distribution given in Figure D1 is described below.

As discussed in Section 8.2.1, the pilot’s level of confidence in their assessment of fluid failure on the wing during various conditions was investigated in the survey of pilots. The survey indicated that the level of precipitation had little effect on their level of confidence, but that the type of precipitation and day/night and lighting at night had a significant effect. On a scale 1 to 5 (1 = very low, 5 = very high) their average rating are given in Table D1. Probabilities were estimated for the five viewing conditions based on these confidence levels and are given in Table D1. The rating applied to the test data was chosen to be between the day-snow and night-snow with external lighting. Night time probabilities of identifying failure corresponding to confidence levels for no external lighting were used in the analysis. These represent aircraft at the runway hold area.

The probability of the pilot identifying fluid failure under different conditions was estimated from the distribution given in Figure D1 for the assessment made at night time during snowfall in good lighting conditions using the relationships:

$$\begin{aligned} &P[ID(t) \mid AFF(t)\ \&\ \{C = c\}\ ] \\ &\qquad = P[\ ID(t) \mid AFF(t)\ \&\ \{C = \text{night/snow/good light}\}\ ] + a1(C) && \text{for Case 1} \\ &\qquad = P[\ ID(t) \mid AFF(t)\ \&\ \{C = \text{night/snow/good light}\}\ ]^{a2(c)} && \text{for Case 2} \quad \text{(D4)} \end{aligned}$$

where ID(t) is the event that the pilot identifies fluid failure; and
a2(C), a1(C) are constants for the viewing condition C = c.

Table D1. Average Ratings in Level of Confidence in Assessment, Estimated Probability of Identifying Fluid Failure and Constant for Probability Distribution

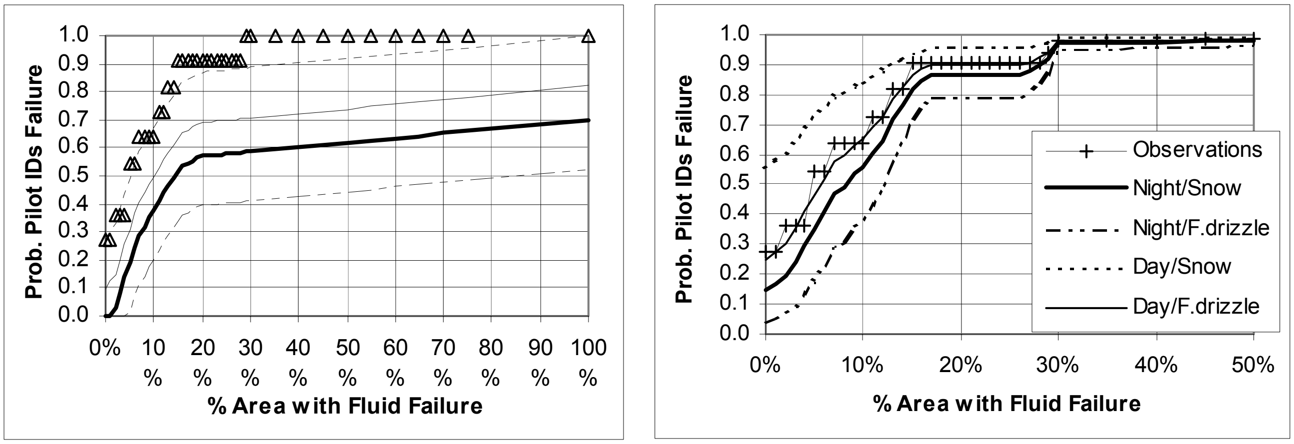
Viewing Conditions		Avg. Rating	Est. Prob.	Constant	
				a1(C)	a2(C)
Night time, good lighting, snowfall			0.6	1.00	1.00
Day time	snowfall	3.95	0.74	0.0	0.45
	freezing rain/drizzle	2.88	0.47	-0.18	1.08
Night time	snowfall	2.4	0.35	-0.3	1.48
(no lighting)	freezing rain/drizzle	1.7	0.18	-0.47	2.45

The probabilities, P[ID(t) | AFF(t) & {C = night/snow/good light}], were found by smoothing the values given in Figure D1. Experience during the winter test programs conducted by APS indicates that there were a number of occasions where failure of the fluid was not identified until near or after full failure of the wing area. To allow for these unlikely events, which would not be expected to occur in the 11 tests with the cabin observer, the following adjustments were made:

Case 1: for percentages of the wing failed over 20%, the probabilities were assumed to increase linearly to 1.0 at 100% contaminated (rather than 1.0 at 30% contaminated).

Case 2: for 30% of the wing area failed, a probability of identifying failure was reduced from 1.0 to 0.98, and for percentages of the wing failed over 30%, the probabilities were assumed to increase linearly to 1.0 at 100% contaminated.

The average ratings were translated to approximate probabilities by assuming that a rating of zero corresponds zero probability of identifying failure and a rating of 5 corresponds to a probability of 1 of identifying failure. The probabilities based on these ratings are given in Table D1. The probability for night/snowfall conditions corresponds to the probability for 6% of the wing area failed. The constant a1(C) and a2(C) for a given condition was chosen so that the probabilities calculated using Equation D4 equaled the probability based on the rating for that condition (6% wing area failed). The estimated constants are also given in Table D1 and the probabilities of identifying fluid failure under each condition are shown in Figure D2.



Visual Identification Case 1 **Visual Identification Case 2**

Figure D2. Estimated Probabilities of Pilot Not Identifying Fluid Failure under Various Viewing Conditions, Given Percentage Area of Wing With Fluid Failure

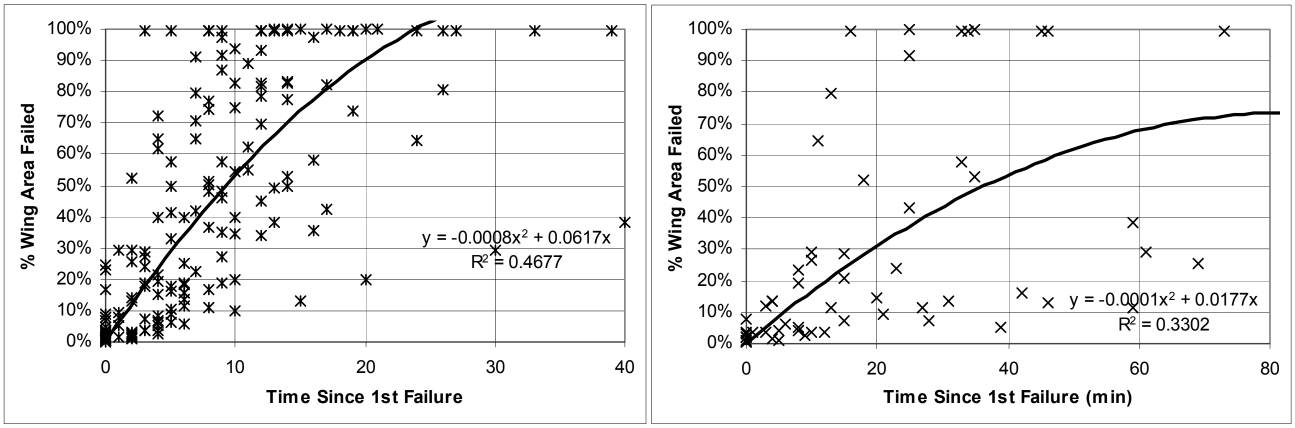
Night time conditions were assumed to extend from 4:30 pm to 7:30 am during the period when icing conditions occur. Departure time distributions for Toronto were used in the analysis and 43% of departures occurred at night during these hours of the day. Precipitation data for Ottawa, discussed in Section 4.4.2, were used in the analysis.

The probability distribution of the percentage area of wing with fluid failure given the time since first fluid failure was estimated from the fluid failure progression tests conducted by APS. The distributions for Types I and IV fluids are shown in Figure D3. The mean value and standard deviation of the percentage area of the wing with fluid failure was estimated by:

Mean AFF $= 6.17\ TF - 0.08\ TF^2$ for Type I fluid
$= 1.21\ TF$ for Type II fluid
$= 1.77\ TF - 0.001\ TF^2$ for Type IV fluid (D5)

SD AFF $= 11.14 + 3.8\ TF - 0.18\ TF^2$ for Type I fluid
$= 5.57 + 3.8\ TF - 0.03\ TF^2$ for Type II fluid
$= 2.53\ TF - 0.03\ TF^2$ for Type IV fluid (D6)

where AFF is the percentage of the wing contaminated; and
TF if the time since first fluid failure (TDT - TFF)



(a) Type I Fluid **(b) Type IV Fluid**

Figure D3. Probability Distribution of Percentage Area of Wing with Fluid Failure Given the Time Since First Fluid Failure for Types I and IV Fluids

When estimating $P_{pt}(t_p,t_f)$, AFF was assumed to follow a normal distribution with the mean and standard deviation given above. The probability assigned to the full wing contaminated was estimated by P[AFF ≥ 1] using the mean and standard deviations above. At least 1% of the wing was assumed to fail at first fluid failure and, the probability of 1% failure was estimated by P[AFF ≤ 1]. Although the normal distribution is not the ideal distribution to model the distribution of the percentage area failed, with the percentages restricted to the range 1% to 100%, the critical highest percentages for a given failure time fall about two standard deviations from the mean value. The distribution should therefore reflect the spread in these high values fairly realistically.

The probability of the pilot not identifying fluid failure at the pre-take-off inspection, given that the fluid had failed at that time, is given by:

$$P_{fp} = P[\ TP > TDT\text{-}TI \mid TFF < TDT\text{-}TI\ ]$$

$$P_{fp} = \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_f>0} P[\ TP > t_d\text{-}t_i \mid TDT\text{-}TI > TFF \ \&\ TDT = t_d \ \&\ TFF = t_f \ \&\ TI = t_i\ ] \text{ x } P[\ TDT = td \ \&\ TFF = tf \ \&\ TI = ti\ ]$$

$$= \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_f<t_d-t_i} P[\ TP > t_d\text{-}t_i \mid TFF = t_f\ ] \text{ x } P[\ TDT = t_d \ \&\ TFF = t_f \ \&\ TI = t_i\ ]$$

$$= \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_f<t_d-t_i} P_{pt}(t_d\text{-}t_i,t_f) \text{ x } P[\ TDT = t_d \ \&\ TFF = t_f \ \&\ TI = t_i\ ] \qquad \text{(D7)}$$

where TI is the time interval between pre-take-off inspection and take-off;
TDT is the time between fluid application and take-off.

The probability of the pilot not identifying fluid failure at the pre-take-off inspection, given that the fluid had failed at that time, was estimated for the four airport-fluid type cases to be:

		Case 1	Case 2
Large airport	Type II fluid	0.42	0.27
	Type IV fluid	0.43	0.28
Small airport, Type I fluid	short taxi time	0.63	0.49
	long taxi time	0.59	0.44

D2. Critical Area Contaminated at Take-off Following Failure to Identify Fluid Failure at Pre-Take-off Inspection

The risk of an accident is dependent on the area contaminated at the time of the pre-take-off inspection and the progression of the failure over time between the pre-take-off inspection and take-off, and the criticality of those areas contaminated. The probability of an accident due to the pilot not identifying fluid failure given fluid failure prior to the pre-take-off inspection is found by:

$$P_A = P[\text{Accident} \mid \text{Fluid failure prior to pre-take-off inspection}\ ]$$

$$= P[\ \text{Accident} \mid TFF < TDF\text{-}TI\ ]$$

$$= \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_f<t_d-t_i} P[\ \text{Accident} \mid TFF = t_f \ \&\ TDT = t_d \ \&\ TI = t_i\ ] \qquad \text{(D8)}$$

Conditioning over the possible values of the critical area contaminated at the time of take-off and on the pilot not identifying fluid failure at the pre-take-off inspection gives:

$$P_A = \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_f<t_d-t_i} \sum_{c_a>0} P[\text{ Accident} \mid CA(t_d-t_f) = c_a \;\&\; TP > t_d-t_i \;\&\; TFF = t_f \;\&\; TDT = t_d \;\&\; TI = t_i] \text{ x } P[\, CA(t_d-t_f) = c_a \;\&\; TP > t_d-t_i \mid TFF = t_f \;\&\; TDT = t_d \;\&\; TI = t_i] \quad \text{(D9)}$$

where CA(t) is the percentage of the wing area contaminated at time t after fluid failure, weighted by criticality.

The last term in Equation D9 is the probability of the pilot not identifying fluid failure at the time of the pre-take-off inspection and the critical area exceeding a threshold, c_a, for a given time between first fluid failure and take-off (application/taxi/delay time minus time of fluid failure, t_d,-t_f). This is denoted by:

$$P_{ctp}(t_d-t_f,c_a,t_d-t_i) = P[\, CA(t_d-t_f) > c_a \;\&\; TP > t_d-t_i \mid t_f < t_d-t_i \,]$$

Using the conditional probability relationship (Equation C2) and conditioning on the area of fluid failure, AFF(t) and the type of fluid, FT, and viewing conditions {C}, this can be written as:

$$P_{ctp}(t_d-t_f,c_a,t_d-t_i) = \sum_{f_t} \sum_{\{C\}} \sum_{a_f>0} P[\, CA(t_d-t_f) > c_a \;\&\; TP > t_d-t_i \mid t_f < t_d-t_i \;\&\; AFF(t_d-t_i) = a_f \;\&\; FT = f_t \;\&\; \{C\}] \text{ x } P[\, AFF(t_d-t_i) = a_f \mid t_f < t_d-t_i \;\&\; FT = f_t \;\&\; \{C\}] \text{ x } P[FT = f_t \mid \{C\}] \text{ x } P[\{C\}] \quad \text{(D10)}$$

Using the conditional probability relationship (Equation C5), this can be written as:

$$P_{ctp}(t_d-t_f,c_a,t_d-t_i) = \sum_{f_t} \sum_{\{C\}} \sum_{a_f>0} P[\, CA(t_d-t_f) > c_a \mid TP > t_d-t_i \;\&\; t_f < t_d-t_i \;\&\; AFF(t_d-t_i) = a_f \;\&\; FT = f_t \;\&\; \{C\}] \text{ x } P[TP > t_d-t_i \mid AFF(t_d-t_i) = a_f \;\&\; t_f < t_d-t_i \;\&\; \{C\}] \text{ x } P[\, AFF(t_d-t_i) = a_f \mid t_f < t_d-t_i \;\&\; FT = f_t \;\&\; \{C\}] \text{ x } P[FT = f_t \mid \{C\}] \text{ x } P[\{C\}] \quad \text{(D11)}$$

The critical area of the wing with fluid failure at time of take-off, $CA(t_d-t_f)$, can be split into the areas to fail before and after the pre-take-off inspection:

$$CA(t_d-t_f) = CA(t_d-t_i-t_f) + DCA(t_d-t_i-t_f\,,t_i) \quad \text{(D12)}$$

where $DCA(t_1,t_2)$ is the critical area to fail in the time interval: t_1 to $t_1 + t_2$.

It is assumed that, given the percentage area of the wing area with fluid failure AFF(t), the critical area contaminated at a given time, CA(t), is independent of the time since fluid failure. With is assumption and using Equation D12, Equation D12 can be written:

$$P_{ctp}(t_d-t_f,c_a,t_d-t_i) = \sum_{f_t} \sum_{\{C\}} \sum_{a_f>0} P[\, CA(t_d-t_f) + DCA(t_d-t_i-t_f\,, t_i) > c_a \mid TP > t_d-t_i \;\&\; t_f < t_d-t_i \;\&\; AFF(t_d-t_i) = a_f \;\&\; FT = f_t \;\&\; \{C\}] \text{ x } P[TP > t_d-t_i \mid AFF(t_d-t_i) = a_f \;\&\; t_f < t_d-t_i \;\&\; \{C\}] \text{ x } P[\, AFF(t_d-t_i) = a_f \mid t_f < t_d-t_i \;\&\; FT = f_t \;\&\; \{C\}] \text{ x } P[\, FT = f_t \mid \{C\}] \text{ x } P[\{C\}] \quad \text{(D13)}$$

Conditioning on possible values of CA(t) less than c_a gives:

$$
\begin{aligned}
&P_{ctp}(t_d-t_f,c_a,t_d-t_i) = \\
&\sum_{f_t}\ \sum_{\{C\}}\ \sum_{a_f>0}\ \sum_{c_{a1}<c_a} P[DCA(t_d-t_i-t_f\,,t_i) > c_a-c_{a1} \mid CA(t_d-t_i-t_f) = c_{a1}\ \&\ TI = t_i\ FT = f_t\ \&\ \{C\}]\ \mathrm{x} \\
&\qquad P[CA(t_d-t_i-t_f) = c_{a1} \mid TDT = t_d\ \&\ t_f < t_d-t_i\ \&\ AFF(t_d-t_i) = a_f\ \&\ FT = f_t \\
&\qquad\ \&\ \{C\}]\ \mathrm{x}\ \ P[\ TP > t_d-t_i \mid AFF(t_d-t_i) = a_f\ \ \&\ t_f < t_d-t_i\ \ \&\ \{C\}]\ \mathrm{x} \\
&\qquad P[\ AFF(t_d-t_i) = a_f \mid t_f < t_d-t_i\ \&\ FT = f_t\ \ \&\ \{C\}]\ \mathrm{x}\ \ P[\ FT = f_t \mid \{C\}]\ \mathrm{x}\ P[\{C\}] \qquad (D14)
\end{aligned}
$$

The probability of an accident due to the pilot not identifying fluid failure given fluid failure prior to the pre-take-off inspection, P_A, is found by substituting Equation D14 into Equation D9.

The relationship between the percentage area of the wing with fluid failure, AFF, and the percentage area contaminated weighted by the criticality factor, CA, was investigated using the fluid failure progression tests and is shown in Figure D4. The critical area contaminated increases linearly with the percentage of the wing contaminated (shown by the trend line on the figure). Similarly, the variation around the trend line (as measured by the standard deviation) increases linearly with percentage are contaminated. When estimating $P_{cpt}(t_d-t_f,c_a,t_p)$, the percentage area of the wing with fluid failure, weighted by criticality (CA), was assumed to follow a normal distribution with the mean and standard deviation given by:

$$
\begin{aligned}
\text{Mean} &= 0.366\ AFF \\
\text{SD} &= 0.26\% + 0.156\ AFF \qquad (D15)
\end{aligned}
$$

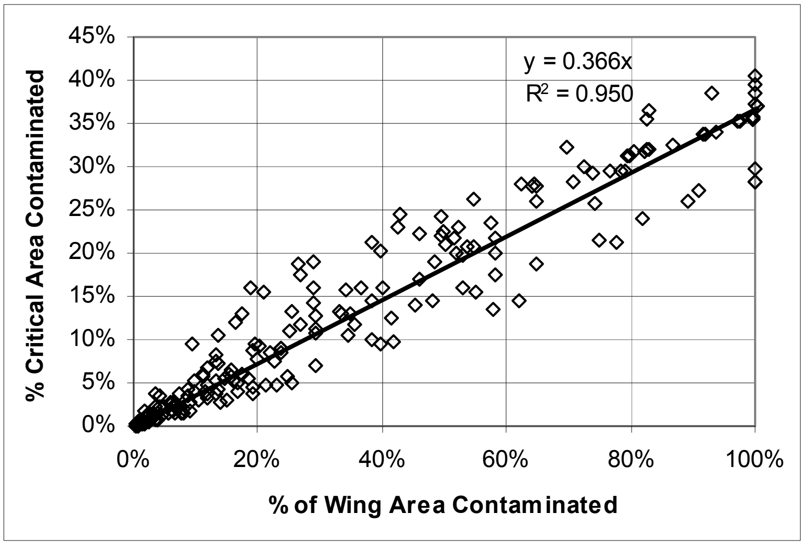
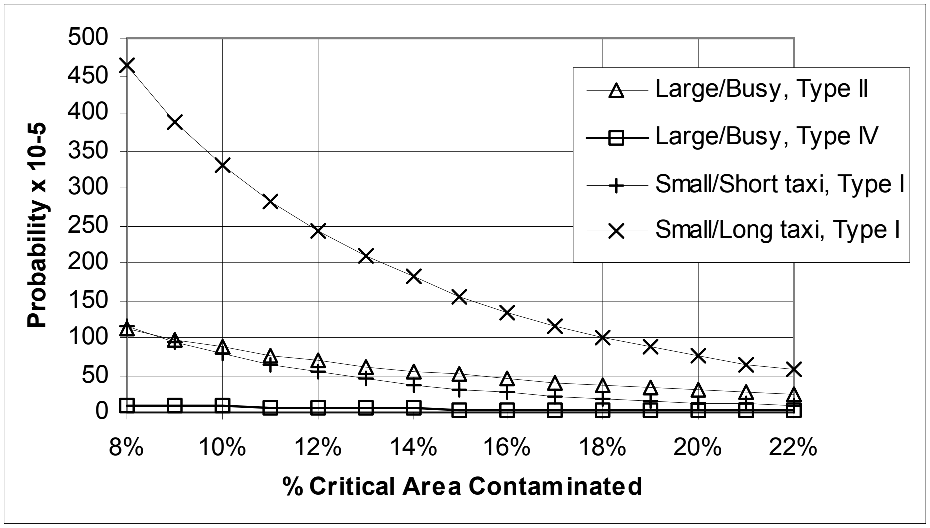


Figure D4. Observed Percentage Area of the Wing with Fluid Failure Versus Percentage Area Weighted by the Criticality Factor

The critical area to fail between the pre-take-off inspection and take-off, DCA(t1,t2), was estimated from Figure D3 and Equations D5 and C6. Essentially, the point on the curve (Figure D3) corresponding to the percentage area failed at the time of the pre-take-off inspection, a_f, was identified for the particular fluid type. The change in the area failed was estimated by the increase in the area failed along the curve for an increase in time of t_i (t_i being the time interval between inspection and take-off). DCA was then estimated from the change in the area failed using Equation D15. Variation in DCA around this estimated value was not modelled. This, however, should not lead to any significant loss in accuracy as significant variation in the area contaminated at the time of the pre-take-off inspection has already been modelled, and the time between inspection and take-off is relatively short.

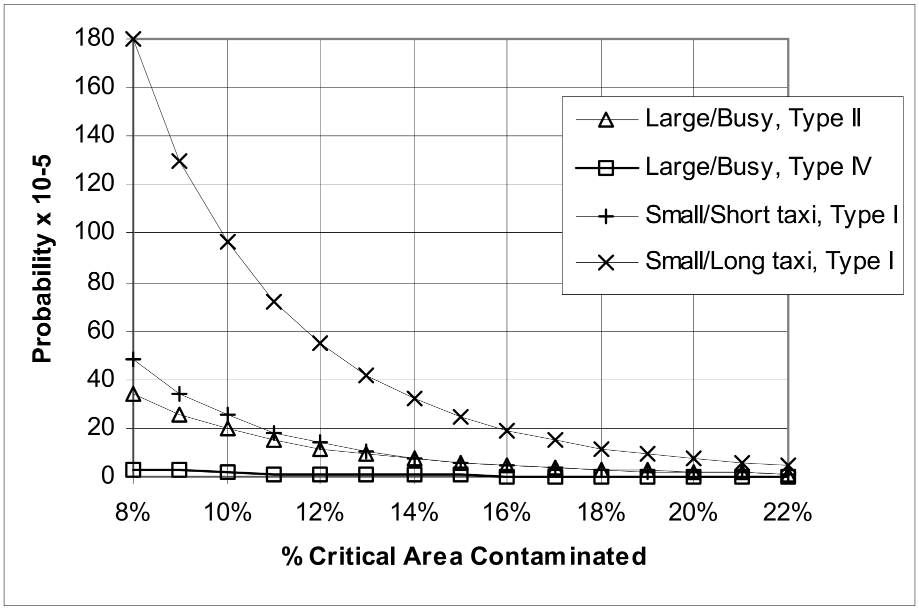
The probabilities of fluid failure prior to the pre-take-off inspection and fluid failure over a given area, weighted by criticality, at the time of take-off, CA, was estimated for the four airport-fluid type combinations and are shown in Figure D5.



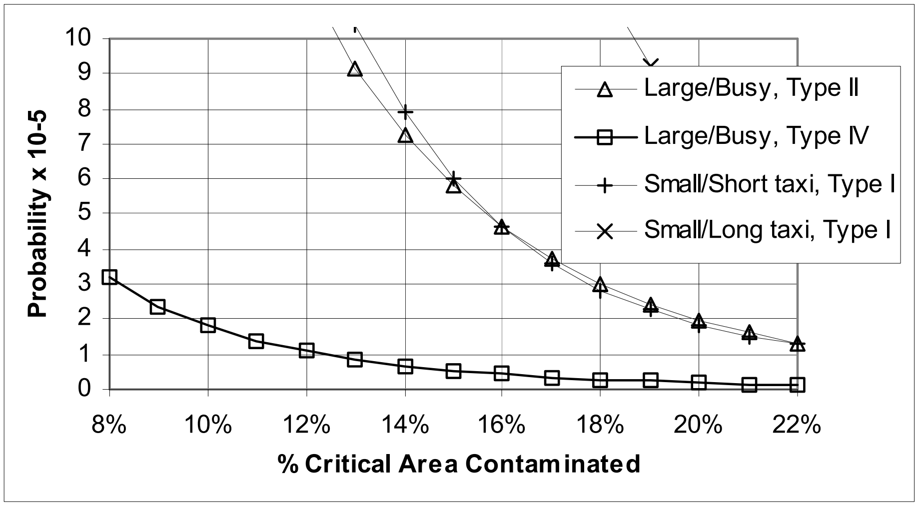
(a) Visual Observation Case 1

Figure D5. Probabilities of Fluid Failure Prior to the Pre-take-off Inspection and Take-off with More than a Given Percentage Area of Fluid Failure, Weighted by Criticality

…………..**Continued on next page**



(b) Visual Identification Case 2, Full Range of Probabilities



(c) Visual Identification Case 2, Restricted Range of Probabilities

Figure D5. Probabilities of Fluid Failure Prior to the Pre-take-off Inspection and Take-off with More than a Given Percentage Area of Fluid Failure, Weighted by Criticality

D3. Critical Area Contaminated at Take-off Following Failure of Fluid Between Pre-Take-off Inspection and Take-off

The risk of an accident due to fluid failure after the pre-take-off inspection and prior to take-off can be estimated using a similar procedure to that given in Appendix C. The distribution of the amount of contamination on the wing at time of take-off, $P_c(p_{ac})$, is found is a similar way to Equation A7, conditioning on the application/taxi/delay, inspection and fluid failure times:

$$P_c(c_a) = P[TFF < TDT \;\&\; CA(t_{of}) = c_a \mid TFF > TDT-TI \;\&\; \text{Deiced}] =$$

$$= \sum_{r \,\&\, t_m} \sum_{t_d>0} \sum_{t_i<t_d} \sum_{t_d-t_i<t_f<t_d} \begin{array}{l} P[TDT = t_d \;\&\; TFF = t_f \;\&\; TI = t_i \mid \text{Deiced} \;\&\; R = r \;\&\; TM = t_m] \times \\ P[\, TI = t_i \mid \text{Deiced} \;\&\; R = r \;\&\; TM = t_m \,] \,/\, P_{PI} \times P_{ct}(t_i-t_f\,, c_a) \\ P[\, R = r \;\&\; TM = t_m \;\&\; \text{Deiced} \,] \,/\, P[\, \text{Deiced} \,] \end{array} \qquad (D16)$$

where $P_{ct}(t, c_a)$ is the probability that contamination level, CA(t), is greater than c_a at the time t after first fluid failure

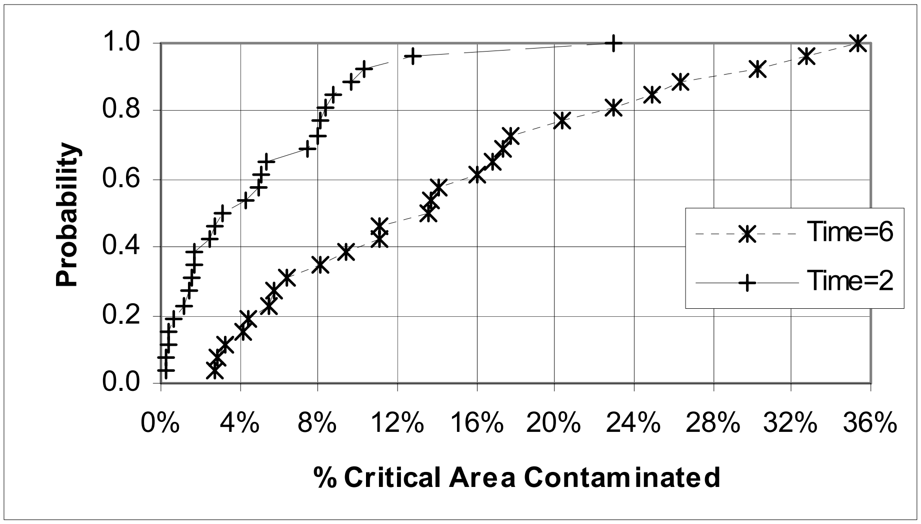
The probability distribution $P_{ct}(t, c_a)$ is not conditional on the pilot or sensor system not identifying fluid failure, unlike the cases considered earlier (Section D2 and Appendix C). The effect of the condition in the previous cases was to reduce the probability of rapid fluid failure since if there was rapid failure, more of the wing would fail and the pilot or sensor system would be more likely to identify the failure.

Using the fluid failure progression data, the cumulative probability distributions of the area of fluid failure, weighted by criticality factor, were estimated for Types I and IV fluids at times of 0, 1, 2, 3, 4, 5 and 6 minutes following the first fluid failure. These distributions are shown in Figure D6 for two and six minutes after the first fluid failure. There was insufficient data to estimate the distributions for Type II fluid (only one test) and it was approximated by the average of the distributions for Types I and IV fluids. As shown in the figure, the spread of failure of Type IV fluid is much slower than Type I fluid.

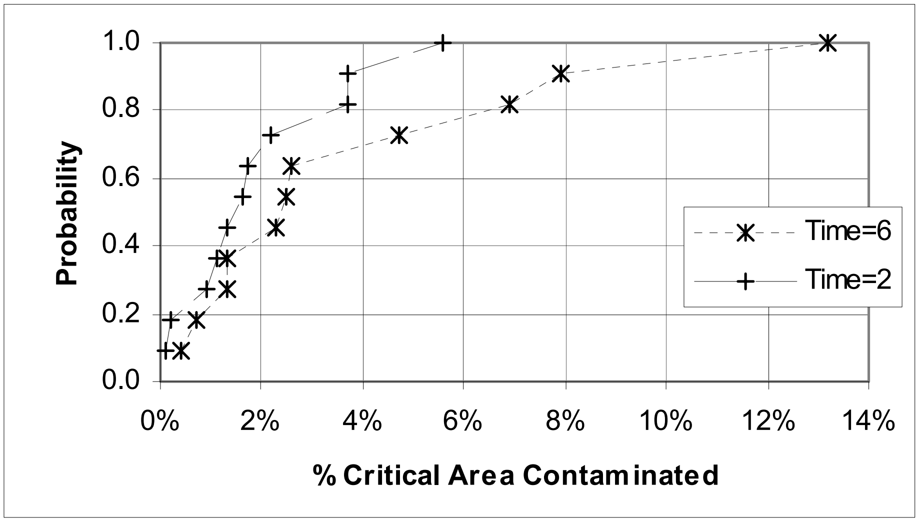
Using Equation D16 and the distributions of the percentage area contaminated for a given time since first failure, the probabilities of fluid failure prior to the pre-take-off inspection and take-off with more than a given percentage area of fluid failure, weighted by criticality, were estimated. These are shown in Figure D7.

D4. Risk Due to Fluid Failure Using Visual Inspection Procedure

The accident risks were estimated by combining these distributions of the critical areas contaminated at take-off found in Sections D2 and D3 with the accident probabilities at given levels of contamination (Figure 6.4). The probabilities are shown on the risk analysis tree for the small short taxi airport case using Type I fluids in Figure D7. The probability of the aircraft being deiced and at risk of fluid failure (i.e., continuing precipitation) was set at 0.02, as discussed in Section 4.4.1. The estimated accident risks for each of the four airport-fluid type cases examined and major assumptions are given in Section 8.

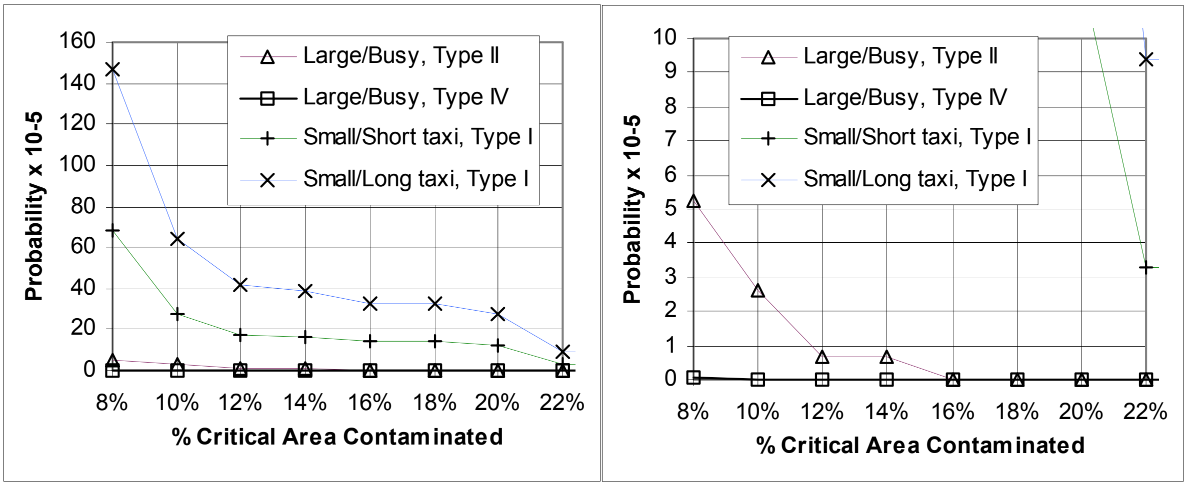


(a) Type I Fluid



(b) Type IV Fluid

Figure D6. Cumulative Probability Distribution of the Area of Fluid Failure, Weighted by Criticality Factor, at Two and Six minutes After First Fluid Failure



(a) Full Range of Probabilities **(b) Blowup for Low Probabilities**

Figure D7. Probabilities of Fluid Failure Between the Pre-take-off Inspection and Take-off and More than a Given Percentage Area of Fluid Failure, Weighted by Criticality, at Take-off

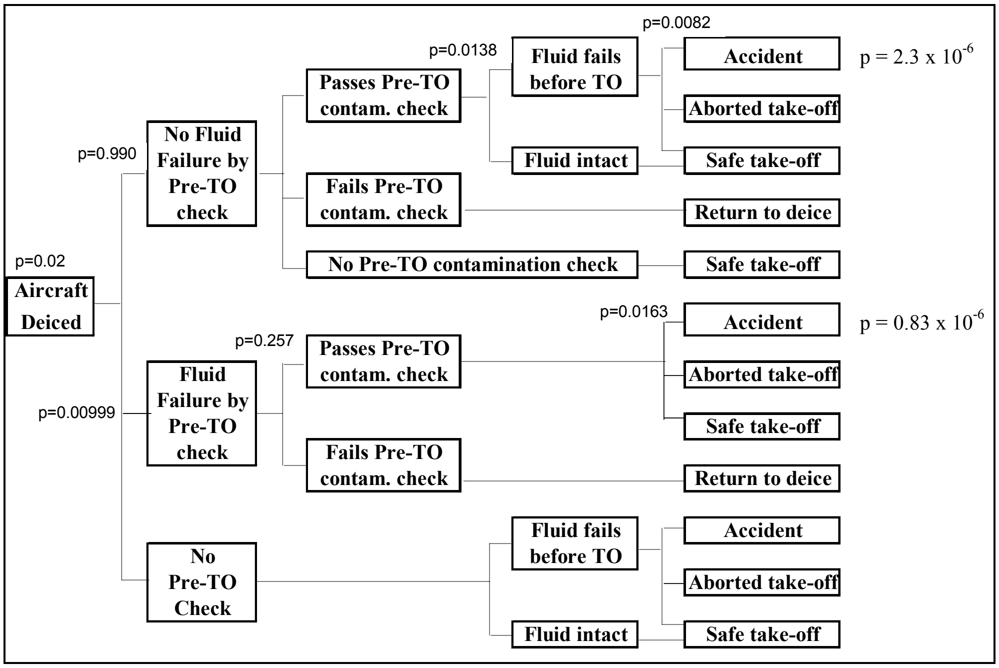


Figure D8. Risk Analysis Tree for Fluid Failure Identification Using Visual Based Procedures with Estimated Probabilities for Small Airport Short Taxi Time Type I Fluid and Visual Identification Case 2

APPENDIX E

RESULTS OF CLEAN WING INSPECTION SURVEY OF PILOTS IN CANADA

RISK MANAGEMENT OF AIRCRAFT CRITICAL SURFACE INSPECTION - SUMMARY RESULTS OF PILOT SURVEY

BACKGROUND

The occurrence of a number of accidents in the last decade has increased concerns about the risks of take-off in ground icing conditions. Regulatory authorities have enacted regulations, and airlines and pilots have improved procedures for ensuring the aircraft is free of frozen contaminants prior to take-off. Improvements in anti-icing fluids have increased holdover times, thus reducing the risk of fluid failure prior to take-off. The poor viewing conditions of the wing from either the flight deck or cabin is no doubt a significant factor in assessing fluid failure and/or the existence of wing contaminant. With the advent of sensors capable of identifying fluid failure, TC initiated a project to:

> *evaluate the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.*

As part of this project, Sypher conducted as survey of commercial pilots in Canada. The purpose of the survey was to improve our understanding of the current wing inspection process and its strengths and weaknesses, and to obtain feedback on the need for additional measures (such as training, operating procedures and/or detection devices).

THE SURVEY

The survey was supported by the Airline Pilots Association - Canada, the Air Canada Pilots Association, ATAC and TC, and the pilot associations assisted in the distribution of the questionnaires. Pilots were asked not to identify themselves or their employer.

The survey was distributed to 4,700 commercial pilots in Canada in June 1997. A copy of the questionnaire is included at the end of this summary of results. Over 700 pilots completed the questionnaire, a response rate of 15%. The survey provides a wealth of information about current de/anti-icing and inspection procedures. The major findings are summarized below.

SUMMARY OF FINDINGS

These findings are based on the responses to questions on the questionnaire and the interpretation of comments made by pilots on the questions. The opinions obtained from the comments are not necessarily representative of the survey population, nor have they been weighted for their frequency of occurrence or the type and level of experience of the respondent.

All findings relate only to pilots of air carriers registered in Canada.

General

The majority of pilots feel that the recent improvements in de/anti-icing standards and procedures have moderately or greatly improved safety. Pilots of turboprop or small jet aircraft are more likely to have found safety to be greatly improved than pilots of larger aircraft. Some of their comments include statements such as:

- greater awareness, less individualism, education benefit;
- everybody now agrees on a clean wing; prevents cutting corners, less pressure on pilots, especially small airlines;
- safety was already high, little need for change, overkill; and
- there is too much de/anti-icing, deicing frequently unnecessary, at a great cost, harmful to environment.

There is a strong acknowledgment of the benefits of anti-icing fluid, especially among pilots of small to medium sized jet aircraft. Pilots were particularly impressed by the long holdover times of Type IV fluids and called for the greater availability of anti-icing fluids at the small and medium sized airports.

Approximately 20% of pilots are still not comfortable with the current de/anti-icing procedures. Pilots of high wing aircraft are less comfortable with the procedures than pilots of low wing aircraft. Pilot's most common concern was that there is too long a delay after deicing, and they suggested that deicing pads should be located near the end of the active runway and deicing and take-off coordinated through ATC. Other concerns included that: decisions are now out of hands of the pilots, there is lots of unnecessary deicing, especially when very cold and light dry snow is falling, and that at some airports there is inferior equipment and a lack of availability of anti-icing fluids. Improvements in communication, training of ground staff and more education were also mentioned.

Generally pilots found the quality of de/anti-icing service to be better at large airports, but there is considerable variability within the large and small airport groups. Small airports often don't have anti-icing fluid available, usually have inferior equipment, especially in Northern areas, and in extreme cases cannot even deice the aircraft within the HOT. This is offset to some extent by the shorter taxi and delay times at those airports. The quality of personnel providing deicing service varies at the small airports, some are very good, some are not. Location, rather than size, was mentioned as an important factor. Vancouver was frequently cited as having a poor deicing service.

Experience

Pilots operating in Canada are generally very experienced, averaging 20 years as a commercial pilot. The average varies from about 14 years for turboprop pilots to 26 years for large jet aircraft. Pilots average 450 take-offs per year, a third of these in temperature of around zero or less. Relative to pilots of larger jet aircraft, pilots of turboprop and small jet (less than 150 passengers) aircraft have:

- far higher number of departures (2 to 10 time as many),
- more frequently fly in winter conditions (about 5% higher),
- have less experience (about 15% to 40% less),
- fly aircraft more susceptible to wing contamination.

The deicing and re-deicing experience indicates that:

- Pilots deice their aircraft on average 25 times per year (5.5% of take-offs).
- About 40% of deicing operations are to turboprop or very small jet (less than 70 seats) aircraft, 40% to jet aircraft in the 70 to 150 seat range, and the remaining 20% to larger aircraft.
- A quarter of deicing operations are to high wing aircraft.
- The aircraft is re-deiced after about 3.2% of deicings.
- Turboprop and very small jet aircraft and, surprisingly, very large aircraft (4 jet engine, low wing) are more likely to require re-deicing than the medium size jet aircraft.
- Over 50% of the aircraft that were re-deiced were turboprop or very small jet aircraft.

Generally take-offs can be completed prior to the HOTs expiring. Almost 50% of pilots reported that pre-take-off inspection was required rarely or never due to expiry of the HOT. About 6% indicated the inspections were necessary frequently. On average pilots made about 5 pre-take-off inspections last winter and re-deiced on average 0.8 times; i.e., after 16% of pre-take-off inspections. Many of these re-deicings will, however, be due to a conservative assessment of the wing after expiry of the HOT in poor viewing conditions. Thus, most pilots do not frequently make pre-take-off inspections and very rarely identify fluid failure, and will therefore not learn about fluid failure “on the job”.

Training

Training on the recognition of fluid failure is inadequate. Less than 60% of pilots have received verbal instructions on how to recognize fluid failure and only 15% to 20% have seen pictures or videos of fluid failure. When asked to describe how they recognize fluid failure only 80% could give a response for failure during snowfall, and only 66% for failure during freezing rain/drizzle or ice pellets. Of the pilots that responded, the responses indicate that most have a general idea of what to look for. Many mentioned more training is required or they use HOTs. Many were confused between the failure properties during snowfall and FZRA/FZDZ. Clearly, if pilots are expected to assess the condition of the wing during the pre-take-off inspection, better training on the recognition of fluid failure is required.

Over 50% of the respondents thought that training of flight and ground crews were fully satisfactory, despite the lack of knowledge about fluid failure recognition. Some of the suggestions for improvements included:

- better training on fluid failure recognition - pictures, videos, hands-on, etc.;
- better timing of recurrent training - just before winter;
- better training for ground crews, especially contract ground crews:
    - ◊ more standardization (application, fluid type, start of HOT),
    - ◊ improve communication (ground crews should communicate what areas of the aircraft they are deicing),
    - ◊ importance of removing snow from fuselage of aircraft with rear mounted engines,
    - ◊ too much turnover in ground crew to become experts,
    - ◊ ground crews need better training on “adhering” contamination - often unnecessary deicing in very cold conditions, and
    - ◊ better training at small stations.

Ground Crew Performance

For the most part pilots are satisfied with the ground deicing service provided. Many found the service to be excellent and have had no problems. Over 75% of pilots did not have reason to question the quality or capability of the deicing service provided and 70% are very confident that the aircraft is clean when cleared by the deicing crew. As mentioned above, many pilots thought ground crew training could be improved. Some ground crew are not sure at what point during the deicing procedure the HOT starts. About 35% of pilots stated they were informed of the fluid type without asking at some airports and not others, while 10% are not routinely informed of the type. Many pilots commented that they found the deicing service better in Canada than the US.

Despite the generally good performance of the deicing service, there were many reported incidents where the deicing was not properly done, e.g., wings still contaminated, or where the prop was not deiced or only deiced on one side. Inconsistent application of fluid can lead to fluid failure prior to expiry of the HOTs. Since the pre-take-off inspection is not mandatory prior to the HOT, instances of fluid failure due to improper fluid application may not be identified and could significantly jeopardize safety.

Assessment of Wing Condition in Pre-take-off Inspection

Representative Surfaces

The majority of pilots indicated that they found the representative surfaces represent the surface condition of the wing well or very well; 12% indicating very well. About 7% indicated they represent the wing poorly. The fluid failure tests conducted by APS on a variety of aircraft types under various conditions have found the locations of first fluid failure to be variable and rarely to occur on the representative surfaces. The fact that the majority of pilots think the representative surfaces work well is possibly not a good sign. As most pilots do not have a lot of experience with recognizing fluid failure, it could be an indication of false confidence in these surfaces. Comments by many pilots refer to inspection of the "rep. surfaces" rather than the critical surfaces or wing, and give the impression they only inspect the representative surfaces. The pilots responding "not well" and "poor" give many examples of contamination on the other areas of the wing prior to contamination on the representative surfaces.

Some of the comments on representative surfaces suggest that both sides of the aircraft should be inspected and that fluid failure is easier to detect on dark coloured surfaces.

Factors Affecting Assessment

Pilots were mixed on whether identification of fluid failure was easier for some fluid types than others. The pilots indicating that the type did make a difference often thought the colours of the fluids helped. Many have had little experience with any but Type I fluid.

Pilots identified lighting as the most important factor affecting their assessment of the condition of the wing. The direction of external lighting and the availability of only wing or emergency exit lighting were the main two factors. These were followed by de/anti-icing fluid on the windows and the option to open the door on high wing aircraft or cockpit window. The ranking of these factors did not vary greatly across categories of aircraft. Other factors included wing span, day/night, precipitation, wind/blowing snow, high/low wing, foaming of fluid and colour of wing.

Confidence in Assessment

Most pilots (87%) have medium to high confidence that they can identify fluid failure during snowfall in daylight, irrespective of whether the snowfall is light or heavy. However, in freezing drizzle only 65% of pilots are as confident. Pilots were not as sure what to look for when identifying fluid failure during freezing drizzle and almost all agreed that the assessment was easier in snowfall. The majority have low or very low confidence in the accuracy of their assessment at night time, especially with no external lighting and in freezing rain. For comparative purposes, confidence in their identifying clear ice over fuel tanks is higher than for identifying fluid failure at night in freezing rain.

There is a strong reliance on the HOTs when deciding on the need to re-deice the aircraft, especially in poor visibility and/or in freezing rain/drizzle. Most pilots (82%) have medium to high confidence that the HOTs reliably indicate the earliest the fluid could fail.

When it is difficult to identify whether the fluid failed due to poor visibility, pilots are for the most part conservative in their decision to re-deice. If the precipitation and HOTs indicate that the fluid has possibly failed and it is very difficult to see, 85% of pilots indicated they would return to re-deice even if they could not identify any fluid failure. This dropped to 63% returning to re-deice if it was somewhat difficult to see. Only 15% indicated that if they could not identify fluid failures (irrespective of visibility and available HOT), they would only return to re-deice if delayed and subsequent inspection revealed fluid failure.

Location and Method of Inspection

Most pilots (70%) indicated that it is not possible to make the pre-take-off inspection from the cockpit. Of those pilots who could inspect the wing from both the cockpit and cabin, 85% found the cabin better in low wing jet aircraft and 25% found the cabin better in low wing turboprop aircraft. In high wing aircraft, very few pilots found inspection better from the cabin.

Pilots that found the cabin better make their inspection from the cabin most of the time (60%), while those who found the cabin and cockpit similar would only go back to the cabin 15% of the time.

The option of opening the door to visually inspect the upper wing surface is used by over a third of pilots of high wing aircraft, most of these only when conditions warrant a close inspection. Many indicated that opening the door is not an option for pre-take-off inspection, many use it for the pre-flight inspection.

Many pilots indicated that a tactile check was the only way of really knowing the condition of the wing, they often requested this to be done or got (or would like to have had) a ladder to check it themselves. About 60% indicated that they have had a tactile check done for the pre-take-off inspection. Those that do, for the most part only have the tactile check done infrequently (less than 20% of the time), but some (10% of pilots) always have a tactile check done. The use of tactile inspections does not vary greatly between aircraft categories, but (surprisingly) appears to be done more for the larger aircraft. [Note: there may have been some confusion between pre-flight and pre-take-off inspection when answering this question - answers may be more representative of pre-flight inspections.]

Holdover Time Tables (HOTs)

Most of pilots (84%) find the range in the HOTs more useful than a single value. Generally they feel that the range provides some flexibility and allows pilots to use their judgment in the various weather conditions that can prevail. The few pilots who do not favour a range find it confusing and would like only a single minimum protection time value as they only use this value. Several pilots indicated that with a range being given, the maximum is used, e.g., “With the urge to depart the maximum value of the range is normally used”.

Procedures

Most pilots indicated that at airports equipped with a deicing pad, their air carrier requires a critical surface inspection prior to push back from the gate. Some indicated that this is done for coordinating use of the deicing pad and some indicated that the check is done by the pilots themselves during their pre-flight “walk around” inspection or by ground crew.

In conditions conductive to ground icing, but the aircraft was not deiced, most pilots will make a pre-take-off inspection either always (63%) or in certain conditions (25%). These conditions typically relate to the type and intensity of precipitation, temperature and due point, humidity, etc. Changes in weather conditions were also noted as a reason to re-check aircraft. About 10% rarely or never check aircraft just prior to take-off. A number of pilots mentioned that in conditions conducive to icing they always deice.

The majority of pilots are aware of their company’s quality management program to assess the quality or capability of the deicing service. However, 35% are not aware of the program and a few pilots indicated their company does not have a program.

A significant number of pilots (20%) indicated that pre-flight data is not available on the type of precipitation, PIREPS concerning critical precipitation and the possible need to reduce take-off weight. Many (30% - 50%) indicated that they were only available at some airports.

Pilots were asked, “given that you are within the HOT limits for light freezing drizzle, does this mean you are can safely take-off in those conditions?” About half the pilots indicated that it was safe, the other half that it was not safe. Most of the pilots indicating that it was not necessarily safe commented that in those conditions they make a visual inspection and/or that HOTs are only a guide. A number pointed out the risks due to runway contamination and cross winds. However, very few pilots (1%) made the link to the risks associated with airborne icing when considering the HOTs available in freezing rain/drizzle conditions.

Use of Sensors for Identifying Fluid Failure

There is widespread acceptance that the use of sensors for identifying fluid failure will improve safety. Over a third of pilots feel they will greatly improve safety. Pilots of high wing aircraft are most positive about their benefit to safety. The benefit of sensors in poor visibility conditions was noted by many pilots. There were, however, many caveats expressed regarding the use of sensors. These include:

- they should be used in conjunction with visual inspection;
- they must be accurate, reliable (“fail safe”) with few/no false warnings (previous experience with ice detectors have tempered the enthusiasm of many pilots);
- would need to gain confidence in them for pilots to trust them, pilots should be able to self test system;
- account for variation along wing span; and
- have a simple display in cockpit.

Pilots who saw little or no benefit in sensors commented that the benefit will depend on the technology, the sensors will likely be too sensitive and they are weary of false alarms. They also commented that reliability will be a problem and unless the sensors are 100% reliable and give few or no false alarms, they will be disregarded by crews. Some pilots are wary of sensors or simply “don’t trust them”.

Many pilots feel that visual inspection is more reliable than sensors, but in cases where visual inspection is almost impossible (high wing aircraft and poor lighting and visibility), reliable accurate sensors offer a real benefit.

AIR LINE PILOTS ASSOCIATION INTERNATIONAL CANADA
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June 2, 1997

TO THE AIRLINES PILOTS OF CANADA

We represent you on Transport Canada's 'STANDING COMMITTEE ON OPERATIONS UNDER ICING CONDITIONS". One of the objectives is to encourage and, where possible, promote aircraft icing related research and development. There is a requirement for direct line pilot feedback by means of the attached questionnaire. Although there is a large amount of ongoing research and development, also numerous papers including ALPA's "INFLIGHT STRUCTURAL ICING", AES's, "A CANADIAN CLIMATOLOGY OF FREEZING PRECIPITATION, and a detailed study using data from St. John's Newfoundland, we need the men and women that actually operate within the environment to send their message to Transport Canada.

To properly evaluate the level of success of the ground icing program, which is our way of preparing for a safe flight, please take the time to complete these questions. They are to be kept completely confidential, and do not ask for nor require your name or particular airline.

As the voice of Airline Pilots in Canada, let us use your valuable input to help achieve our primary goal, "ZERO ACCIDENTS" in air transport!

Captain Peter Foreman
Canada Central Air Safety Chairman

TAKE-OFF CLEAN WING INSPECTION RISK ASSESSMENT

QUESTIONNAIRE

The recent advances in ground de/anti-icing owe much to the TC Ground Icing Operations Standard established in conjunction with the airlines and pilots, in addition to the improved de/anti-icing fluids, and the ongoing research into techniques for implementing the clean aircraft concept.

The safety record suggests that PICs are acting responsibly within the TC Ground Icing Operations Standard by returning to the deicing pad when they are unable to verify that the aircraft is clean just prior to take-off even though the specified holdover time (HOT) may not have expired.

The advent of wing sensors to detect de/anti-icing fluid failure offers an additional means of continuous monitoring to supplement the visual inspection by flight crews. The consequences of fluid failure, and therefore the actual risks, depend upon many factors including the flight crew's success in assessing the clean wing condition prior to take-off roll.

Poor viewing conditions of the wing from either the flight deck or cabin is no doubt a significant factor in assessing fluid failure and/or the existence of wing contaminant. Accordingly, TC has initiated a project to:

> *evaluate the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.*

The analysis will be assisted by obtaining information from as many active commercial pilots as possible.

Purpose of the Questionnaire

- To assess the level of success achieved in recent years in addressing the problem of ground icing
- To obtain feedback on the need for additional measures to improve the situation (such as training, operating procedures and/or detection devices)

How You Can Assist

Within this background, your input is being requested by means of the attached questionnaire. The questionnaire has been reviewed by the Airline Pilot Association of Canada, the Air Canada Pilot Association, ATAC, TC and NAV CANADA, and is being distributed and collected by the pilot associations.

If you do not know an answer because a question includes details you have not been exposed to, it would be helpful it you could be frank and tell us.

Please do not identify yourself or your employer

Please insert the completed questionnaire in the pre-paid business reply envelop in which you received the questionnaire and post by June 20, 1997. Thank you very much for your assistance

QUESTIONNAIRE

A. GENERAL

A1. Do you feel recent changes in de/anti-icing standards and procedures have improved safety?

☐ Greatly ☐ Moderately ☐ A little ☐ No effect ☐ No opinion

Comment:____

A2. Do you feel that the wider availability and recent improvements in anti-icing fluids have improved safety?

☐ Greatly ☐ Moderately ☐ A little ☐ No effect ☐ No opinion

Comment:____

A3. Do you feel comfortable with the de/anti-icing procedures in use today?

☐ Yes ☐ No If no, please explain:____________________________

____

A4. Does the size of the airport affect the quality of de/anti-icing service provided?

☐ Yes ☐ No Comment:__________________________________

____

B. PILOT EXPERIENCE

B1. Please indicate the configuration of aircraft you currently fly:

☐ Twin Turboprop High Wing
☐ Twin Turboprop Low Wing
☐ Twin Turbofans - maximum 70 passengers
☐ Twin Turbofans - maximum 150 passengers
☐ Twin Turbofans - over 150 passengers
☐ Three Turbofans
☐ Four Turbofans High Wing
☐ Four Turbofans Low Wing

B2. How frequently do you fly:

◊ no. of departures per year __________
◊ no. of hour flown per year __________ hours
◊ no. of times your aircraft was deiced during last winter ___________
◊ no. of times your aircraft was re-deiced last winter due to delay in take-off _________

B3. Approximately what percentage of your departures last year were made under near or sub-zero temperatures (OAT): __________ %

B4. How many years have you been:

◊ a commercial pilot? ________ years
◊ operating in areas subject to ground icing? ________ years

B5. During the past <u>two</u> winter seasons when you have been part of the flight crew, how frequently have pre-take-off inspections been necessary because take-off could not be attempted before the HOT expired:

☐ frequently	(about 20 or more times each winter)
☐ infrequently	(about 10 times each winter)
☐ rarely	(about 5 times each winter)
☐ very rarely	(1 or 2 times each winter)
☐ never	(not once in the 2 winters when you have been crew)

C. CONFIDENCE

C1. During your training for ground icing, have you:

◊ received verbal instructions for recognizing fluid failure...........	☐ Yes	☐ No
◊ been shown black and white pictures of fluid failure.................	☐ Yes	☐ No
◊ been shown colour photos of fluid before and soon after fluid failure..	☐ Yes	☐ No
◊ been shown videos of fluid failing...	☐ Yes	☐ No
◊ been shown (live) fluid in process of failure..............................	☐ Yes	☐ No

C2. Is the training of flight and ground crews fully satisfactory?

☐ Yes ☐ No

If no, please suggest improvements:____

____

____

C3. In this past winter season have you had reason to question the quality or capability of deicing service provided to your aircraft prior to departing the deicing pad?

☐ Yes ☐ No

If yes, what action did you take? ____

____

C4. How well have you found the representative surfaces to represent the surface conditions of the wing? (answer only if you have been able to assess condition on most of the wing)

☐ Very well ☐ Well ☐ Not well ☐ Poorly ☐ Not able to assess most of wing

Comment: ______________________________

C5. How do you recognize failure of de/anti-icing fluid:

a) during snowfall? ______________________________
b) in freezing drizzle/rain or ice pellets? ______________________________
____

C6. Is it easier to identify fluid failure during falling snow or during freezing drizzle/rain?

☐ Easier in snow ☐ Easier in FZDZ/FZRA ☐ Both similar ☐ Not enough experience

Comment: ______________________________

Does the type of fluid influence your response? ☐ Yes ☐ No ☐ Not enough experience

If yes please comment: ______________________________

C7. How confident are you that:

	Confidence: Low				High
a) You can identify fluid failure accurately under the following:					
◊ Daylight, light snow	1	2	3	4	5
◊ Daylight, heavy snow	1	2	3	4	5
◊ Daylight, freezing rain	1	2	3	4	5
◊ Night time, light snow,					
- minimal external lighting (eg. on apron)	1	2	3	4	5
- no external lighting (eg. end of runway)	1	2	3	4	5
◊ Night time, heavy snow					
- minimal external lighting (eg. on apron)	1	2	3	4	5
- no external lighting (eg. end of runway)	1	2	3	4	5
◊ Night time, freezing rain					
- minimal external lighting (eg. on apron)	1	2	3	4	5
- no external lighting (eg. end of runway)	1	2	3	4	5
b)You can visually identify clear ice over the fuel tanks on the wing from inside the aircraft?	1	2	3	4	5
c)The HOT reliably indicates the earliest the fluid could fail?	1	2	3	4	5

C8. Please rate the importance of the following factors in affecting your assessment of the condition of the wing (rate on scale 1 - 5):

	Importance: Low				High
◊ wing span	1	2	3	4	5
◊ availability of only wing & emergency exit lighting	1	2	3	4	5
◊ direction of lighting at night	1	2	3	4	5
◊ de/anti-icing fluid on windows	1	2	3	4	5
◊ option to open door or window to get a better view of the wing	1	2	3	4	5
◊ other factors ______________________________	1	2	3	4	5

Comments on above factors or interactions between factors

C9. If, just prior to take-off, you make your <u>best</u> judgment of the wing condition and <u>cannot</u> identify whether the fluid has failed or not, would you return to deice again :

☐ only if take-off is delayed and subsequent inspection revealed fluid failure (i.e., irrespective of HOT and visibility),

OR, fluid condition is

☐ very difficult to see & HOT/precipitation indicates fluid possibly failed
☐ somewhat difficult to see & HOT/precipitation indicates fluid possibly failed
☐ very difficult to see & irrespective of HOT
☐ somewhat difficult to see & irrespective of HOT

(select the most appropriate <u>one</u> from the list above)

C10. On the aircraft you fly, is it possible to conduct the pre-take-off inspection from the cockpit?

☐ Yes ☐ No

If Yes,

a) From your experience, can you make a better assessment of the wing condition from the cabin or cockpit? The cabin is:

☐ better ☐ similar ☐ worse ☐ varies depending on section of wing

b) Please give the % of time you make the inspection from the cabin ________%

C11. If you fly a high wing aircraft, when conducting a pre-take-off inspection do you open the door and visually inspect the upper wing surface?

☐ I don’t fly high wing aircraft
☐ Yes - always
☐ Yes - in certain condition, please specify ______________________________
☐ No

C12. Would a signal in the cockpit linked to sensors capable of identifying fluid failure located on areas of the wing where the fluid typically fails first improve safety?

☐ Greatly ☐ Moderately ☐ A little ☐ No effect ☐ No opinion

Please comment: ____
____
____
____

D. PROCEDURES

D1. Are you, or would you be, comfortable with a ground deicing program which allows take-off within the specified HOT without conducting a further pre-take-off inspection?

☐ Yes ☐ No Comment ______________________________

If no, do you routinely make a visual pre-take-off inspection in these situations?
  ☐ Yes - always
  ☐ Yes - in certain conditions, please specify_________________________
  ☐ No - rarely/never

D2. In conditions conducive to ground icing, but the aircraft was NOT deiced, do you routinely make a visual pre-take-off inspection just prior to take-off?

☐ Yes - always
☐ Yes - in certain conditions, please specify
____
☐ No - rarely/never

D3. As part of the pre-take-off inspection, do you ever have a tactile inspection of the critical surfaces done by personnel outside the aircraft? ☐ Yes ☐ No

If yes, give approximate % of pre-take-off inspections where tactile inspection was done _________%

D4. The holdover time tables give a range of holdover times for a specific weather condition. Do you find a range more useful than a single value?

☐ Yes ☐ No Comment ______________________________

D5. How confident are you that the aircraft is clean when cleared by the deicer crew?

☐ Very confident ☐ Fairly confident ☐ Not confident

Comment: ____________________

D6. At each airport, are you informed of the type of fluid in use for deicing and anti-icing without specifically asking?

☐ Yes, at all airports ☐ Yes, at some airports ☐ No

Comment: ____________________

D7. At airports equipped with a deicing pad, does your air carrier require a critical surface inspection prior to pushback from the gate?

☐ Yes, at all airports ☐ Yes, at some airports ☐ No

Comment: ____________________

D8. Does your company have a quality management program to assess the quality or capability of deicing service provided in accordance with TC Ground Icing Operations Standard?

☐ Yes ☐ No ☐ Not aware of QM program

Comment:____________________

D9. Given that you are within the HOT limits for light freezing drizzle, does this mean you can safely take-off in those conditions?

☐ Yes ☐ No Comment ____________________

____

D10. During preflight is data available on the expected delay due to:

	Yes	Yes at some airports	No
◊ type of precipitation	☐	☐	☐
◊ pireps concerning critical precipitation	☐	☐	☐
◊ possible runway contamination	☐	☐	☐
◊ possible need to reduce take-off weight	☐	☐	☐

D11. Do you have any general comments on devices, training and/or procedures to improve safety in icing conditions - please attach comments

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Please insert the completed questionnaire in the pre-paid business reply envelop in which you received the questionnaire and post by June 20, 1997. Thank you very much for your assistance