TP 13427E

# Risk Management of Aircraft Critical Surface Inspection, Comparative Risks of Visual and Sensor-based Inspection

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Prepared by
**D.C. Biggs and G.B. Hamilton**
**SYPHER:MUELLER International Inc.**
**Ottawa, Ontario**

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16. Abstract

This study of ground icing of aircraft surfaces evaluated the comparative risks of conducting pre-take-off inspection based primarily on visual observation or point detection sensor systems. In the first phase of the project, a methodology was developed to evaluate the comparative risks of visual observation and point sensor systems and was applied using the limited current data available. The second phase undertook a comprehensive analysis of the comparative risks. It included sensitivity analyses of the effects of data limitations and of the assumptions made in the analysis, and made allowance for the pilot to return to re-deice, based on holdover times, delays, and weather conditions. False alarm rates were estimated for the different inspection procedures. Conclusions were drawn regarding the comparative risks for point sensor systems.

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16. Résumé

Cette étude sur le givrage au sol des surfaces d'aéronefs avait pour objet d'évaluer et de comparer les risques associés à une inspection avant le décollage fondée principalement sur l'observation visuelle et sur un système de capteurs ponctuels. Dans la première phase du projet, une méthodologie d'évaluation et de comparaison des risques associés à l'une et l'autre de ces deux méthodes d'inspection a été élaborée et appliquée en utilisant les données limitées disponibles. Dans une deuxième phase, les chercheurs ont mené une analyse comparative exhaustive des risques, incluant des analyses de sensibilité des résultats obtenus à une limitation des données et aux prémisses sur lesquelles a été fondée l'analyse et tenant compte de l'éventualité d'un retour au dégivrage en raison d'un dépassement de la durée d'efficacité du liquide antigivrage, du temps écoulé depuis son application ou des conditions météorologiques. Les taux de retours non nécessaires au dégivrage ont été estimés, et des conclusions ont été dégagées quant aux risques liés à chacune des deux méthodes d'inspection.

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# SUMMARY

## Background

A number of take-off accidents in the late 1980s and early 1990s 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 aircraft are 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. The regulations require the pilot to conduct a pre-take-off contamination inspection[1] to assess the condition of the fluid and/or the existence of contaminant on the wing if precipitation is falling and, under Canadian regulations, if the HOT has been exceeded. This inspection is usually conducted at the runway hold area just prior to take-off, without the assistance of ground crew. Visual observation by the pilot from inside the aircraft can be difficult, especially with deicing fluid on the windows and at night, away from terminal area lighting.

Sensors capable of identifying the presence of ice/snow on the wing and distinguishing between fluid that has failed and fluid that is still protecting the wing were seen as potential ways of improving safety in ground icing conditions. Research in the early 1990s, some sponsored by Transport Canada (TC), led to the development of two types of sensors that are now being tested: point sensors, mounted on the aircraft surface, usually the wing; and remote sensors that scan large areas of the aircraft from a distance. With the advent of these sensors, TDC initiated a project to compare the safety of the different inspection procedures. Specifically, the objective was 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 two-phase project began in January 1997. The primary objectives of each phase were:

Phase 1 – to develop a methodology for evaluating the comparative risks, to identify deficiencies in the data, and to recommend additional data that should be collected to complete the analysis.

Phase 2 – to implement the recommendations of the first phase and reach conclusions regarding the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.

The results of the first phase are given in the three-volume report, Risk Management of Aircraft Critical Surface Inspection (TP 13267E) prepared for TDC. Volume 1 covers the

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[1] Canadian Regulations call for an *inspection*, while the US/FAA regulations call for a *check*.

background and methodology for the comparative risk analysis for pre-take-off inspection based on visual and point sensor systems and includes some results for low-wing aircraft. Further field data are required before a similar analysis can be done using remote scanning/area sensors. Surveys of Canadian and U.S. airline pilots, reported in Volumes 2 and 3, were conducted to better understand the strengths and weaknesses of current ground icing and clean wing inspection procedures, and to obtain feedback on the need for additional measures.

One of the recommendations of the first phase was to collect additional field data on visual inspection by the pilot and fluid failure progression on additional aircraft types, over the 1997/98 winter. However, due to lack of suitable weather conditions at times when the aircraft were available for tests, no aircraft field data were collected. Without these data the focus of the analysis shifted to better use of the existing data and use of sensitivity analyses to determine the possible range in comparative risks. Risks for specific aircraft types could not be calculated due to the lack of data.

It should be noted that the focus of this study was the pre-take-off inspection just prior to departure, rather than the pre-flight inspection at the gate or the post deicing inspection immediately following deicing.

## Methodology

The approach developed during Phase 1 was used as the basis for estimating the risk of wing contamination when using visual and sensor-based pre-take-off inspection procedures. Due to the lack of suitable data for analysis of remote area sensors systems for pre-take-off inspection, the analysis focuses on comparative risks using point sensor systems. The following approach was used to evaluate the comparative risks:

- Using existing test data on the time and location of first fluid failure and the progression of the fluid failure across the wing, estimate the risk of wing contamination at the time of take-off due to a point sensor system not identifying the fluid failure;
- Using data on the area of the wing with fluid failure when an observer inside the cabin first observes the fluid failure, the view of the different sections of the wing from within the aircraft, and the fluid failure progression data, estimate the probability of the pilot not identifying fluid failure at the pre-take-off inspections and the risks at the time of take-off;
- Using results of the pilot survey and other information, include with the visual inspection procedures allowance for the pilot to not proceed with the take-off, based on the HOT, time since de/anti-icing, and weather conditions;
- Compare the risk measures estimated for the current visual pre-take-off inspection, the sensor system, and combined visual and sensor-based inspection;
- Determine the sensitivity of the estimated comparative risks to the effects of data limitations, analytical assumptions, and other factors, including:

  - location of sensors,
  - ability of pilot to visually identify fluid failure,
  - delay/taxi times,
  - time interval between pre-take-off inspection and take-off,
  - additional delay due to visual pre-take-off inspection,
  - effect of amount of contamination on aerodynamic performance,
  - consistency of the location of initial fluid failure,
  - time interval between visually observed fluid failure and a contamination level causing a significant effect on aerodynamic performance,
  - fluid failure progression test data which are very different from other tests (outlyers),
  - variation in location and time of fluid failure,
  - inclusion in the analysis of some tests where fluid failure data was available on only a limited area of the wing, and
  - the methodology used to estimate the risks using visual inspection.

- Determine the change in unnecessary re-deicings (false alarms) due to the use of point sensor systems by comparing estimates of:
  - the proportion of take-offs where the pilot identifies fluid failure at the pre-take-off inspection when the fluid would not have failed prior to take-off, with
  - the proportion of take-offs where the sensors system identifies fluid failure, but only a very small area of the critical parts of the wing is contaminated.

## Conclusions

*Comparative Risks of Visual and Sensor-based Pre-take-off Inspection*

Based on the risk analysis conducted, and the sensitivity of the risks to assumptions made in the analysis, it can be concluded that the risk associated with a serious aerodynamic performance penalty due to undetected failure of anti-icing fluids can be reduced significantly by the use of a point contamination detection sensor system.

- During aircraft ground operations with commonly experienced time delays between pre-take-off inspection and take-off, the risk when using an inspection system based on two point detection sensors per wing is less than the risk associated with the current visual inspection procedures, even under conditions of good visibility. The risk associated with visual inspection is 1.5 to 50 times greater than the risk associated with the use of point detection sensors, the value depending on the ground operational circumstances and analysis assumptions. This conclusion is valid when the sensors are placed in areas where the onset of fluid failure typically occurs in the areas most critical to aerodynamic performance, or where sensors are placed so that the state of the fluid can be reliably predicted in those areas.

- The use of an inspection system based on three point detection sensors per wing reduces the risk by a further 30% to 50%.

- The risk associated with a point detection sensor system used in conjunction with visual inspection is significantly lower than when either visual or sensor-based inspection is used separately in typical daytime and good viewing conditions. At night, any reduction in risk caused by conducting a visual inspection in addition to a sensor system inspection will be small.
- The risk incurred by using a two sensor per wing system, only (i.e., no visual inspection), for pre-take-off inspection is similar to, or slightly greater than, the risk associated with:
    - ➢ visual inspection, only, under very good viewing conditions with no delay between pre-take-off inspection and take-off, and
    - ➢ returning to re-deice on expiry of the HOT.

*False Alarm/Unnecessary Turnback Rates*

- Visual Inspection:

  Using visual pre-take-off inspection procedures, the percentage of re-deicings that are unnecessary (where the pilot in command returns for deicing, but the fluid would not in fact have failed prior to take-off) is approximately 90%.

- Point Detection Inspection

  Using point sensor systems, the proportion of returns with only a very small amount of contamination present would be much less than when using visual inspection procedures (except in very good viewing conditions).

- Holdover Time as Decision Criteria

  Use of expiry of the HOT (minimum value in HOT range) as the sole criteria for the decision to return to de-ice would:

    - ➢ for Type I fluid, lead to an unworkably high proportion of delayed take-offs.
    - ➢ for Type IV fluid, lead to a much lower number of returns. The rate would be only marginally higher than that for visual inspection at night.

*Allowance for HOTs, Delays, and Weather Conditions*

When using visual pre-take-off inspection procedures to decide whether to re-deice (or call for a tactile check), pilots consider the HOT and assess whether the protection time of the fluid is greater than the total of the fluid application, the taxi and the delay times. They estimate the protection time based on the range of HOTs given in the HOT Tables and the prevailing weather conditions.

The study shows that in order to keep risks at similar levels as those experienced in good viewing conditions, pilots *must* consider the HOT in deciding whether to re-deice in poor viewing conditions and must make reasonable estimates of the protection time.

The study also shows that in order to keep risks at similar levels as those applicable to low-wing aircraft, pilots of high-wing aircraft pilots *must* consider the HOT and need to be very conservative in the selection of protection times.

*Area/Scanning Sensors*

- The data is insufficient 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, or would be removed during the take-off run, when the sensors identify fluid failure;
  - ➢ the sensitivity of identification of fluid failure to transient contamination accumulation which is subsequently absorbed by the anti-icing fluid;
  - ➢ the view of the wing surface from the intended location of the sensor cameras; and
  - ➢ demonstrated use of the system for identifying fluid failure in operational conditions.
- Remote area sensors can significantly reduce the risks associated with post-deicing inspection, but this use of area sensors was not considered further in this report.

## Recommendations

- Point sensor systems should be used in conjunction with current pre-take-off inspection procedures to provide additional information to the pilot on the wing condition prior to take-off.
- Work with remote area sensor manufacturers, airports, and air carriers should be continued, to collect the data required for comparisons of the risks of using sensors and current inspection procedures.
- The data required for determining the reliability of tactile inspection should be collected and minimum reliability criteria for use of remote area sensors as an alternative to tactile inspection should be established.
- When the required data is available, the comparative risks of using remote area sensors and current procedures for both post-deicing critical surface inspection and pre-take-off inspection should be evaluated. In the latter case, risks associated with a remote area sensor mounted on a truck, or on a fixed or retractable pole near the runway apron should be considered.

# SOMMAIRE

## Contexte

Des accidents d’avions au décollage survenus à la fin des années 1980 et au début des années 1990 ont fait ressortir toute l’acuité des risques liés au décollage dans des conditions propices au givrage. Les autorités ont adopté une réglementation à cet égard, et les transporteurs aériens, avec la collaboration des pilotes, ont amélioré les procédures d’inspection visant à s’assurer avant le décollage de l’absence de givre sur l’appareil. Les liquides antigivrage ont par ailleurs été améliorés pour augmenter leur durée d’efficacité, donc diminuer le risque de perte d’efficacité pendant que l’appareil est en attente de décollage. La réglementation exige qu’en conditions de précipitations, le pilote fasse une inspection[2] de la surface de la voilure avant le décollage pour évaluer l’état du liquide antigivrage et déceler l’éventuelle présence de givre et, dans le cas de la réglementation canadienne, pour déterminer si la durée d’efficacité du liquide est dépassée. En règle générale, le pilote procède à cette inspection sur l’aire d’attente juste avant le décollage, sans l’aide du personnel au sol. Or, il peut être difficile de se rendre compte visuellement de la perte d’efficacité d’un liquide antigivrage depuis l’intérieur du poste de pilotage, surtout à cause de la présence de liquide dégivrant sur le pare-brise et du manque d’éclairage la nuit lorsque l’appareil est loin de l’aérogare.

On a d’abord songé, comme moyen de rehausser la sécurité des décollages en conditions de givrage, à utiliser des capteurs qui pourraient déceler la présence de glace ou de neige sur la voilure et reconnaître si le liquide antigivrage est toujours opérant ou s’il a perdu son efficacité. Des recherches menées dans ce sens au début des années 1990, dont certaines avec l’appui de Transports Canada (TC), ont débouché sur la mise au point de deux types de capteurs qui sont aujourd’hui à l’essai, soit des capteurs ponctuels que l’on place sur la surface de l’appareil, généralement sur la voilure, et des capteurs qui balaient à distance la surface de l’appareil. Après l’apparition de ces capteurs, le CDT a lancé un projet visant à comparer l’efficacité de différentes procédures d’inspection, dont l’objet était plus précisément:

> *évaluer et comparer les risques 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.*

Ce projet a été entrepris en janvier 1997 et devait être mené en deux étapes, dont les objectifs étaient les suivants:

Phase 1 – élaborer une méthodologie d’évaluation des risques, cerner les lacunes dans les données disponibles et formuler des recommandations quant aux données complémentaires à colliger pour compléter l’analyse.

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[2] La réglementation canadienne exige une inspection, tandis que celle de la FAA (É.-U.) exige une vérification.

Phase 2 – donner suite aux recommandations formulées à l'issue de la phase 1 et dégager des conclusions quant aux risques relatifs liés à une inspection avant le décollage fondée principalement sur l'observation visuelle, un système de capteurs ponctuels ou la détection à distance.

Les résultats de la première phase ont été présentés dans un rapport en trois volumes intitulé Risk Management of Aircraft Critical Surface Inspection (TP 13267E), préparé pour le compte du CDT. Le premier volume concerne la mise en contexte et la méthodologie appliquée à l'analyse comparative des risques associés à l'inspection avant décollage par observation visuelle et par capteurs ponctuels et présente des résultats sommaires valables pour des appareils à voilure basse. Les données n'étaient pas suffisantes pour étendre l'analyse à l'inspection par détection à distance. Les deuxième et troisième volumes présentent les résultats d'un questionnaire envoyé à des pilotes canadiens et américains en vue de dégager les points forts et les points faibles des procédures courantes d'inspection des conditions de givrage de la voilure avant décollage et de déterminer s'il y lieu de perfectionner ou de compléter ces mesures.

Une des recommandations des chercheurs à l'issue de la première phase du projet était de recueillir des données complémentaires en service sur l'inspection par observation visuelle et sur la progression de la perte d'efficacité des liquides antigivrage sur la voilure pour d'autres types d'appareils, au cours de l'hiver 1997-1998. Cependant, les conditions météorologiques recherchées n'étant pas au rendez-vous aux moments où les appareils étaient disponibles pour les essais, il n'a pas été possible de recueillir ces données. Il a donc fallu réorienter l'analyse pour tirer le maximum d'information des données disponibles et avoir recours à des analyses de sensibilité pour déterminer l'ampleur possible des risques. Il n'a pas été possible d'évaluer les risques en fonction de types d'appareils en particulier en raison d'une insuffisance de données.

À noter que cette étude était axée sur l'inspection effectuée par le pilote juste avant le décollage, et non sur celle qui se fait un peu avant au poste de stationnement, ni sur celle qui se fait immédiatement après le déglaçage avant décollage.

## Méthodologie

Les chercheurs se sont fondés sur la méthodologie élaborée au cours de la première phase du projet pour évaluer les risques de contamination des ailes lorsque l'inspection avant le décollage se fait par observation visuelle, puis par capteurs ponctuels. Faute de données suffisantes, le scénario de détection par capteurs à distance a dû être exclu de cette analyse comparative. L'approche suivante a donc été adoptée pour comparer les risques associés à l'une et l'autre des méthodes de contrôle précitées:

- à partir des données d'essais disponibles sur le moment et l'endroit où le liquide antigivrage cesse d'être efficace et sur la progression de la perte d'efficacité sur la voilure, évaluer les risques liés à une éventuelle incapacité d'un système à capteurs ponctuels à détecter la présence de contaminants sur les ailes au moment du décollage;

- à partir des données disponibles sur la première zone de la voilure où la perte d'efficacité du liquide antigivrage est observée depuis le poste de pilotage, sur les différentes zones de la voilure visibles depuis le poste de pilotage et sur la progression de la perte d'efficacité du liquide antigivrage sur la voilure, évaluer la probabilité que le pilote soit incapable de déceler les signes de perte d'efficacité du liquide antigivrage au moment du décollage et les risques liés à cette éventualité;

- en se fondant sur les réponses des pilotes au questionnaire et sur des données d'autres sources, intégrer à la procédure d'inspection visuelle la possibilité que le pilote décide de ne pas décoller en raison d'un dépassement de la durée d'efficacité, du temps écoulé depuis l'application de liquide de dégivrage/ antigivrage ou des conditions météorologiques;

- comparer les risques liés aux trois procédures d'inspection avant décollage suivantes: procédure d'inspection par observation visuelle actuellement en usage, contrôle par système à capteurs ponctuels, combinaison de ces deux méthodes;

- déterminer la sensibilité des résultats de l'analyse comparative des risques à la limitation des données, aux prémisses sur lesquelles repose l'analyse et à d'autres facteurs, notamment:
  - l'emplacement des capteurs sur la voilure;
  - la capacité du pilote à percevoir la perte d'efficacité du liquide antigivrage;
  - les temps d'attente et de roulage au sol;
  - le délai entre l'inspection et le décollage;
  - le délai supplémentaire attribuable à la durée de l'inspection visuelle avant le décollage;
  - l'effet de la quantité de contaminant sur la performance aérodynamique de l'appareil;
  - la régularité quant à la zone de la voilure où se manifeste en premier la perte d'efficacité du liquide antigivrage;
  - le délai entre la détection visuelle de la perte d'efficacité du liquide antigivrage et le début d'un effet de la contamination sur la performance aérodynamique de l'appareil;
  - le large écart constaté entre les résultats des essais de progression de perte d'efficacité et ceux des autres essais (valeurs aberrantes);
  - la variation quant au temps couru jusqu'à la perte d'efficacité et aux zones où elle est observée;
  - la prise en compte, dans l'analyse, de certains essais pour lesquels on ne disposait que de résultats partiels, limités à une certaine zone de l'aile, concernant la perte d'efficacité du liquide antigivrage;
  - la méthodologie appliquée à l'estimation des risques associés à l'inspection visuelle;

- déterminer la différence dans le nombre de retours non nécessaires au dégivrage attribuable à l'utilisation d'un système de détection à capteurs ponctuels en comparant les résultats des estimations suivantes:

  - le pourcentage de fois où, à l’inspection avant le décollage, le pilote juge à tort qu’il y a perte d’efficacité du liquide antigivrage;
  - le pourcentage de fois où le système de détection à capteurs ponctuels indique une perte d’efficacité du liquide antigivrage alors qu’une partie très restreinte des zones critiques de la voilure seulement est contaminée.

## Conclusions

*Comparaison des risques associés à une inspection par observation visuelle et par capteurs ponctuels*

D’après les résultats de l’analyse comparative des risques et la sensibilité de ces résultats aux prémisses qui ont servi de fondement à l’analyse, on peut affirmer que les risques d’accident au décollage liés à une dégradation sensible de la performance aérodynamique de l’appareil attribuable à une perte d’efficacité non détectée du liquide antigivrage peuvent être réduits considérablement par l’utilisation d’un système de détection de contaminants à capteurs ponctuels.

- Lors des manoeuvres au sol d’aéronefs assorties de délais normaux entre l’inspection et le décollage, l’utilisation d’un système de détection comportant deux capteurs ponctuels par aile réduit les risques comparativement à la procédure d’inspection visuelle actuellement en usage, et ce, même lorsque la visibilité est bonne. De fait, le risque associé à une inspection visuelle est de 1,5 à 50 fois supérieur au risque lié à l’utilisation de capteurs ponctuels, la valeur du multiplicateur étant fonction des conditions opérationnelles et des prémisses fondant l’analyse. Cette conclusion vaut lorsque les capteurs sont placés de façon à détecter les premiers signes de perte d’efficacité dans les zones les plus critiques pour la performance aérodynamique de l’appareil, ou lorsqu’ils sont placés de façon à autoriser des prédictions fiables quant à l’état du liquide antigivrage dans les zones considérées.

- L’utilisation d’un système de détection à trois capteurs par aile réduit les risques davantage, de l’ordre de 30 p. 100 à 50 p. 100.

- L’utilisation d’un système de détection à capteurs ponctuels jumelé à la procédure d’inspection visuelle réduit considérablement les risques comparativement à l’une ou l’autre méthodes prises séparément, le jour et dans des conditions de bonne visibilité. De nuit, une inspection visuelle en tant qu’appoint au système de capteurs a peu d’effet sur la réduction des risques.

- Le niveau de risque associé à l’utilisation exclusive (c.-à-d. sans le compléter par une inspection visuelle) d’un système de détection comportant deux capteurs par aile est égal ou légèrement supérieur à celui:
  - d’une inspection visuelle seule, dans d’excellentes conditions de visibilité, sans aucun délai entre l’inspection et le décollage;
  - d’un retour au poste de dégivrage à la fin de la durée d’efficacité du liquide antigivrage.

*Taux de retours non nécessaires au dégivrage*

- Inspection visuelle

  Dans le cas des inspections visuelles, le pourcentage de retours non nécessaires au dégivrage (cas où le pilote commandant de bord retourne au poste de dégivrage, mais où le liquide antigivrage n’a pas perdu son efficacité avant le décollage) est d’environ 90 p. 100.

- Système de détection à capteurs ponctuels

  Dans le cas où un système de détection à capteurs ponctuels est utilisé, le pourcentage de retours au dégivrage alors que la quantité de contaminant sur la voilure est très faible est largement inférieur à celui constaté pour les inspections visuelles (sauf en cas d’excellentes conditions de visibilité).

- Utilisation de la durée d’efficacité en tant que critère de décision

  Une décision fondée uniquement sur le dépassement de la durée d’efficacité (valeur minimale de la gamme) aurait les effets suivants:

  - ➢ avec un liquide antigivrage de type I, le taux de retours au dégivrage serait si élevé qu’il en résulterait une paralysie des opérations;
  - ➢ avec un liquide de type IV, le taux de retours non nécessaires au dégivrage serait beaucoup plus faible, à peine plus élevé que celui associé à l’inspection visuelle la nuit.

*Marge de sécurité concernant les durées d’efficacité, les attentes et les conditions météorologiques*

Lorsqu’ils recourent à une inspection visuelle pour décider s’il y a lieu de retourner au dégivrage (ou de demander une vérification par le toucher), les pilotes prennent connaissance de la durée d’efficacité du fluide appliqué et vérifient si elle est supérieure aux temps combinés de l’application du fluide, du roulage au sol et des autres attentes. La durée d’efficacité du liquide antigivrage est établie selon la gamme de valeurs indiquées dans les tables de durées d’efficacité et les conditions météorologiques du moment.

L’étude révèle que, pour que le niveau de risque associé à une inspection visuelle ne soit guère plus élevé en conditions de visibilité réduite qu’en conditions de bonne visibilité, le pilote doit, lorsque la visibilité est réduite, tenir compte de la durée d’efficacité du fluide dans sa décision de retourner ou non au poste de dégivrage, et doit faire une estimation prudente de la durée de la protection assurée par le fluide antigivrage.

La recherche révèle en outre que, pour que le risque associé aux aéronefs à voilure haute ne soit pas plus élevé que celui associé aux aéronefs à voilure basse, les pilotes d’aéronefs à voilure haute doivent utiliser les tables de durées d’efficacité et être très prudents dans le choix des valeurs.

*Détection à distance*

- Les données disponibles ne permettaient pas de comparer les risques associés à l'inspection avant décollage par la procédure d'observation visuelle et par la détection à distance par capteurs à balayage. Cette analyse exigerait les données suivantes:
    - les temps courus jusqu'à la perte d'efficacité, indiqués par les capteurs et observés par les pilotes lors d'essais sur des appareils sous diverses conditions naturelles de précipitation;
    - dans les cas où les capteurs enregistrent une perte d'efficacité du liquide antigivrage, le degré d'adhérence des contaminants à la surface de la voilure ou la mesure dans laquelle ils en seraient détachés lors du roulement au décollage;
    - la sensibilité du système de détection aux pertes d'efficacité transitoires, attribuables à une accumulation temporaire des contaminants, qui sont par la suite absorbés par le liquide antigivrage;
    - la zone de l'aile balayée par le détecteur depuis l'emplacement envisagé;
    - l'efficacité démontrée du système pour détecter la perte d'efficacité du liquide antigivrage en conditions de service.

- Les capteurs à balayage utilisés à distance peuvent réduire considérablement les risques associés à l'inspection après déglaçage, mais cet emploi des capteurs n'a pas été considéré plus avant dans la présente étude.

## Recommandations

- Les capteurs ponctuels devraient être utilisés comme appoint à la procédure en usage d'inspection visuelle avant le décollage pour fournir au pilote des données additionnelles sur l'état de la surface de la voilure.

- La collaboration avec les constructeurs de systèmes de détection à distance par capteurs à balayage, les autorités aéroportuaires et les transporteurs aériens devrait se poursuivre en vue de recueillir les données nécessaires à une analyse comparative des risques associés à ces systèmes et à la procédure d'inspection visuelle en usage.

- Les données nécessaires pour déterminer la fiabilité de la vérification par le toucher devraient être recueillies, et des critères minimaux de fiabilité applicables à l'utilisation de systèmes de détection à distance par capteurs à balayage en remplacement de la vérification par le toucher devraient être établis.

- Lorsque les données nécessaires auront été rassemblées, les risques associés respectivement à la détection à distance par capteurs à balayage et aux procédures actuellement en usage pour l'inspection après dégivrage des surfaces critiques et l'inspection avant décollage devraient être évalués et comparés. Dans le cas de l'inspection avant décollage, il y aurait lieu de considérer les risques associés à la détection par capteurs à balayage montés sur un camion ou sur une tige fixe ou escamotable placée à proximité de l'aire d'attente.

# Risk Management of Aircraft Critical Surface Inspection – Comparative Risks of Visual and Sensor-based Inspection

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# Glossary of Terms

| | |
|---|---|
| AD | Airworthiness Directive |
| AC | Advisory Circular |
| ARP | Aerospace Recommended Practice (SAE) |
| 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 |
| CAR | Canadian Aviation Regulation |
| Fluid Failure | The visual fluid failure definition is used in this report where fluid failure is 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 substantially 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 |
| PIC | Pilot In Command |
| 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 |

# 1. INTRODUCTION

## 1.1 Background

A number of take-off accidents in the late 1980s and early 1990s 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 aircraft are 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. The regulations require the pilot to conduct a pre-take-off contamination inspection to assess the condition of the fluid and/or the existence of contaminant on the wing if precipitation is falling and, under Canadian regulations, if the HOT has been exceeded. This inspection is usually conducted at the runway hold area just prior to take-off, without the assistance of ground crew. Visual observation by the pilot from inside the aircraft can be difficult, especially with deicing fluid on the windows and at night, away from terminal area lighting.

Sensors capable of identifying the presence of ice/snow on the wing and distinguishing between fluid that has failed and fluid that is still protecting the wing were seen as potential ways of improving safety in ground icing conditions. Research in the early 1990s, some sponsored by Transport Canada (TC), led to the development of two types of sensors that are now being tested: point sensors, mounted on the aircraft surface, usually the wing; and remote sensors that scan large areas of the aircraft from a distance. With the advent of these sensors, the Transportation Development Centre (TDC) initiated a project to compare the safety of the different inspection procedures. Specifically, the objective was 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 two-phase project began in January 1997. The primary objectives of each phase were:

Phase 1 – to develop a methodology for evaluating the comparative risks, to identify deficiencies in the data, and to recommend additional data that should be collected to complete the analysis.

Phase 2 – to implement the recommendations of the first phase and reach conclusions regarding the comparative risks of conducting pre-take-off inspection based primarily on visual observation, point detection sensor systems, or remote detection sensors.

The results of the first phase are given in the three-volume report, Risk Management of Aircraft Critical Surface Inspection (1). Volume 1 covers the background and methodology for the comparative risk analysis for pre-take-off inspection based on visual and point sensor systems and includes some results for low-wing aircraft. Further field data are required before a similar analysis can be done using remote scanning/area sensors. Surveys of Canadian and U.S. airline pilots, reported in Volumes 2 and 3, were conducted to better understand the strengths and weaknesses of current ground icing and clean wing inspection procedures, and to obtain feedback on the need for additional measures. Recommendations given in the report were:

- 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 the holdover time (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.

These recommendations were to be implemented during the second phase of the project. TC engaged APS Aviation to collect the additional field data on visual inspection by the pilot and fluid failure progression on additional aircraft types over the 1997/98 winter. However, due to lack of suitable weather conditions at times when the aircraft were available for use in the tests, no aircraft field data were collected. Without this data the focus of the analysis shifted to better use of the existing data and use of sensitivity analyses to determine the likely range in comparative risks. Risks for specific aircraft types could not be calculated due to the lack of data.

This report describes the methodology for the extensions of the risk analyses, and gives a comprehensive analysis of the comparative risks, including a sensitivity analysis of the assumptions and estimated parameters. The remaining sections of this introduction provide the context in which the risk analysis was conducted. The current regulations, procedures and practices, the latest developments with the sensor systems, fluids and protecting the wing, and the effect of wing contamination on aerodynamic performance are briefly summarized.

## 1.2 Current Regulations, Procedures and Practices

The current Canadian regulations covering ground icing are given in CAR 602-11. The regulations state that take-off should not be attempted in an aircraft which has frost, ice or snow adhering to any of its critical surfaces. It is the responsibility of the pilot-in-charge (PIC) to ensure the aircraft is “clean” before initiating take-off. The regulations also require the operator to have a program established in accordance with standards specified in the **Ground Icing Operations Standard,** and that 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 a further inspection is required immediately following de/anti-icing. For certain aircraft under particular conditions a tactile inspection is mandatory.

In Canada 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. Important aspects of this inspection include:

- 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 five-minute period in which to take-off after the pre-take-off inspection; this time period is not mentioned specifically in the regulations or the Ground Icing Operations Standard, but is given in the SAE Recommended Practices, ARP4737 (18); and
- 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 check even if the take-off can be commenced before the HOT has expired[3].

There 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 AlliedSignal (2) and are summarized briefly below:

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[3] 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.

- 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 that 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; and
- Fluid failure could occur after the pre-take-off inspection but before take-off.

A number of the conclusions drawn from the surveys of airline pilots during the first phase of the study are particularly relevant to the analysis of comparative risks and are repeated below:

- 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;
- 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 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;
- 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; and

- 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.

## 1.3 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 used primarily for identifying clear ice buildup over wing fuel tanks on aircraft with rear-mounted engines.

In the early 1990s, sensors were developed that are capable of not only identifying ice buildup on a clean wing, but also the presence of de/anti-icing fluid and whether the fluid is continuing to absorb freezing and frozen precipitation. The information provided by these sensors could be of use to the pilot in conducting the pre-take-off inspection and could, ultimately, be used as an alternative to the pre-take-off inspection.

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 categories of sensors are discussed below. 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.

### 1.3.1 Point Sensors

Point sensors are typically small, with a diameter of about 1 to 5 cm (0.5 to 2 inches), and measure the properties of the fluid over the sensor head. The sensors can measure, among other things, the integrity of the fluid and its thickness, and the temperature of the wing surface.

The Allied Signal (C-FIMS) (2) (3) (4) sensor system has been installed on in-service aircraft and tested over three winters. Tests have been conducted with one or two sensors per wing. Aircraft requiring a tactile check have been used in the tests so as to provide a means of checking the sensor readings. The tests have been very successful. Allied Signal has applied for FAA certification of C-FIMS as an advisory system to provide additional information to the pilot on the condition of the wing.

The Intertechnique Wing Contamination Monitoring System (WCMS) (5) (6) has been installed on in-service aircraft operated by TRANSWEDE and tested over two winters. Tests have been conducted with four sensors on one wing (two on the leading edge, one on the wing tip and one on the trailing edge). The objectives of this evaluation were to determine whether the system provides an alternative to:

- HOT tables; and
- The Airworthiness Directive (AD) on the Fokker F100 aircraft requiring a tactile inspection after deicing.

The tests were designed to demonstrate the ability of the system to:

- provide advisory indications about the de/anti-icing fluid effectiveness when the airplane is operating on the ground in icing conditions both within and after expiry of the HOT; and
- detect the presence of frozen contamination on specific airplane surfaces after deicing.

Mechanical tactile checks after deicing, automatic data recording at take-off, pilot reports and specific overnight tests under icing conditions have been used in the tests to provide a means of checking the sensor readings. Tests with sensors have been very successful. Intertechnique plans to certify their system with JAA once the EUROCAE Minimum Operational Performance Specifications for the In-flight and On-ground Ice Detection Systems, which are currently being drafted, have been completed.

Several other point detection systems, including VibroMeter and Sextant Avionique, are being developed for in-flight ice detection and in their current form are not suitable for pre-take-off contamination detection.

The primary concern with point sensors is the small area covered by the sensors and their ability to predict the condition of the entire wing. This is considered in the risk analysis in Section 3.

### 1.3.2 Area/ Scanning Sensors

Area/scanning 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.

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 can be shown in different colours or colour intensities (7). Laboratory tests indicate that the sensors can differentiate frozen precipitation (ice, snow and slush) from water, fluids and a range of aircraft surface materials and colours with high reliability.

Area sensors developed by Spar Aerospace/Cox and Company (8) (7) (9), and BF Goodrich/Robotic Vision System Inc. (RVSI) (4) (10) (11) (12) have been tested at a number of airports for verifying that an aircraft is clean after it has been deiced. The sensors are either handheld or 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.

### *Use in Pre-take-off Inspections*

Use of area sensors for pre-take-off inspection requires that the sensors be either mounted on the aircraft or on a pole, either on a vehicle or possibly a retractable or “break-away” pole, that could be located near the start of the runway where the pre-take-off inspection takes place. Operational tests of an area sensor mounted on vehicle with a 12.5 m (42 ft) pole were conducted by APS for TC in February and March, 1999. Preliminary results of the trials “demonstrated that the scanner camera can be located in a position that is operationally acceptable, and where viable information can be obtained from a remote ice detection system” (17). Other issues, such as restrictions on the location of vehicles near the runway, due to safety considerations, will need to be fully addressed before vehicle-mounted system are approved for use in conducting pre-take-off inspections.

BF Goodrich Aircraft Sensor Division installed one of their area sensors on a B727 aircraft above a window overlooking the wing. Initial tests for identifying contamination of the wing were successful, but more comprehensive testing is required. Aircraft-mounted versions of the area sensors have not yet been fully developed and are likely several years away.

Initial indications are that the area/scanning sensors will be able to identify the presence of frozen contamination prior to deicing, or of residual ice or fluid failure following deicing, with high reliability on all surfaces that can be viewed by the camera. 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 and the frequent occurrence of fluid failure in that location. A full evaluation of these systems for pre-take-off inspection is not presently possible due to the lack of test data and operational experience in the identifying fluid failure. The risk comparisons therefore concentrated on point sensors systems.

The data requirements for conducting a comparative risk assessment using area scanning sensors mounted on the aircraft for conducting pre-take-off inspections, discussed in the previous report (1), are as follows:

- 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 either adhering to the wing surface, or would be removed during the take-off run, when the sensors first 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 comparative assessment of risks using primarily visual and point sensor-based systems can be extended to include area/scanning sensors once the data is available.

### *Use in Post-Deicing Critical Surface Inspection*

Area sensors could provide significant safety improvements when used as remote sensors to confirm the aircraft is free of ice contamination following deicing. The post deicing inspection of critical surfaces is an important component of the safety procedure as many of the critical surfaces are not visible during the pre-take-off inspection and HOTs are only applicable if the aircraft is clean following deicing and the anti-icing fluid has been applied properly. Also, residual contamination may be obscured by anti-icing fluid during the pre-take-off inspection.

Important aspects of the post deicing inspection of critical surfaces affecting safety are:

- Visual inspection can be difficult depending on the viewing conditions and the type and location of residual contamination following deicing:
  - remote sensors have identified areas of contamination missed by visual inspection in operational tests conducted by Delta airlines;
  - one carrier reported cases of some contamination found on the trailing edge following deicing due to run back of some melted ice from ice being cleared from an adjoining part of the wing. These problems have been identified during the visual inspection, but it is unknown how frequently these occur and are not picked up by visual inspection.

- Clear ice is very difficult to visually detect and can be particularly hazardous on aircraft with rear-mounted engines. Tactile checks of areas where clear ice commonly forms are mandatory on some aircraft immediately following deicing. However, reliability of tactile checks is influenced by factors such as:
  - location – ice may be in areas other than those checked;
  - texture – clear ice is smooth and can be difficult to tell apart from the wing surface; some procedures call for a thumb nail scratch test, while in others the aircraft has some pre-marked roughness on the surface and, if the roughness cannot be felt using fingers or a rod, clear ice may be present;
  - tactile checks can be messy with glycol getting on the hands of those doing the checks. In cold weather when wearing gloves, this is a problem that discourages doing a thorough job; and

  - tactile checks in some locations require the engines to be shutdown, which discourages the use of tactile checks in these locations.

- Deicing fluid cannot in most cases be sprayed directly in the engine inlet and clearing of any contamination in these areas is therefore difficult. Thorough inspection of these areas following deicing requires a tactile check and cannot be done without shutting down the engines. Furthermore, the engine inlet of the #2 engine on a three-engine aircraft is very difficult to access to conduct a tactile check. There have been several incidents in recent years involving damage to the rotor blades where ice from the engine inlet was the suspected cause.

Remote area sensors have the potential to significantly reduce the risks associated with post deicing inspection of critical surfaces. The remote area sensors have the potential to:

- inspect most critical areas of the wing quickly and more thoroughly than visual observation;
- allow inspection without the need to shut down the engines;
- identify both clear and rough ice without contacting the surface being inspected;
- inspect hard-to-access areas such as the #2 engine on a three-engine aircraft.

Tests have been conducted to demonstrate these attributes of remote area sensors, but the results have not yet been published.

The main advantage of remote area sensors for use in post deicing inspection is the ease and speed of conducting a thorough inspection of critical surfaces relative to visual/tactile inspections. Risk reduction will likely come mainly from identification of residual contamination that was not identified visually and not inspected using a tactile check.

Remote area sensors also offer significant operational and safety advantages over the mandatory tactile checks on aircraft such as the Canadair RJ, Fokker 28 and McDonnell Douglas MD80 and MD88. The tactile check procedures on these aircraft focus on the identification of clear ice on the wing surface that poses the threat of foreign object ingestion in the rear-mounted engines. These procedures vary among aircraft types and air carriers. The FAA has approved the use of the BF Goodrich ice detection point sensor as an alternative to the mandatory tactile checks on the MD80 and MD88.

Before remote area sensors are approved for use as an alternative to tactile inspection, it will be necessary to show that, as a minimum, the remote sensor is at least as reliable as current tactile inspection procedures and will reduce the risk. However, the reliability of tactile inspection procedures is difficult to assess due to:

- the strong influence of operational factors such as weather conditions, deicing procedures and personnel, tactile check procedures and training, quality of the deicing and tactile checks performed, and fuel temperature in the various fuel tanks;
- the true condition of the wing when no contamination is found using a tactile inspection being unknown; and
- the lack of documented data on the results of tactile checks on different parts of the wings, or results of tests of remote sensors when used in conjunction with tactile inspections.

Operational test data were collected in March by Hudson General at Toronto airport and by Delta Airlines. Using these data and other more qualitative data collected on tactile inspections, it is hoped that at least upper bounds on the reliability of tactile inspections can be determined. These could then be used as a minimum when setting reliability levels for remote area sensors.

## 1.4 Fluids and Protection of the Wing

Deicing fluids are used to clean accumulated 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.

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 set a standard for the acceptable 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 dilution of the fluid due to precipitation.

Under conditions of precipitation, the fluid becomes diluted and the viscosity and thickness change. This affects the wave formations of the fluids under take-off conditions. In the early stages of contamination the wave heights will be reduced and the aerodynamic impact 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 effect on the lift characteristics 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 accumulation of precipitation, serious and possibly catastrophic aerodynamic effects may result; but just how long it takes to reach this condition is not well understood.

The buildup of ice crystals in the fluid is difficult to see, particularly at night in precipitation conditions. Generally, for the buildup 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. However, in continuing precipitation, the areas will grow until much of the wing surface is covered with evident contamination. At some point the crystals will either penetrate to the solid wing surface and bond, or form a layer that is not blown off the wing on take-off. In either case, a very severe (and lasting) roughness will be produced that could be catastrophic.

The problem of visually observing fluid failure is that the condition whereby the fluid fails to protect the underlying surface frequently occurs when a substantial amount of slush has accumulated on top of the fluid. This slush obscures the aircraft surface making it difficult to assess whether adhesion is occurring. Also, tests by TC indicate that fluids with a substantial amount of slush on top, but no adhesion of ice underneath, are not always stripped from the wing on the take-off run and can affect aerodynamic performance in a similar way to adhering contamination. Therefore, in the absence of any better indicators, the beginning of visually observable contamination of the surface of the fluid has been accepted as a conservative boundary condition for the end of the period where the anti-icing fluid protects the critical surfaces. This condition has been used to establish the safe time for exposing the fluid to contamination.

### *Visual Fluid Failure and Adhesion*

Throughout this report fluid failure is taken to be the state of the fluid when it is visually observed to fail, i.e., when ice crystals cease to be absorbed into the fluid and begin to build up on the surface of the fluid. Test data used in the risk analysis were collected using this classification of the fluid condition and it was therefore necessary to use the same classification in the analysis. Care should be taken not to confuse the definition with the criteria for fluid failure used by the SAE in tests with standardized plates to determine HOTs.

As discussed above, the protection time of the fluid is greater than the visually observed failure time. Significant changes in aerodynamic performance are known to occur when the ice crystals either penetrate to the solid wing surface and bond, or form a layer that is not blown off the wing on take-off.

The time period between visual failure and the protection time was investigated by APS (13) by examining the time till adhesion of ice to the surface following visual failure. The investigation was limited to tests using flat plates during simulated freezing drizzle with Type I and Type IV fluids. Their results showed that Type I fluid “adheres very quickly after [visual] failure”: 1 to 2 minutes in their tests. Type IV fluid did “not adhere immediately at the time of [visual] failure, but only gradually when exposed to ongoing precipitation”. Adhesion took place 4 to 5 minutes after visual failure. Tests with snowfall on flat plates have not found strong bonding to the surface following fluid failure. However, wind tunnel tests indicate the frozen contamination in the fluid becomes sufficiently rigid to not be blown off during take-off, independent of whether or not the contaminant has actually adhered to the surface.

The time interval between visually observed fluid failure and a significant effect on aerodynamic performance is important for two reasons. A delay in the onset of an effect on performance reduces the likelihood of critical lift loss, and reduces the risk associated with conducting the pre-take-off inspection several minutes prior to take-off.

*Holdover Time*

The 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 wing surface. On the contrary, the holdover time represents the minimum 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 the fluid will provide protection and thus there needs to be continuous checking of the condition of the fluid 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, does not result in significant lift losses. Also, no accidents have occurred where the aircraft has taken off within the holdover time since holdover times were specified by the SAE (since 1990).

## 1.5 Effect of Fluid Failure on Aerodynamic Performance

The major 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, as are the resulting increase in take-off distance and reduction in climb rate. However, 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. As noted by Brumby (15), 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.

As discussed in the Volume 1 report (1), the aerodynamic performance is related to the form of roughness, not the thickness of the ice, and is much more sensitive to contamination of the leading edge than other parts of the wing. The reduction in maximum attainable lift is the major factor contributing to the accident risk. It has been found to decrease as the ratio of the roughness height to the wing cord increases, but the rate varies with the wing configuration and the area and location of the contamination.

The approach used to relate the amount and location of wing contamination to the risks is described in detail in the Volume 1 report (1), and is summarized in Section 3.1.4.

# 2. APPROACH

## 2.1 Overview

To investigate the comparative risks of critical surface inspection the analysis was broken into four main components:

A. Current Regulations and Airline Practices
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. Components related to the background (A) and fluid failure and assessment (B) are only briefly summarized here. The following topics are not considered here and the reader is referred to the Volume 1 report (1) for a discussion of these topics:

- recent accident history;
- training on, confidence in, and accuracy of, visual identification of fluid failure; and
- accuracy of point sensors in identifying fluid failure.

Other steps in components C and D dealt with in the earlier report are summarized here, and in some cases, updated with more recent information. Improvements to the methodology are described. Some steps, such as frequency of false alarms and risks associated with not conducting a pre-take-off inspection, are only dealt with in this report.

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.

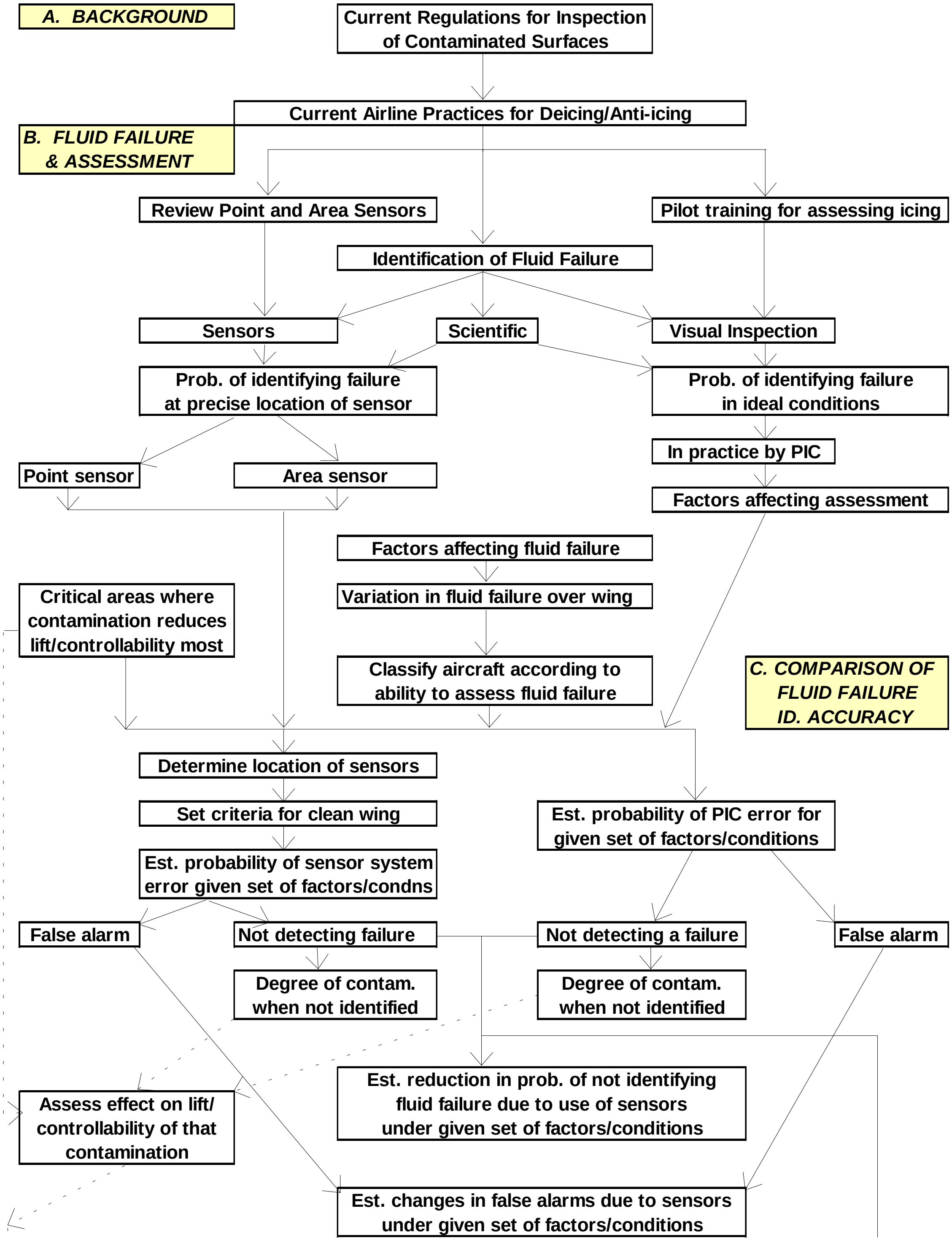


**Figure 2.1 Flowchart of Steps of Comparative Risk Analysis**

*(figure continued on next page)*

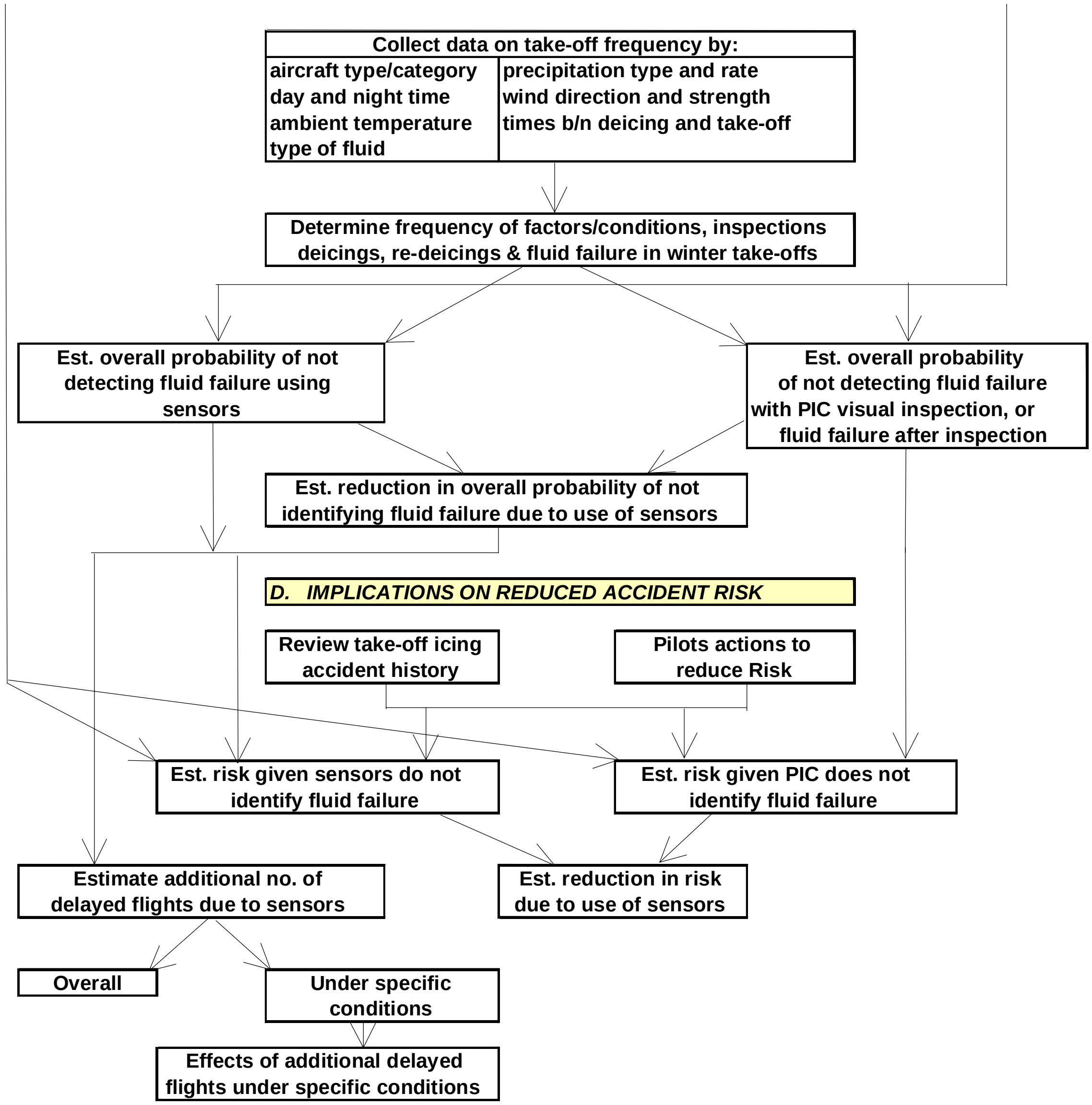


**Figure 2.1 Flowchart of Steps of Comparative Risk Analysis (continued)**

The results of the surveys, given in Volumes 2 and 3 (1), have been used throughout this and the Volume 1 report.

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 analytical procedures developed.

## 2.2 Risk Analysis

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 the use of point or area 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 a take-off free from the risks inherent in winter operations. 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 2.2.

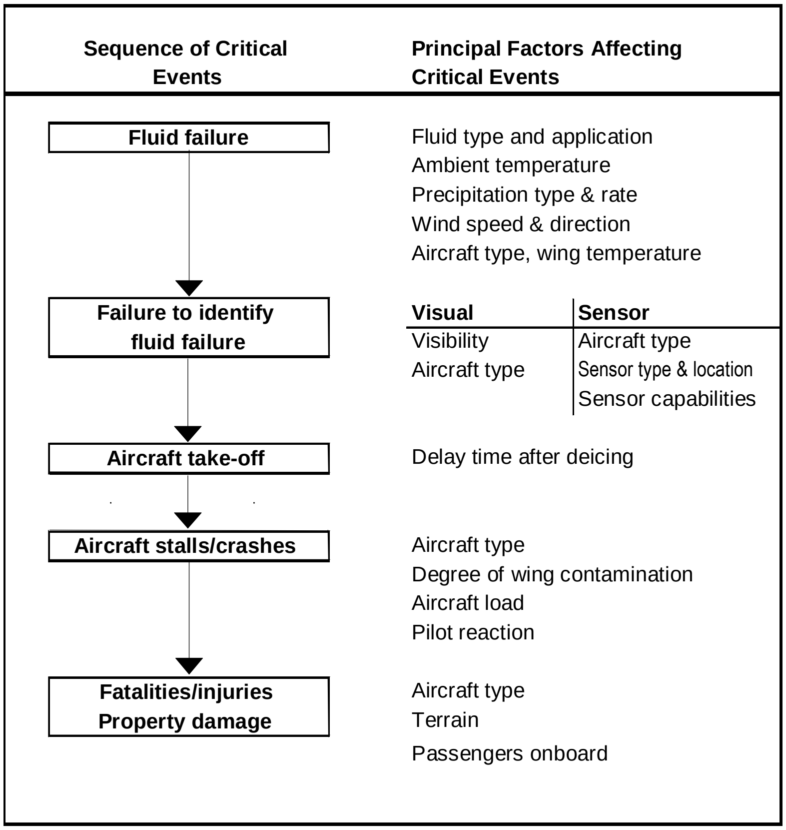
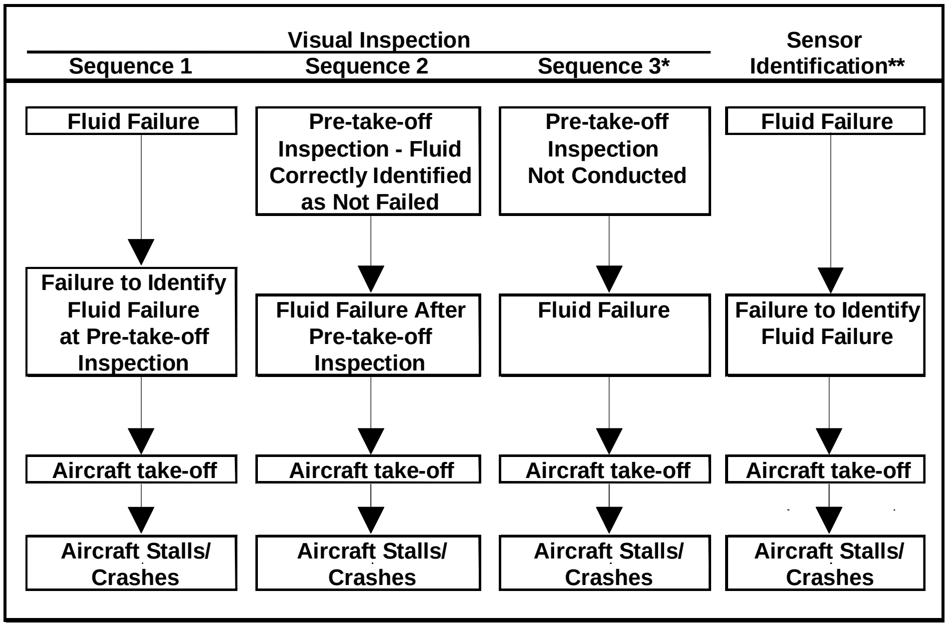


**Figure 2.2 Risk Analysis Critical Sequence of Events and Principal Factors Affecting those Events**

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. Also, with visual inspection, the pilot may opt not to conduct a pre-take-off inspection when the aircraft could take-off within the minimum HOT. This sequence is not an issue in the US where pre-take-off inspections are required if the aircraft is 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 condition. The sequences of events leading to a loss considered in the risk analysis can therefore be refined, as shown in Figure 2.3.



* Pre-take-off inspection mandatory in Canada only after HOT has expired

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

**Figure 2.3 Risk Analysis Critical Sequence of Events for Visual and Sensor Procedures in Relation to Pre Take-off Inspection**

The risk analysis initially focused on estimating the probabilities of identifying fluid failure in cases where it has failed, and of fluid failure after the pre-take-off inspection, and the factors and conditions affecting those probabilities. The likelihood and consequences of subsequent events (e.g., spread of contamination and effect on aerodynamic performance) were then considered to assess the risks of the two detection procedures. The amount and location of contamination on the critical surfaces at take-off are the main factors in determining the likelihood of an accident. Since the consequences of an accident (fatalities, injuries and aircraft damage) given an accident has occurred are not dependent on the amount and location of contamination, and thus the inspection method, the analysis focuses on the comparative probabilities of an accident.

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 2.4 for sensor-based inspection and in Figure 2.5 for visual inspection. 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 2.3 relating to pre-take-off inspection are included in the bottom half of the trees. The top half of the trees, 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.

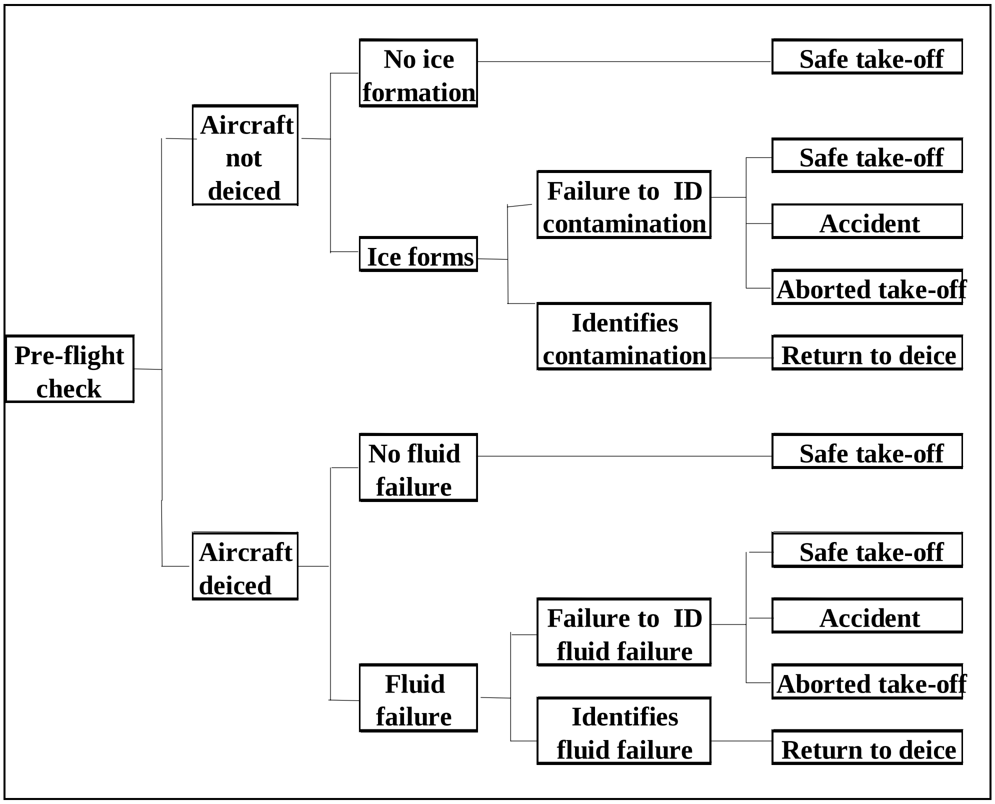


**Figure 2.4 Risk Analysis Tree for Take-off in Ground Icing Conditions Using Sensor System to Identify Wing Contamination**

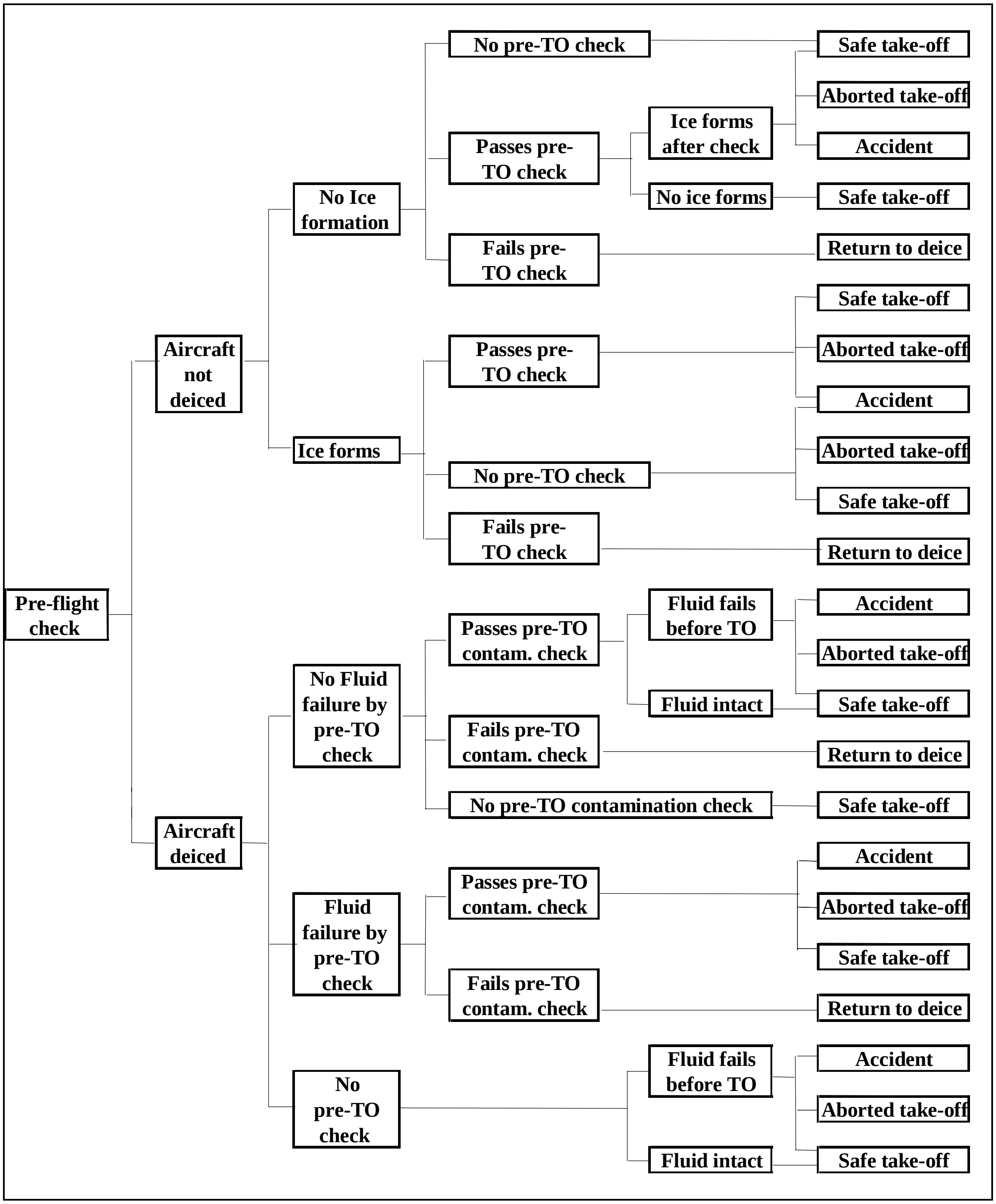


**Figure 2.5** Risk Analysis Tree for Take-off in Ground Icing Conditions Using Current Inspection Procedures

# 3. METHODOLOGY FOR ESTIMATING THE RISKS

The methodologies used to estimate the risks with visual and sensor-based inspection were similar to ensure that any differences in the estimated risks are related to the inspection method, and not the analysis methodology. In addition, use of similar methodologies allows estimation of the risk with sensors used in conjunction with visual inspection. The types of visual/sensor inspection systems that can be analysed using the approach employed are:

- visual inspection at the pre-take-off inspection;
- sensor inspection up to the commencement of take-off using up to three point sensors per wing; and
- combined visual and sensor inspection.

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.

It is also assumed that the pilots will not proceed with take-off once fluid failure is identified either visually, or by any one of the sensors. No warning of imminent failure of the fluid by the sensors is included in this analysis, although the approach could be extended to analyse this.

Figure 2.3 shows the chains of events using visual and sensor-based inspection procedures that could lead to an accident due to failure of the fluid. The critical events are:

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

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 and is therefore not critical when comparing the risks. The chain of events for visual inspection is complicated by the pre-take-off inspection occurring prior to the commencement of take-off, and the fact that, in Canada, the pre-take-off inspection is not mandatory. The three sequences for visual inspection are characterized by:

- fluid failure before the pre-take-off inspection and the pilot does not identify the failure at the inspection;

- first fluid failure after the pre-take-off inspection and the pilot has correctly identified the fluid as not failed at this inspection; and
- pilot does not conduct a pre-take-off inspection and fluid fails prior to take-off.

The methodology used for determining the risks when the pilot does not conduct a pre-take-off inspection is a little different from the case where an inspection is made and is described in Section 3.4. The methodology for when an inspection is made, whether it be sensor and/or visual, is described below.

## 3.1 Methodology for Visual/Sensor Inspection Systems

The probability of the inspection process not identifying fluid failure prior to take-off and the extent and criticality of contamination at the time of take-off, given that fluid failure has not been identified, were estimated from fluid failure progression data collected by APS on aircraft in outside tests during winter precipitation conditions (10, 11, 12). The fluid failure progression tests are summarized in Appendix A. The analysis procedure used was as follows:

- divide the wing into seven sections along the span and three sections across the span (leading edge, middle and trailing edge)[4]; an example for the Boeing 737 is shown in Figure 3.1;
- for each test, from the fluid failure progression data determine the percentage of each wing section with fluid failure for a range of times between first fluid failure and complete failure over the whole wing;
- at one-minute intervals commencing with first fluid failure,
    - ◊ for each wing section estimate the probability of the visual/sensor system identifying fluid failure on that section – use these to estimate the probability of identifying fluid failure anywhere on the wing, and
    - ◊ for each wing section estimate the probability distribution of the area of the wing contaminated, weighted by the criticality of the location of the contamination to aerodynamic performance, given that the visual/sensor system has not identified the fluid failure;
- using the distribution of times between de/anti-icing and the pre-take-off inspection and take-off, estimate the probability of the visual/sensor system identifying the fluid failure prior to take-off given the fluid failed prior to take-off;
- estimate the probability distribution of the area of the wing contaminated, weighted by criticality, at take-off given the fluid failure was not identified; and
- given the extent and criticality of fluid failure at take-off, estimate the risk due to fluid failure.

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[4] The test sections used were those specified by APS in their full-scale aircraft winter tests.

In determining the probabilities of identifying fluid failure for visual inspection, given the fluid has failed at take-off, the areas contaminated on each wing section at the time of the pre-take-off inspection are used rather than the those at the time of take-off.

The derivation of the risks, expressed in probabilistic notation, is given in Appendix C of the Volume 1 report (1).

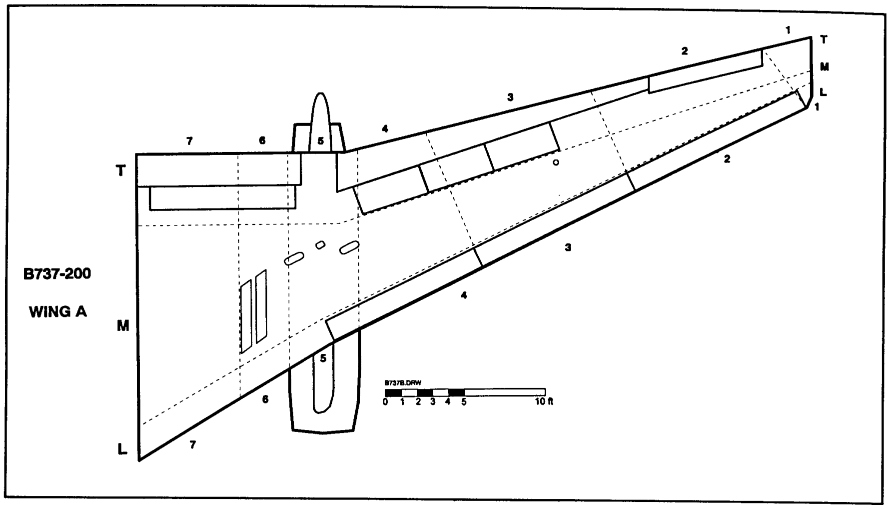


**Figure 3.1. Diagram of B737 Wing with Wing Sections Marked**

The approach used to determine the probabilities of not identifying fluid failure at particular times after first failure, and the corresponding areas contaminated at those times, differs for the visual and sensor-based inspection methods. The approaches are described in detail in the earlier Volume 1 report (1), which includes figures showing the estimated probability distributions of identifying fluid failure prior to take-off, and of the percentage area contaminated, using point sensor and visual based inspection. The approaches are summarized below.

### 3.1.1 Point Sensor Identification of Fluid Failure

Point sensors were found to be highly accurate at identifying the failure of fluid over the sensor head. Thus, the probability of a point sensor identifying fluid failure is estimated by the probability that the sensor is on the part of the wing where the fluid has failed. The area of fluid failure on each of the wing sections with a sensor, and the consistency of fluid failure on that wing section, are used to estimate the probability of the sensor being under the failed fluid. It is assumed that the sensors will be placed on different sections of the wing and in the locations of most frequent early fluid failure on those sections.

### 3.1.2 Visual Identification of Fluid Failure

Unlike identification of fluid failure using point sensors, visual inspection involves an assessment of all sections of the wing and the accuracy of the assessment is dependent on the viewing conditions under which the inspection is made. Unfortunately, data available on the accuracy of visual inspection from the cabin was limited, and no test data were available on the accuracy under poor viewing conditions and of fluid failure on particular sections of the wing. It was therefore necessary to construct hypothetical relationships of the accuracy under various conditions and to use sensitivity analyses to determine likely ranges in the comparative risks. These relationships were constructed using test data on visually observed fluid failure from within the aircraft and outside close to the wing, and information on the factors affecting visual inspection and pilots' confidence in their assessment obtained from the surveys of airline pilots (see (1) for a full discussion). The approach used was as follows:

- specify probabilities of identifying fluid failure as a function of the percentage area of the wing with failed fluid for nine view ratings of the wing, shown in Figure 3.2;
- for each aircraft type, using photographs, comments on the surveys and other sources, classify the view of each section of the wing from the best viewing position inside the aircraft under typical daytime viewing conditions as one of these nine view ratings or as no view. Factors considered included:
  - ◊ 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 view of the fluid on the wing under typical winter precipitation conditions (e.g., overcast, snow falling, etc.);
- specify adjustments to these view ratings for different viewing conditions – four viewing conditions were analysed:
  - ◊ *very good*,
  - ◊ *daytime typical*,
  - ◊ *daytime poor*, and
  - ◊ *nighttime*;
- using the fluid failure progression data, the view rating for each wing section and the probabilities shown in Figure 3.2, estimate the probability of not visually identifying fluid failure on each wing section given the area of fluid failure on that section; and
- accounting for the size of each section, estimate the probability of not visually identifying fluid failure any part of the wing.

There are insufficient data to do an analysis by aircraft type and the greatly different views of the wing on some aircraft necessitates grouping aircraft into a number of categories for analysing the risks. The estimated risk measures will not account for the possible variation in fluid failure progression characteristics of these categories of aircraft, but will account for the different views of the wing. Thus, for the purposes of rating views of the wing, aircraft were grouped into three categories and the photographs of aircraft types used in setting the ratings were:

- low-wing aircraft – photographs used: A320, B737, F28, DC9
- high-wing, do not open any door – photographs used: BAe 146, DHC 8, ATR 42
- high-wing, open back door – photographs used: ATR 42

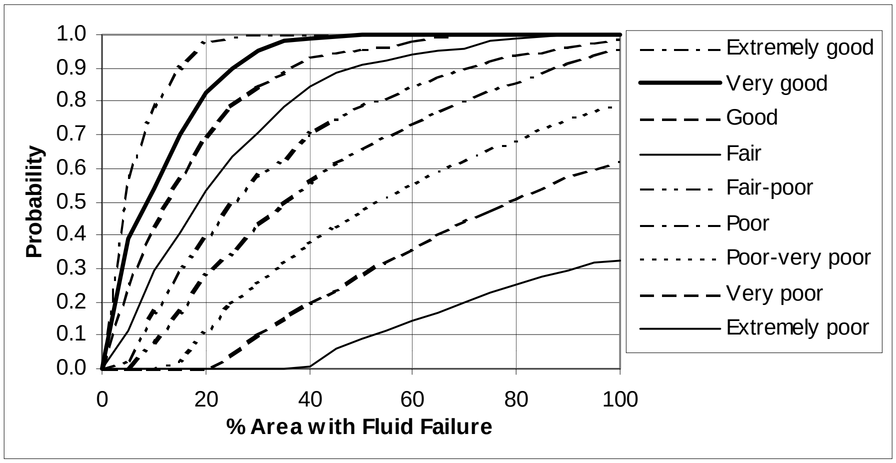


**Figure 3.2** **Hypothetical Probabilities of Visually Identifying Fluid Failure for Various View Ratings and Percentage Areas with Fluid Failure Used in the Analysis**

The views of the wing on low-wing aircraft are fairly similar; the main difference being the longer sight distance and corresponding lower angles of incidence of larger aircraft. The view of the upper wing surface is very limited on high-wing aircraft and varies more by aircraft type than for low-wing aircraft. On high-wing aircraft with a passenger door in the rear, some pilots have indicated that they open this door during pre-take-off inspections to check the trailing edge of the wing and upper fuselage on that side of the aircraft. This is not an option on aircraft with passenger doors located only at the front of the aircraft, such as the DHC 8, due to the proximity of the engines. Some airlines prohibit pilots from opening the door during pre-take-off inspections.

View ratings of each section of the wing were specified for each aircraft, using photographs of the wing from the cockpit and various positions in the cabin, and from the rear exit of the ATR 42. The aircraft geometry results in shorter sight distances and/or higher angles of incidence for viewing the trailing edge compared to the leading edge. This allows a slightly better view of the trailing edge sections. Some pilots of high-wing aircraft responding to the surveys indicated that they deploy the spoilers to check for contamination and thus, in effect a small part of the trailing edge section can be seen on some high-wing aircraft. Since the early failure of the fluid usually occurs on the downward side of joints, the spoilers, flaps and ailerons are good surfaces to check for early fluid failure if they are visible. The fluid is also likely to fail early on steep surfaces such as the front of the leading edge that is the only part of the leading edge section visible on high-wing aircraft. In setting the view ratings when only a part of the wing section is visible to the pilot, the proportion of the area visible and the likelihood of early fluid failure on the visible parts were taken into account. Ratings for each category of aircraft were found by averaging the rating for each aircraft type in that category and are given in Table 3.1. More details are given in the Volume 1 report (1) and Appendix B.

**Table 3.1 Viewing Ratings Assigned to Each Wing Section for Typical Daylight Conditions for the Three Aircraft Categories***

| Wing Section | | | Low-wing Aircraft | High-wing Aircraft with: | |
|---|---|---|---|---|---|
| | | | | No Door Open | Back Door Open |
| Wing Root | 7 | Leading | Fair-poor | Very poor | Poor-very poor |
| | | Middle | Fair-poor | No view | Poor |
| | | Trailing | Fair-poor | No view | Fair |
| | 6 | Leading | Very good | Fair-poor | Fair |
| | | Middle | Very good | No view | No view |
| | | Trailing | Very good | No view | Fair |
| Over Engine* | 5 | Leading | Good | Fair-poor | Poor |
| | | Middle | Good | No view | No view |
| | | Trailing | Very good | Very poor | Fair-poor |
| | 4 | Leading | Fair | Very poor | No view |
| | | Middle | Fair | No view | No view |
| | | Trailing | Good | No view | Fair-poor |
| | 3 | Leading | Fair-poor | Poor-very poor | Poor-very poor |
| | | Middle | Fair | No view | No view |
| | | Trailing | Fair | Very poor | Poor |
| | 2 | Leading | Poor | Poor-very poor | Poor-very poor |
| | | Middle | Poor | No view | No view |
| | | Trailing | Fair-poor | Very poor | Poor |
| Wing Tip | 1 | Leading | Very poor | Very poor | Very poor |
| | | Middle | Very poor | No view | No view |
| | | Trailing | Poor-very poor | No view | Poor-very poor |

* on twin engine aircraft

As a check of the accuracy of these ratings and the probabilities shown in Figure 3.2, the estimated probabilities of the pilot identifying fluid failure for very good viewing conditions were compared with observed values and found to be similar (see Figure 8.7, Vol. 1 report (1)).

The view ratings applicable for *daytime typical* viewing conditions were assumed to increase by one level in *very good* viewing conditions (levels shown in Figure 3.2), to decrease by one level in *daytime poor* conditions, and to decrease by two levels in *nighttime* conditions.

In determining the risks, the area of contamination at take-off, not at the time of the pre-take-off inspection, is used. This will usually be greater than the area of contamination at the time of the pre-take-off inspection. Probabilities of fluid failure after the pre-take-off inspection and the corresponding areas of contamination at take-off are also included in determining the risks.

### 3.1.3 Visual and Sensor Identification of Fluid Failure

For a combined visual-sensor inspection system, the probability of not identifying fluid failure by the time of take-off is dependent on the areas of fluid failure at both the time of the pre-take-off inspection (for visual inspection) and the time of take-off (for sensor system). The joint probability of neither system identifying fluid failure for a given time of take-off was estimated from fluid failure progression data for each test. The time intervals between pre-take-off inspection and take-off were included in the analysis. The risks were determined using the distribution of the area of contamination at the time of take-off, given the combined system had not identified fluid failure at that time.

### 3.1.4 Estimation of Risks for Given Fluid Failure Patterns

The above procedures provide a method for determining the probability of the wing being contaminated at take-off and the probability distribution of the amount and location of contamination using the different visual/sensor inspection systems. Critical elements for conducting the comparative risk analysis are:

- what are the effects on aerodynamic performance of small areas of failed fluid on the wing; and
- how does the location of these areas of fluid failure affect the aerodynamic performance.

The analysis procedure makes use of fluid failure progression data on aircraft to calculate the probability of take-off with various amounts of contamination on the different parts of the wing for a given inspection procedure. To compare the risks, these probabilities were combined by relating the areas of fluid failure to the risks. The method attempts to estimate the probability of exceeding the safety margin in the maximum lift given the area and location of contamination. A full discussion of the method is given in the Volume 1 report (1) and is briefly summarized below.

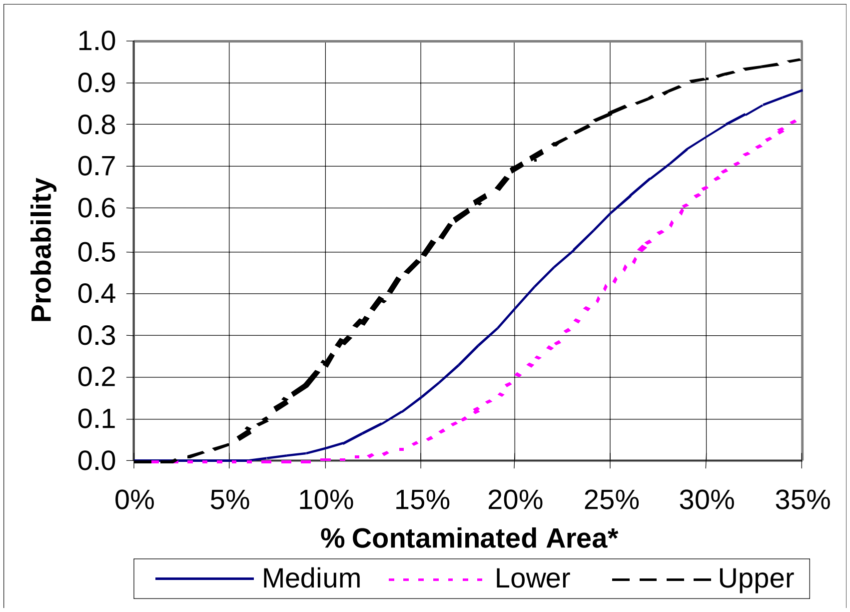
- The distribution of the reduction in maximum lift loss for a given roughness height and cord length was estimated using wind tunnel test data for when the whole wing is contaminated and when the leading edge is contaminated;
- The distribution of roughness heights of failed fluid was estimated from static tests on aircraft wings;
- The distribution of wing cord lengths was estimated for typical aircraft operating in Canada;
- The location and area of fluid failure were combined into a single measure by weighting areas of contamination on the different wing sections according to their effect on maximum lift and controllability of the aircraft. The weighting factors used were:
    - ◊ leading edge sections – criticality factor = 1.0
    - ◊ middle sections – criticality factor = 0.2
    - ◊ trailing edge sections – criticality factor = 0.2
- The distributions of wing cord lengths, levels of roughness and reductions in maximum lift loss for a given roughness height and cord length were used to estimate the probability of exceeding the safety margin in maximum lift as a function of the area of fluid failure weighted by its criticality. This relationship is shown in Figure 3.3. Due to the high degree of uncertainty in these estimates, low and high values were also estimated to reflect the possible range in values and are shown in the figure.

The reduction in maximum lift and controllability, the latter caused by loss of lift in the aileron area of the wing, are the major factors contributing to accident risk, and both are correlated. The probabilities of exceeding the safety margin therefore provide a good measure of the risk due to wing contamination for comparing risks associated with sensor and visual based inspection. Other possible factors that could cause an accident, such as the direct loss in lift and increased drag, are also correlated with reductions in maximum lift.

The accuracy of this method of relating the contamination to the probability of exceeding the safety margin is open to debate. However, the method does provide a logical and consistent means of combining the probabilities of various areas of wing contamination at take-off that is related to the contamination's effect on aerodynamic performance. The resulting risk measures will therefore provide a reasonable basis for comparison of the risks.

The possible activation of the stall warning devices has not been considered here. For small reductions in maximum lift, the stall warning device 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 safety margin, the devices are unlikely to warn of approaching stall and would therefore not affect the risks. The stall warning devices therefore do not invalidate the use of the probability of exceeding the safety margin in maximum lift as the risk measure.

The risks shown in Figure 3.3 are overestimated for the cases where pilots are able to increase take-off speeds and reduce the climb rate and angle of incidence under conditions of freezing precipitation. These measures are likely employed by some pilots in these higher risk situations and will significantly reduce the risk of the aircraft stalling, but should have little effect on the comparative risks of visual and sensor-based inspection.



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

**Figure 3.3 Approximate Probability of the Decrease in the Maximum Lift Exceeding the Safety Margin Versus Percentage of Wing Area Contaminated, Weighted by Criticality**

## 3.2 Effect on Risks of Incorrectly Identifying a Fluid as Failed

Misclassification of a fluid as failed prior to actual failure has little effect on the risks because, if the fluid has not failed and is therefore still protecting the wing, there is (essentially) no chance of an accident due to wing contamination. The main effect of misclassification of fluid failure is an increase in the number of unnecessary re-deicings or delays for tactile checks. However, incorrect identification of a fluid as having failed at the pre-take-off inspection can reduce the risks associated with fluid failure between pre-take-off inspection and take-off. The effect on the risks will be small if the times at which the pilots misclassify the fluid failure are random; but could be significant if the misclassifications occur when fluid failure is imminent.

In the tests conducted by APS (14) comparing visual identification of fluid failure from inside and outside the aircraft, the inside observer identified first fluid failure prior to the outside observers in three of the eleven tests. The failure call was early by 2 and 3 minutes in two of the tests involving Type I fluid (first failure around 10 minutes) and by 5 minutes in a test using Type II fluid (first failure at 30 minutes). Based on these data, 25% to 30% of visually observed fluid failures identified from the cabin could be premature, and the timing of the call appears to be related to the type of fluid, and therefore its HOT. This is not surprising, as one would expect that, as the time since fluid application gets longer and especially if HOT is exceeded, pilots would be increasingly more likely to error on the side of safety, and call the fluid failure before it has actually failed.

Premature identification of fluid failure is closely linked with the pilot allowing for HOT, weather conditions and delays in deciding whether to proceed with the take-off. Both have the same outcome, not proceeding with the take-off, and in both cases, as the time of take-off draws close to and exceeds the HOT, the probabilities of not proceeding with the take-off increase. Thus, rather than model the effect of premature classification of fluid failure separately, it is included in the allowance for HOT, weather conditions and delays analysis described in Section 3.3.

Sensor systems identify fluid failure up to the commencement of take-off and premature identification of fluid failure will therefore not affect the risks associated with fluid failure at take-off. In any case, point sensor systems have been found to accurately identify fluid failure when the fluid has failed over the sensor head. Premature fluid failure calls by the sensor were primarily calibration problems in early sensor designs which were based on comparisons with visual observation.

## 3.3 Allowance for HOTs with Visual Inspection

Conditions under which pilots make pre-take-off inspections can vary greatly. When assessing the condition of the fluid in daylight during snowfall, the surveys of pilots indicate that they are confident in their ability to identify fluid failure. Deicing fluid on the windows and no view of some parts of the wing are two of the main obstacles to identifying failed fluid in these circumstances.

At nighttime or during freezing drizzle/rain, their confidence in identifying fluid failure is much lower and they rely more heavily on HOTs and past experience under these conditions. In these circumstances, risks can be kept low if the pilot is very conservative and only proceeds with the take-off if the visual inspection **positively** confirms there is no fluid failure. However, in these conditions it is "next to impossible"[5] to confirm this visually from within the aircraft. The pilot would therefore be either returning to re-deice or having a tactile check done for each take-off. The fact that most departures at night during snowfall do occur without re-deicing (or a tactile check just prior to take-off) indicates that perhaps most pilots are not this conservative. The survey of pilots also indicates that most pilots do not require positive confirmation of no fluid failure if they are within the HOT.

When using HOTs and past experience to judge whether the fluid has possibly failed, the pilots account for many factors, including:

- the type and rate of precipitation;
- the wind conditions and blowing snow;
- the ambient temperature;
- aircraft skin temperature and possible cold soak of the wing;
- humidity;
- the time since aircraft was deiced and likely time of take-off; and
- the experience and professionalism of the de-icing crew.

Two values are given for the HOT; these represent protection times over a range of conditions. Some pilots would like a single time where, after that time, the take-off does not proceed. However, most pilots acknowledge the great variation in conditions that affect the protection time and use their experience and observations of the conditions to determine a protection time based on the HOT range.

Conservative pilots would tend to use the lower value in the range for all conditions, while others would use a value based on the range accounting for the factors given above. In the later case, training and past experience are important in accurately choosing the protection time. Past experience is also important in extreme conditions where the fluid could fail prior to the HOT.

The survey of pilots also indicated that when the viewing conditions are marginal, most pilots take into account the HOTs and weather conditions in deciding whether to proceed with take-off. Also, as discussed in Section 3.2, premature identification of fluid failure appears to be related to the HOTs and, like the conservatism associated with the viewing conditions, also results in not proceeding with the take-off.

When comparing the risks associated with the use of visual inspection and sensor-based systems, it is important that the use of HOTs associated with visual based inspection be

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[5] Quote from survey of US airline pilots, typical of comments made in the survey

taken into account. This use of HOTs leads to a reduction in the risks associated with strictly visual assessment of the fluid condition. It will, however, result in more unnecessary re-deicings and delays. Any reductions in unnecessary re-deicings and delays as a result of using point sensors would be tangible benefits and are estimated in Section 6.

To account for the use of HOTs by pilots in the comparative risk analysis, the probability of not proceeding with the take-off following deicing is considered rather than the probability of identifying fluid failure. If fluid failure is identified, either visually or by the sensor system, it is assumed the take-off will not proceed. In addition, this approach allows for the take-off to not proceed if, in less than ideal viewing conditions, the pilot *feels* that the fluid may have stopped protecting the wing. This latter condition is difficult to model and is subjective, but must be expressed in mathematical terms for it to be included in the risk model.

The approach used is summarized in below.

- Combinations of three possible methods for determining whether to not proceed with take-off were considered:
    - ◊ visual assessment of the fluid condition at pre-take-off inspection;
    - ◊ likely fluid condition given HOT and weather conditions at any time prior to take-off; and
    - ◊ point sensor system assessment of the fluid condition, with continuous assessment to time of take-off.
- If any one of these methods indicates likely fluid failure, the take-off will not proceed.
- The “allowance for HOT, weather condition and delay” method assumes that the time at which the pilot would return based on HOTs is related to viewing conditions; the worse the conditions, the more conservative the pilots become in their use of HOTs.
- For the “allowance for HOT, weather condition and delay” method, it is assumed that, for a given HOT and set of weather conditions, the probability of pilots returning to re-deice (or call for a tactile check) increases as:
    - ◊ the viewing conditions get worse;
    - ◊ the delay in time of take-off increases (in relation to the HOT range);
    - ◊ the precipitation rate increases; and
    - ◊ the wind speed increases.

  For example, for nighttime departures, the probability of returning would be high if delayed more than the (lower) HOT in a heavy snowstorm with strong winds. However, the probability of returning would be low with the same delay during light snow and calm winds.
- Due to greater difficulty in visually identifying fluid failure in freezing drizzle/rain, the proportion returning is assumed to be greater for freezing precipitation rather than snow, for the same precipitation rates, wind speeds and delays relative to the HOTs.

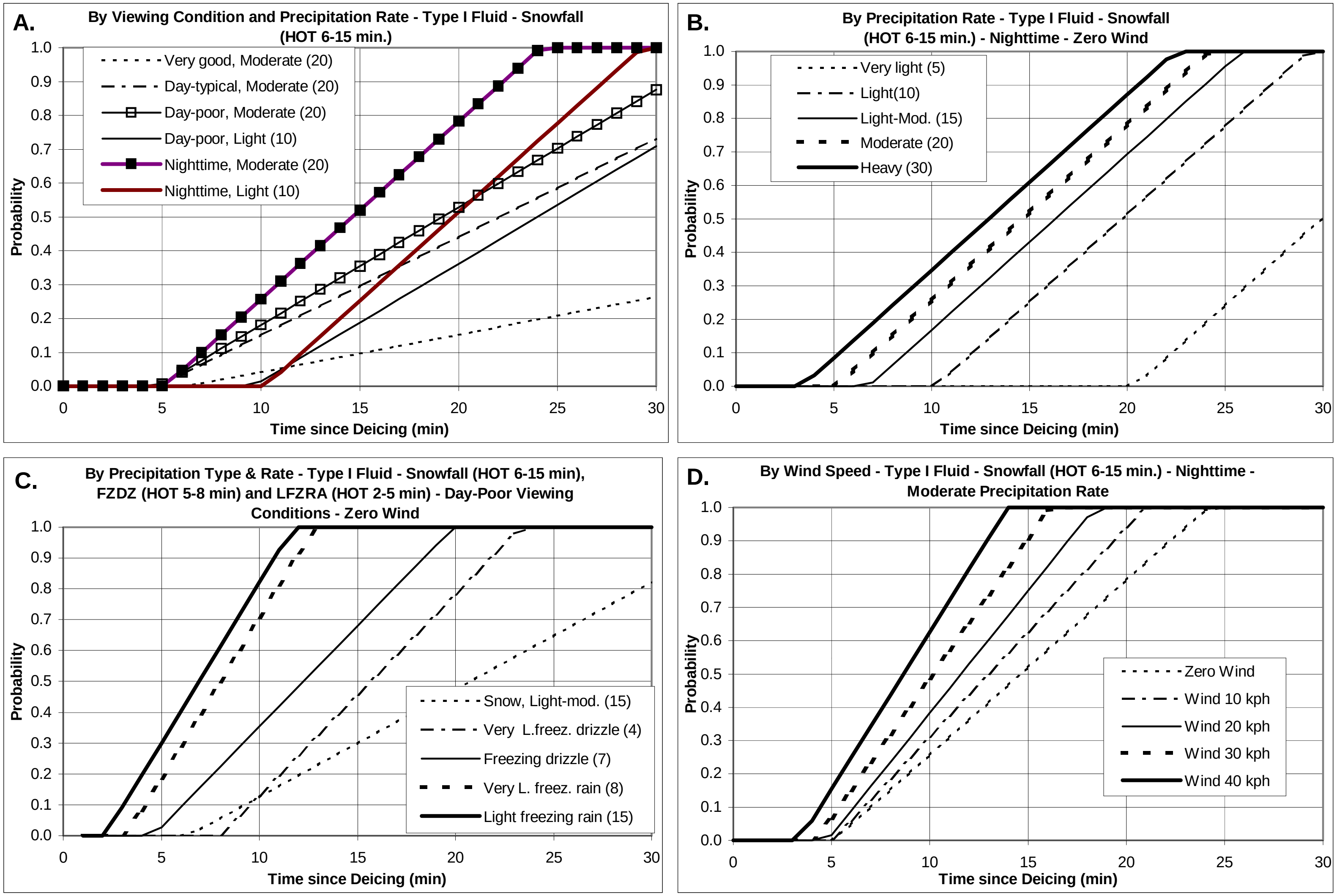
- To account for the premature misclassification of the fluid as having failed, it is assumed that the pilot would return prior to the fluid failing due to the HOT, weather and delay when viewing conditions are very good in 25-30% of cases. In worse viewing conditions, the probability of pilots returning due to premature misclassification of fluid failure is assumed to increase in line with the conservatism of pilots in these conditions.

The directions of the relationships between probability of returning to re-deice (or calling for a tactile check) and the delay, HOT and weather variables are known, and rough estimates are available of the proportion of flights requiring re-deicing or tactile checks during the pre-take-off inspections. The exact relationships are, however, not known. In the analysis it was therefore necessary to use hypothetical relationships based on data from the pilot surveys.

Other information from the pilot surveys was also used in setting parameters used in these relationships. Pilots were asked whether they would re-deice if they were “unable to identify any failed fluid, but the condition of the fluid is *very difficult to see* and the HOT & precipitation rate indicates the fluid possibly failed”. A similar question was asked where the fluid was *somewhat difficult to see*. For the Canadian survey, 85% indicated they would re-deice under the *very difficult* viewing conditions and 62% under the *somewhat difficult* viewing conditions. These percentages were related to the estimated probability of pilots that would return due to HOT/weather/delays in *nighttime* viewing conditions for the *very difficult to see* case, and *daytime poor* and *daytime typical* viewing conditions for the *somewhat difficult to see* case. The probability of returning under very good viewing conditions was equated to the error rate in prematurely misclassifying a fluid as failed under very good viewing conditions since, under these conditions, most pilots rely on their visual assessment of the wing condition rather than the HOT. It was also assumed that the probabilities of pilots returning prior to the time of fluid failure would be similar for the different fluid types.

These data and assumptions were used to calibrate the HOT-returning relationships. The reasonableness of these relationships can best be judged by graphically displaying the sensitivities of the estimated probability of pilots returning/calling for tactile check under various conditions. These are shown in Figure 3.4 using Type I fluid as an example.

These relationships predict that using Type I fluid in calm conditions during light snowfall (10 $g/dm^2/h$) with a delay of 15 minutes after deicing (upper value in HOT range), 15% of pilots would return in poor daytime viewing conditions, while 25% would return at night. If the snowfall was moderate (20 $g/dm^2/h$), this increases to 50% of pilots in poor daytime conditions and 75% at night. With heavy snow (30 $g/dm^2/h$), 93% would return at night with a 15 minute delay and 10% would return if delayed 5 minutes, 1 minute less than the lower HOT. Winds are assumed to have a significant impact; in light-moderate snowfall (15 $g/dm^2/h$) at night, if delayed 10 minutes 33% would return in calm conditions, but over 90% would return with 40 km/h winds.



[Precipitation rates given in brackets are in g/dm$^2$/hr]

**Figure 3.4** **Hypothetical Relationships of the Probability of Pilots Returning to Re-deice or Calling for a Tactile Check Based Solely on HOT Under Various Conditions**

The functions used to estimate the probability of pilots returning and a similar figure for Type IV fluid are included in Appendix D.

Using these relationships and the distributions of weather conditions and delay times following de/anti-icing described in Section 4.2, the proportion of pilots returning to re-deice based solely on allowance for HOT (i.e., no visual inspection) by the time of fluid failure were estimated to be:

- 0.30 under *very good* viewing conditions
- 0.50 under *daytime typical* viewing conditions
- 0.65 under *daytime poor* viewing conditions
- 0.80 under *nighttime* viewing conditions

The 30% under *very good* viewing conditions corresponds to the observed error rate discussed earlier.

Checks were made to ensure that the resulting estimates of the percentage of times the pilot would return to re-deice (or have a tactile check done) were close to observed values. These comparisons are given in Section 5.2.2. The HOT-returning relationships and the distributions of weather conditions and delay times were then used to estimate the proportion of pilots returning to re-deice (or calling for a tactile check) under the following conditions:

- four viewing conditions: *very good, daytime typical, daytime poor* and *nighttime* (see Section 5.2.2); and
- given that the fluid has not failed by the time of take-off to determine false alarm rates (see Section 6).

The HOT-returning relationships were included with visual and sensor inspection as a third element in the take-off decision process and, using the fluid failure progression data and analysis procedures described earlier in Section 3.1, the change in the risk due to wing contamination was estimated. The estimated proportion of pilots returning and the change in risks are given in Section 5.2.2.

## 3.4 Risks Associated with Not Conducting a Visual Pre-Take-off Inspection

Canadian regulations covering ground icing require a pre-take-off contamination inspection if the take-off cannot be made within the lower time of the HOT range. Pilots are warned that the protection time of the fluids may be less than the published HOTs in certain specified conditions and that under these conditions a pre-take-off contamination check should be conducted.

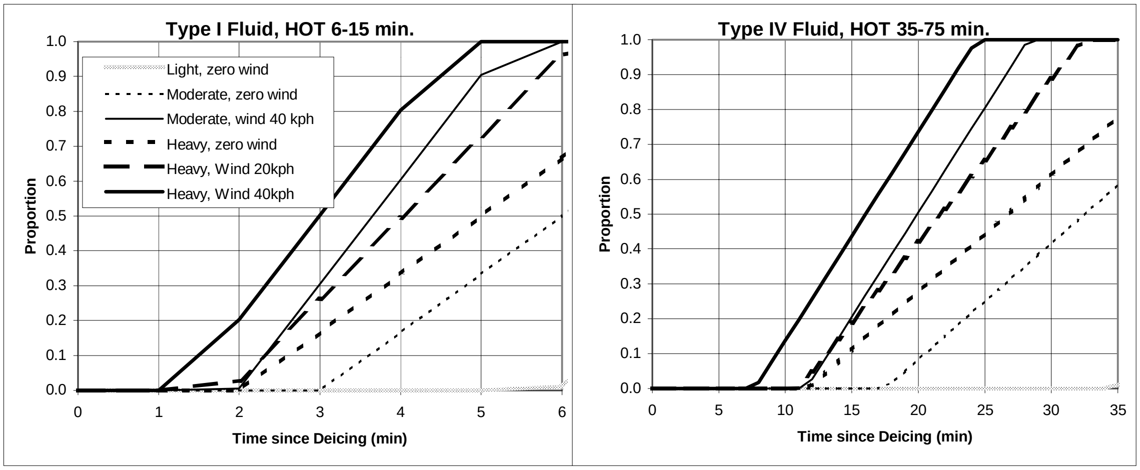
US regulations still require a pre-take-off check, similar to a pre-take-off contamination check, in conditions of freezing/frozen precipitation, even if the aircraft can take off within the lower HOT value. Thus, under these regulations, a pre-take-off check will always be conducted when there is any risk of fluid failure and the risk associated with not conducting a visual inspection of the critical surfaces is zero.

The fluid failure progression data includes the fluid type and the weather conditions for each test. The HOT for each test can therefore be determined. There are no clear guidelines specifying under which conditions a pre-take-off inspection prior to the expiry of the lower HOT is required. The decision to conduct a pre-take-off inspection in these situations is closely related to the prevailing weather conditions and delay relative to the HOT, but is subjective and varies between pilots. With little data on which to base any relationship between the decision to conduct the inspection and the HOT, weather and delay, risks were estimated for *high, medium* and *low cases* as follows:

- *High case* – pre-take-off inspections are only conducted if the lower HOT will expire prior to take-off;
- *Medium case* – specify relationships between decision to conduct inspection and HOT, weather and delay to match existing information as closely as possible; and
- *Low case* – pre-take-off inspection conducted for all take-off following de/anti-icing in conditions of freezing/frozen precipitation.

Hypothetical relationships giving the proportion of pilots that would opt to conduct a pre-take-off inspection prior to the expiry of the holdover time were specified using a similar approach to that used for pilots opting to return to re-deice based on HOT, weather and delays described in Section 3.3. However, in this case the likelihood of conducting an inspection is not related to the viewing conditions. Under the same HOT, weather and delay conditions, one would expect the likelihood of the pilot deciding to conduct an inspection prior to HOT expiring to be similar to, but slightly greater than, the likelihood of returning to re-deice based only on the HOT in poor viewing conditions. Hypothetical relationships were specified for the *medium case* and are shown in Figure 3.5. The reasonableness of the relationships used can best be judged by considering the sensitivities of the estimated proportions of pilots that would opt to conduct an inspection under various conditions.

The analysis procedure for estimating the risks with visual inspection using the fluid failure progression data described in Section 3.1 was then modified by adjusting the probability of visually identifying fluid failure to zero for the proportion of departures where a pre-take-off inspection would not be conducted. The resulting estimate of risk is that due to the combined effect of the visual inspection, when an inspection is conducted, and of not conducting the visual inspection prior to expiry of HOT. The risks associated with the latter can be found by subtracting the risk for when visual inspection is conducted for all take-offs.



**(a) Type I Fluid** **(b) Type IV Fluid -3°C to -14°C**

**Figure 3.5 Proportions of Pilots that Would Conduct a Pre-take-off Inspection Prior to Expiry of HOT Under Various Precipitation Rates and Wind Conditions During Snowfall – Hypothetical Relationships Used in Analysis for the *Medium Case***

# 4. FLUIDS AND AIRPORTS ANALYSED

The risks of take-off due to wing contamination vary depending on the fluids, dilutions, airport characteristics and weather conditions. Due to the large number of combinations of these elements, it was not feasible to estimate the risks for all departures in Canada. For determining the usefulness of sensors for reducing the risks, it is sufficient to examine the comparative risks in a number of typical cases. These cases are described below.

## 4.1 Fluids

The comparative risks were analysed for the two fluid types:

- Type I fluid
- Type IV fluid (100% concentration)

Type I fluid, although a de-icing fluid, is still widely used for anti-icing primarily at small, non-hub airports (finding from US and Canadian surveys of airline pilots) and on low rotation speed (typically turboprop) aircraft due to the lack of availability of a Type III fluid[6]. Type IV fluid is, however, used on many turboprop aircraft. Type IV fluid is generally used at 100% concentration, unless factors such as temporary shortages influence the decision.

Fluid failure progression data used in the analysis were available for 27 aircraft field tests using Type I fluid, 10 tests using Type IV fluid and one test using Type II fluid. The single test with Type II fluid was grouped with the Type IV fluid tests in the analysis. The progression of the fluid failure after the initial failure for the Type II fluid test was similar to those for the Type IV fluids and should not unduly influence the results for the Type IV fluids. Due to the much larger data set for Type I fluid, the discussion focuses more on Type I than Type IV fluid and the accuracy of the estimates are better for Type I fluid.

The failure mechanisms and appearance of fluid failure of ethylene-glycol and propylene-glycol based Type IV fluids were observed to differ in limited field tests comparing the two fluids last winter (16). Differences were also observed in the degree to which the fluids were stripped from the wing during the take-off run after visually observed fluid failure. Further testing is required to confirm these preliminary observations. The possibility of differences in the accuracy of pilot's visual identification of fluid failure and the effect of the fluid failure on performance are considered in Section 5.4.4.

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[6] This differs from practices in Europe where many operators use heated Type II fluid for de-icing

The comparative risks using visual and sensor-based inspection are independent of the frequency of fluid failure as this frequency influences the risks with each type of inspection by the same factor. This is considered in the sensitivity analysis in Section 5.4.3.

The HOTs used in the analysis were those published in the Canadian Air Carrier Advisory Circular ACAC No. 113.

## 4.2 Airports and Taxi/Delay Times

The main airport characteristics affecting the risks due to wing contamination are:

- the taxi time from the location of deicing to the active runway; and
- delays due to runway congestion.

The quality and speed of de/anti-icing, and the quality of the critical surface inspection conducted by the deicing crew also greatly affect the risks due to wing contamination. These procedures are conducted by the air carriers, or under contract to the carrier, at most airports. However, a number of large airports now have centralized deicing facilities for use by all aircraft. The variation in the quality of the deicing service used in the risk analysis was that which occurred in the 38 aircraft tests used in the analysis.

The analysis was conducted for three typical airports chosen to represent the range of airports:

- a large busy airport where runway congestion can result in significant delays – mainly jet aircraft;
- a small airport with long-taxi times and little if any runway congestion – small to medium jet aircraft and turbo-prop aircraft; and
- a small airports with short-taxi times and no runway congestion – mainly turbo-prop aircraft.

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. An allowance for fluid application was added to this time. The distributions of the total fluid application, taxi and delay times for small airports were chosen based on the limited data available and experience. The distributions are described below.

The time between final fluid application and take-off varies across the sections of the aircraft depending on the order in which the different sections are anti-iced. The full application time is applicable only to the first part of the wing treated. Since the risk analysis considers the amount of fluid failure on all parts of the wing and this is predicted from the time since application, it 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. An allowance of 5 to 7 minutes was added to the taxi/delay times to account for final application. Shorter application times were used at the smaller airports due to the larger proportion of turbo-prop aircraft, although the size of aircraft is offset by the capability of the deicing equipment at these airports. Characteristics of the fluid application, taxi and delay time distributions for the three airports used in the analysis are given in Table 4.1 and the distributions are shown in Figure 4.1

**Table 4.1 Fluid Application, Taxi and Delay Time Characteristics of Airports Used in Analysis**

| Airport | Average Times (minutes) | | | | Standard Deviation (minutes) |
|---|---|---|---|---|---|
| | Taxi-Delay | Final Fluid Application | Total | Adjusted Total* | |
| Large, Busy | 10.2 | 7 | 17.2 | 15 | 6.0 |
| Small, Long-taxi | 6 | 6 | 12.0 | 10 | 1.5 |
| Small, Short-taxi | 2 | 5 | 7.0 | 5.5 | 2.5 |

* Adjusted to include 70% of final fluid application time (as discussed in text)

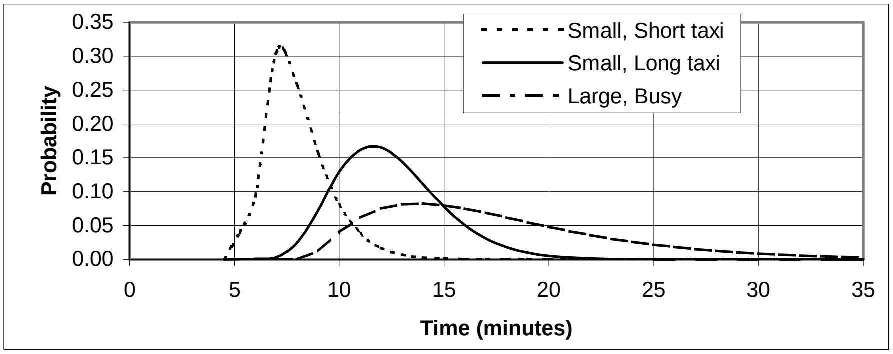


**Figure 4.1 Estimated Frequency Distributions of Fluid Application/Taxi/Delay Times for Three Airport Groupings Used in Analysis**

## 4.3 Time Between Pre-take-off Inspection and Take-off

The pre-take-off inspection is conducted near the holding bay of the departure runway, but there is a delay of a number of minutes between the visual inspection of the wing and the commencement of the take off roll. Approved airline ground icing procedures in Canada and the US allow the aircraft to take-off provided that the take-off roll can be commenced within 5 minutes of the pre-take-off inspection. Accurate data on this time interval and how it varies with airport, aircraft type and, weather and viewing conditions were not available. The survey of US airline pilots included several questions asking pilots the typical time between the pre-take-off check and commencement of take-off, and how frequently they required the full 5 minutes allowed for in their operating procedures. The average times between the pre-take-off inspection and take-off were:

- 2.5 minutes by pilots of turboprop aircraft
- 3.5 minutes by pilots of jet aircraft

The risk analysis was greatly simplified by using fixed times for the interval between pre-take-off inspection and take-off, rather than a distribution of times. The analysis procedure used discrete time intervals of 1 minute and it was not possible to use the observed mean values of 2.5 and 3.5 minutes. The values were rounded down to 2 and 3 minutes, rather than up, to offset the effect of a possible short delay between visually observed fluid failure and a significant effect of the fluid failure on aerodynamic performance.

Use of a distribution of time intervals would better reflect the risks as the risks increase greatly as the time intervals get larger. Therefore, use of a distribution of times, rather than fixed times, was examined in the sensitivity analysis of the comparative risks of sensor and visual based inspection considered in Section 5.4.3. Based on the responses to the questions in the survey, the distribution of time between the pre-take-off inspection and take-off at small and large airports was derived and is shown in Figure 4.2.

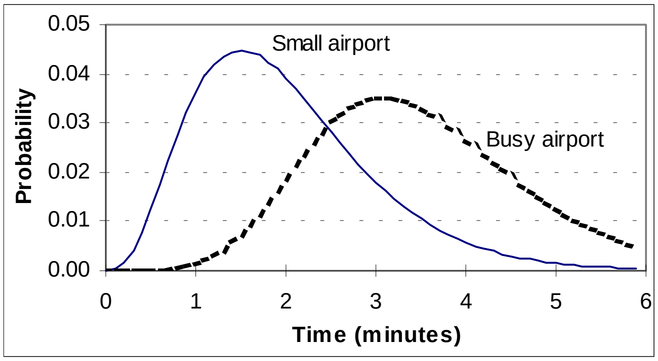


**Figure 4.2 Distribution of Time Interval Between Pre-take-off Inspection and Take-off at Small and Busy Airports**

Pre-take-off inspections take several minutes to complete and will therefore delay the flight and increase both the chance of the fluid failing prior to take-off and the area of contamination. If the pilot conducts a visual inspection and does not identify a fluid failure, the inspection delay increases the risks due to wing contamination. With the use of a sensor system as an *alternative* to visual inspection, this inspection delay will be minimal (a check of the display in the cockpit). Thus, comparisons of risks should include the additional delay due to the visual pre-take-off inspection. However, due to lack of data on the length of this delay and the desire not to overestimate the risks with visual inspection, zero inspection delay was used in the analysis, and the effect of a delay was examined in the sensitivity analysis in Section 5.4.3.

The effect on the comparative risks of inspection delays when visual inspection is used in conjunction with sensor systems is considered in Section 5.4.1.

## 4.4 Frequency of HOT Expiry and Fluid Failure

Approximate estimates of the frequency of expiry of HOTs and of fluid failure were found, as described in the Volume 1 report (1), two ways:

- estimated from information collected in the surveys of airline pilots, data collected during sensor testing and airport deicing operation data; and
- using the distribution of times between fluid application and take-off and the distribution of fluid failure times for departures from several airports.

Pilots responding to the surveys of airline pilots indicated that their HOTs rarely expired prior to take-off during precipitation conditions. A small percentage (about 6%) indicated that HOTs expired more than 10 times per year. On average, pilots in Canada indicated they made about five pre-take-off inspections during the 1996/97 winter due to expiry of the HOT. This represents 20% of take-offs where the aircraft was deiced. The survey of US airline pilots indicated that HOT expires during precipitation conditions following about 13% of deicings.

*Frequencies Based on Distributions of Delays and Weather Conditions*

The probabilities of exceeding the HOT and of fluid failure are dependent on the fluid application, taxi and delay times, the prevailing weather conditions and the type of fluid used. The variation in fluid application/taxi/delay times after deicing is critical in determining the likelihood of HOT expiry and 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 also be important. Given the large number of combinations of fluids, dilutions, airports and weather conditions, estimates were found for the three airport groupings given previously and Type I fluid, and non-diluted Type IV fluid. Use of non-diluted Type IV fluid should not lead to significant underestimation of the HOT expiry and fluid failure rates as non-diluted fluids are generally used and pilots would not accept use of diluted fluids if, by diluting the fluid, it is at risk of failing. The following approach was used to estimate these rates:

- determine the fluid application/taxi/delay time distributions for each of the airport groupings being examined;

- determine the HOT and estimate the expected protection times of fluids for given precipitation rates and types and ambient temperatures;
- estimate the variation in protection times around this expected value to allow for other factors (wind, humidity, etc.);
- determine the joint probability distributions of precipitation rate and type and temperature (distribution for Ottawa was used);
- allow for the variation in flight frequency and temperature distribution by time of day;
- estimate the fluid failure time for particular values of each of these factors and the probability of that combination of factors, and for each combination:
  - compare the fluid failure times with each value of the range of possible fluid application/taxi/delay times,
  - sum the joint probabilities of that fluid failure time and fluid application/taxi/delay time over values of fluid failure times less than the fluid application/taxi/delay time;
  - sum the joint probabilities of the precipitation type, temperature and fluid application/taxi/delay time over values of the HOT less than the fluid application/taxi/delay time; and
- repeat the calculations to determine the frequency that HOTs and fluid failure times were less than the application/taxi/delay times for each airport grouping.

A detailed description of the statistical analysis, derivation of the probability distributions and of the distributions used in this analysis are given in the Volume 1 report (1).

The estimated probabilities of HOT expiring and fluid failure for the three airport groupings considered are given in Table 4.2. These estimates are not critical to the risk comparisons, but are important in the estimation of the false alarm rates.

**Table 4.2 Estimated Probabilities of HOT Expiring and Fluid Failure Prior to Time of Take-off for the Three Airport Groupings**

| Airport | | Prob. HOT Expiring Before Take-off | | Prob. Fluid Failure Before Take-off | |
|---|---|---|---|---|---|
| | | Type I | Type IV | Type I | Type IV |
| Small Airport | Short-taxi | 39% | 0.00% | 2.4% | 0.00% |
| | Long-taxi | 98% | 0.02% | 9.0% | 0.01% |
| Busy Airport | | 100% | 0.7% | 21% | 0.1% |

# 5. RESULTS OF RISK ANALYSIS

The risk measures given in this section have been estimated using a consistent methodology, as outlined in Section 3, and provide good measures for comparing the risks under the different inspection procedures. The risk measures are first given separately for each inspection process under various options, then the comparative risks of visual and point sensor-based inspection are given. In most of the comparisons, results are only presented for the airport-fluid combinations: Type I fluid at small short-taxi airport, and Type IV fluid at busy airport. The comparative risks at small long-taxi airports using Type I and Type IV fluids are similar to the comparative risks presented, although the actual values of the risk measures differ significantly (as shown in Section 5.4.1).

The probability of the sensor and visual based inspection systems identifying fluid failure prior to take-off is discussed in the previous report (1) and is not repeated here. Similarly, the probability distributions of the areas contaminated at take-off given fluid failure prior to take-off, weighted by criticality, for visual and sensor-based inspection are given in the Volume 1 report.

It was necessary to make many assumptions in estimating the risk measures and the estimates are influenced by these assumptions. The assumptions, the reasons for them and their possible effect were given in the previous Volume 1 report (1) and are repeated in Appendix C. Also included in the appendix are the assumptions made for the extensions to the analysis described in this report. A sensitivity analysis of the effect of these assumptions on the comparative risks of visual and sensor-based inspection is given in Section 5.4.3.

## 5.1 Point Sensor Systems

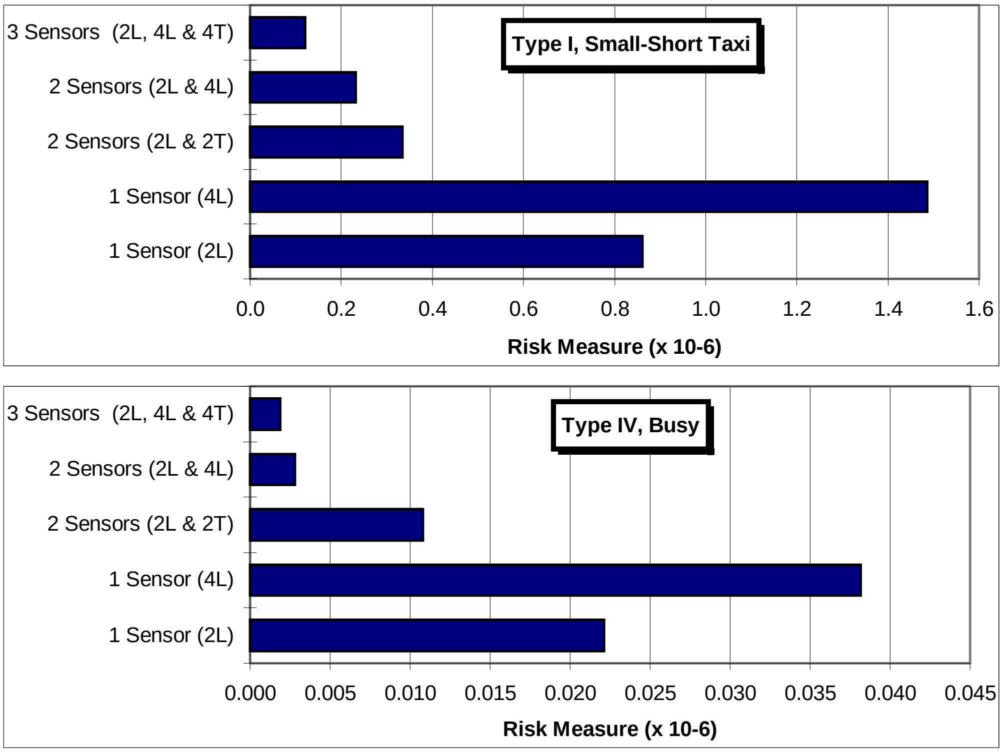
The estimated risk measures for one, two and three sensor per wing systems are summarized in Figure 5.1. As expected, the risks drop as more sensors are added, but the location of sensors is also very important. With only one point sensor per wing, the risks are almost halved when the sensor is located on the leading edge towards the wing tip rather than mid-span. With two sensors per wing, the risks with both sensors on the leading edge are 30-75% less than the risks with one on the leading edge and the other on the trailing edge. This is despite a higher probability of the sensor system identifying a fluid failure prior to take-off with one of the two sensors on the trailing edge.

The estimated risk measures for use of Type IV fluid at busy airports are roughly 35 times less than those at small short-taxi airports using Type I fluid. As shown in Figure 5.1, the trend in risks for the different sensors systems are very similar for the airports and fluid types examined.

The effect on the estimated risk measure of adding more sensors, given the best location for those sensors, is as follows:

- increase sensors per wing from 1 to 2 per wing: risks reduced by approximately 80%
- increase sensors per wing from 2 to 3 per wing: risks reduced by approximately 50%
- increase sensors per wing from 1 to 3 per wing: risks reduced by approximately 90%

Thus, there are large reductions in risk with two rather than one sensor per wing, and more modest reductions due to the addition of a third sensor per wing.



* Refer to Figure 3.1 for locations of sections (2L=leading edge towards wing tip, 4L=leading edge mid-span, 2T=trailing edge towards wing tip)

**Figure 5.1 Estimated Risk Measures for One, Two and Three Point Sensor per Wing Systems for Various Sensor Locations***

## 5.2 Visual Inspection

### 5.2.1 Under Various Viewing Conditions

With visual inspection, the estimated risk measures increase as the viewing conditions deteriorate. The risks are shown in Figure 5.2 for low-wing aircraft and do not include any allowance for the pilot deciding to return to deice (or have a tactile check done) based on the HOT, taxi-delay times and weather conditions. Thus, these risks are for when the decision to proceed is based solely on the visual identification of fluid failure by the pilot from inside the aircraft. The risks are estimated to increase greatly as the viewing conditions deteriorate and, at night, are over seven times greater than under very good viewing conditions.

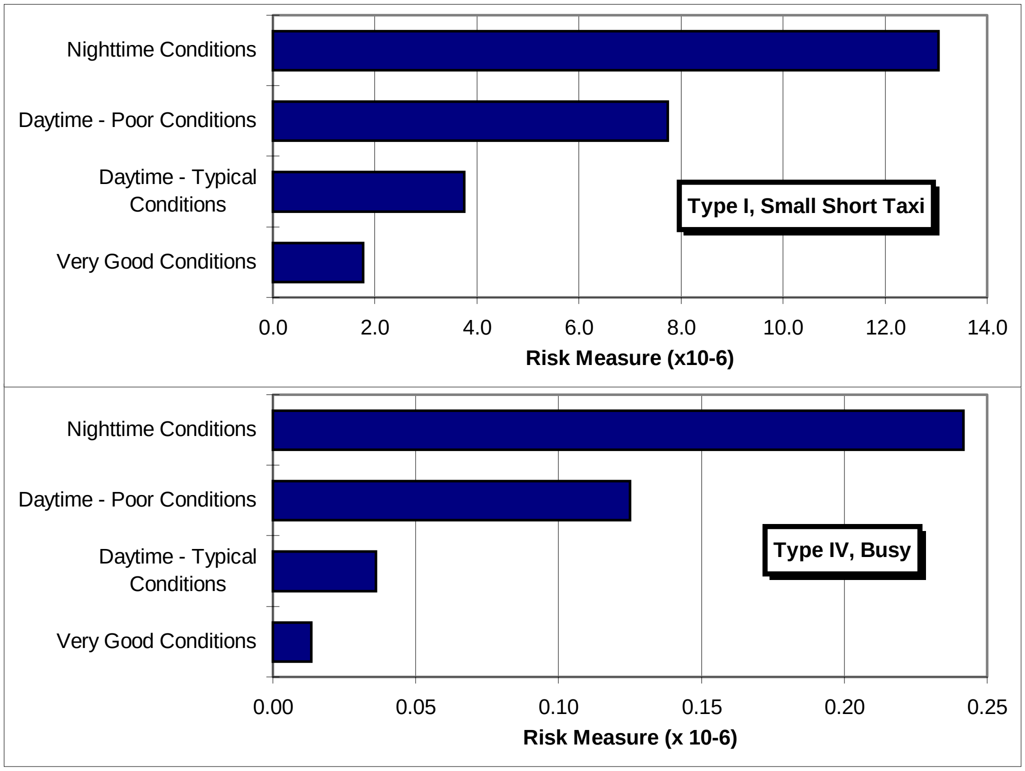


**Figure 5.2 Estimated Risk Measures Using Visual Inspection Only (No Allowance for HOTs) Under Various Viewing Conditions – Low-wing Aircraft**

### 5.2.2 Allowance for HOTs

As discussed in Section 3.3, when using visual inspection procedures, pilots make some allowance for the HOT, taxi-delay time and weather conditions when deciding whether to proceed with take-off, especially when viewing conditions are poor. The estimated risk measures under the various viewing conditions with and without allowance for HOTs are given in Figure 5.3. Allowance for HOT greatly reduces the variation in estimated risk measures with poor viewing conditions, especially for Type I fluid. As shown in Figure 5.3 for Type I fluid at small short-taxi airports, the estimated risk measures only increase by 45% from very good to nighttime viewing conditions compared to a factor of 7 with no allowance for HOTs.

The estimated risk measures are very dependent on the assumptions regarding the HOT, taxi-delay and weather conditions under which pilots would not proceed with take-off. These are displayed in Figure 3.3. The reasonableness of these relationships was tested by estimating the proportion of flights to return to re-deice, or be delayed for a tactile inspection using these relationships, and comparing these estimates with observed values. The estimated values for the airports and fluids examined are given in Table 5.1.

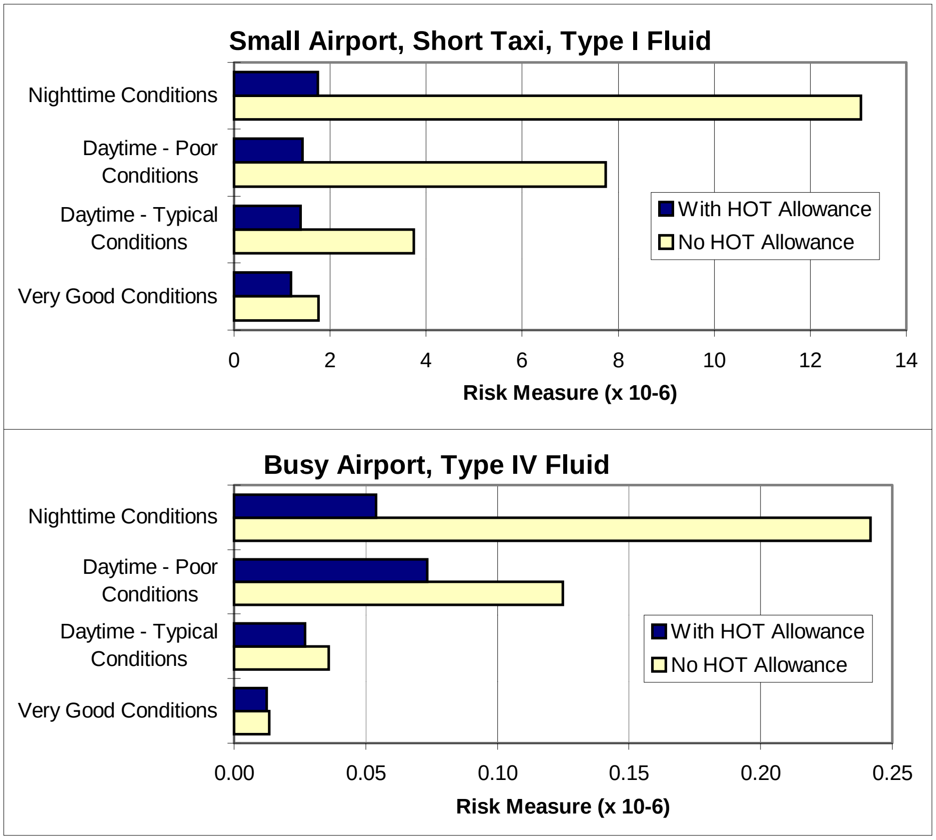


**Figure 5.3** **Estimated Risk Measures with Visual Inspection Under Various Viewing Conditions With and Without Allowance for HOTs – Low-wing Aircraft**

Using departure data for several Canadian airports, it was estimated that just under half the departures during icing conditions occur at night. Allowing for the proportion of departures at the different categories of airports, the fluid types used and the daytime viewing conditions[7], the relationships predict that following deicing 6% of take-offs would not proceed due to concerns regarding the fluid condition based on the HOTs and weather conditions. The survey of airline pilots in Canada indicated that pilots return to re-deice following roughly 3% of deicings. In addition, a number of pilots indicated that they delay the take-off following the pre-take-off inspection to do a tactile check. Thus, the relationships modelling the conservatism of pilots in poor viewing conditions give at least roughly similar overall results to those found in practice.

**Table 5.1 Estimated Percentage of Times Following Deicing that the Pilot Would Not Proceed with the Take-off Based Only on the HOTs and Weather Conditions**

| Airport | | Viewing Conditions | Type of Fluid | |
|---|---|---|---|---|
| | | | I | IV |
| Small Airport | Short-taxi | *Very Good* | 3% | |
| | | *Daytime typical* | 6% | |
| | | *Daytime poor* | 12% | |
| | | *Nighttime* | 16% | |
| | Long-taxi | *Very Good* | 8% | 0.1% |
| | | *Daytime typical* | 20% | 0.2% |
| | | *Daytime poor* | 25% | 0.3% |
| | | *Nighttime* | 30% | 0.5% |
| Busy Airport | | *Very Good* | | 0.2% |
| | | *Daytime typical* | | 1.0% |
| | | *Daytime poor* | | 1.2% |
| | | *Nighttime* | | 1.6% |

These results indicate that the allowance for HOTs appears to have the desired effect of reducing risks during poor viewing conditions to the same order of magnitude as during very good viewing conditions. There will, however, be a corresponding penalty of a higher false alarm rate, which is discussed in Section 6.

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[7] It was assumed that during the daytime half the departures are in "typical" conditions, a one third in poor conditions with the remaining 8% in very good conditions. Rough estimates of the percentages of departures by airport and aircraft type, based on Statistics Canada data at the 20 largest airports in Canada were: 48% jet & 12% large turboprop (t/p) at four busy airports, 20% jet & 8% t/p at small long-taxi-airports and 4% jet and 9% t/p and small short-taxi airports. Assumed fluid use was:

| | Jet aircraft | Turboprop aircraft |
|---|---|---|
| Small short-taxi airport | Type I | Type I |
| Small long-taxi airport | Type IV | 50% Type I, 50% Type IV |
| Busy airport | Type IV | Type IV |

### 5.2.3 Low- and High-wing Aircraft

The estimated risk measures for low- and high-wing aircraft, with and without allowance for HOT, taxi-delay and weather conditions, are shown for *daytime typical* viewing conditions in Figure 5.4. The view of the wing for high-wing aircraft is improved if it is possible to open the rear door during the pre-take-off inspection, and results are given separately for this case. The view of the upper wing surface varies more between aircraft types for high-wing aircraft than for low-wing aircraft. The estimated risk measures are based on an aggregation of the views over a number of high-wing aircraft types and may not represent a particular aircraft type well.

The estimated risk measures are much higher for high-wing aircraft than for low-wing aircraft, especially if it is not possible to open the rear door for the pre-take-off inspection. As with inspection in poor viewing conditions, allowance for HOTs significantly reduces the risks for high-wing aircraft. However, even allowing for HOTs, the estimated risk measures are 3 to 15 times greater for most high-wing aircraft than for low-wing aircraft. In these comparisons it is assumed that the allowance for HOT/delay/weather is the same for low- and high-wing aircraft. However, as the view of the wing for high-wing aircraft is worse, pilots are likely to be more conservative in the use of HOTs. If, for example, pilots of high-wing aircraft return based on HOT, delay and weather conditions in the same way as pilots of low-wing aircraft at night, the risk measures are reduced to:

- $4.4 \times 10^{-6}$ for Type I fluid at small short-taxi airports, and
- $0.12 \times 10^{-6}$ at busy airports.

Some high-wing aircraft, such as the DHC 8, have airfoils that maintain the maximum lift characteristics with turbulent flow and are more tolerant to minor amounts of wing contamination than high performance airfoils. Tolerance to minor contamination will reduce the risks for those aircraft, but will not greatly affect the comparative risks of visual and sensor-based inspection.

Pilots of high-wing aircraft could reduce their risk to below those for low-wing aircraft using visual inspection automatically returned to re-deice when their HOT expired (see results in Section 5.3). This reduction in the risks will be offset by an increase in the false alarm rate.

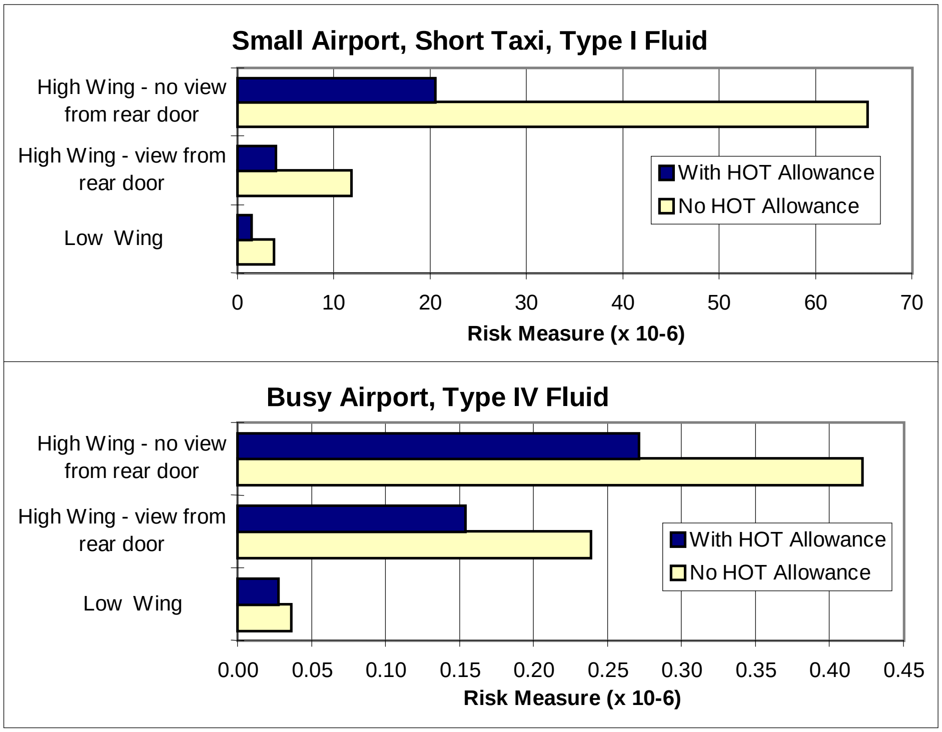

**Figure 5.4 Estimated Risk Measures with Visual Inspection for Low- and High-wing Aircraft Under *Daytime Typical* Viewing Conditions With and Without Allowance for HOTs/Delay/Weather**

### 5.2.4 Risk Associated with No Pre-take-off Inspection

The risks associated with take-off when a pre-take-off inspection is not conducted are very dependent on the assumptions regarding when an inspection is done. The risks were therefore estimated for three cases:

- *High risk case* – pre-take-off inspection is not conducted unless the lower HOT will expire prior to take-off;
- *Medium risk case* – pre-take-off inspection is not conducted unless the lower HOT will expire prior to take-off or, based on the HOT, weather and delays, the pilot thinks the fluid may fail prior to the lower HOT value; and
- *Low risk case* – there are no take-offs following de/anti-icing in conditions of freezing/frozen precipitation where pilot does not conduct a pre-take-off inspection.

The estimated risk measures for low-wing aircraft with visual inspection under *daytime typical* viewing conditions at small short-taxi airports are given in Figure 5.5[8] for these three cases. Not conducting inspections prior to expiry of the lower HOT increases the

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[8] Due to the small data set and the variation in fluid failure patterns relative to the HOT for Type IV fluid, estimates for Type IV were unreliable and are not given.

estimated risk measures by over 50% for *daytime typical* viewing conditions. Allowing for HOT, taxi-delay time and weather conditions in deciding whether to conduct a pre-take-off inspection prior to expiry of the HOT reduces the change in risk to roughly 20% greater than if inspections are conducted for all take-offs in winter precipitation conditions. These percentage increases in risk are similar if allowance for HOTs is made in the decision on whether to proceed with take-off.

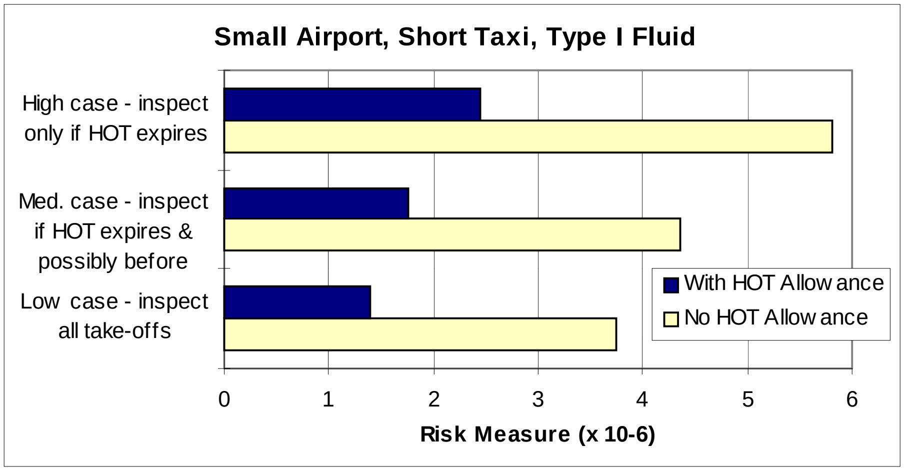

**Figure 5.5 Estimated Risk Measures with Visual Inspection for Three Scenarios for Conducting an Inspection – *Daytime Typical* Viewing Conditions With and Without Allowance for HOTs, Low-wing Aircraft**

The effect of a one-minute delay in take-off to conduct the visual inspection was investigated as in the *low* case all take-offs will be subject to the inspection delay, while in the other cases only those take-offs where an inspection is done will have the additional delay. The effect of the inspection delay was found to be small: with zero inspection delay the increase in risks from the *low* (inspect all) to *high* (inspect on HOT expiry) case was 55%, while with a one minute inspection delay the risks increased by 50%, a difference of only 5%.

## 5.3 Return On Expiry of Holdover Time

Rather than of conducting a pre-take-off inspection, expiry of the HOT could be used as a criteria to re-deice (or call for a tactile inspection). This criteria is used by some European carriers. The risks were estimated for returning to re-deice on expiry of HOT (with no pre-take-off inspection) for two cases:

- re-deice only if HOT expires; and
- re-deice if HOT expires or if HOT, taxi-delay time and weather conditions indicate fluid may have failed.

The estimated risk measures are given in Figure 5.6[9] for these two cases and values for visual inspection under *daytime typical* viewing conditions for low-wing aircraft are also given for comparison. The estimated risk measures using the conservative procedure of returning to re-deice whenever the HOT expires are approximately one fifth the risks using visual inspection procedures in *daytime typical* viewing conditions with allowance for HOT, delay and weather conditions. The risks with return on expiry of HOT are reduced marginally by allowing for possible fluid failure prior to the HOT expiring.

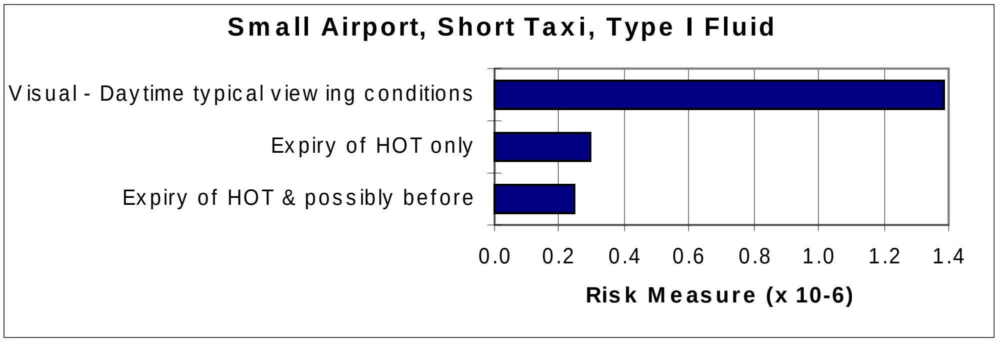

**Figure 5.6 Comparison of Estimated Risk Measures where Decision to Re-deice is Based on Expiry of HOT, with Visual Based Inspection in *Daytime Typical* Viewing Conditions with Allowance for HOTs for Low-wing Aircraft**

Use of the return on expiry of HOT criteria for high-wing aircraft where the rear door cannot be opened to inspect the wing would reduce the risks to below those of low-wing aircraft in very good viewing conditions. The disadvantage of re-deicing whenever the HOT expires is the higher false alarm rate, discussed in Section 6.

## 5.4 Comparative Risks of Visual and Sensor-based Inspection

### 5.4.1 Low-wing Aircraft

The risk measures for the two point sensors per wing system and visual inspection (no allowance for HOT, delays and weather conditions) under four viewing conditions are given in Table 5.2 for each of the airport-fluid cases examined. The risk measures were found to be much lower using the sensor system than using visual inspection, especially when viewing conditions are poor. As shown in Figure 5.7, the risks using the two-sensors-per-wing system were estimated to be around one fifth the risk using visual inspection during *very good* viewing conditions, and one sixtieth the risk during *nighttime* viewing conditions. Allowing for HOT, delays and weather conditions during *nighttime*

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[9] As with the estimated risks when pre-take-off inspections are not mandatory prior to expiry of HOT, estimates for Type IV were unreliable and are not given.

viewing conditions, the risks with the point sensor system were estimated to be less than with visual inspection by a factor of between eight and twenty depending on the airport and fluid type.

**Table 5.2 Risk Measures (per million departures) Due to the Inspection Process Not Identifying Fluid Failure Prior to Take-off – Low-wing Aircraft**

| Airport | Fluid Type | Inspection System* | Viewing Conditions | | | |
|---|---|---|---|---|---|---|
| | | | *Very Good* | *Daytime typical* | *Daytime poor* | *Nighttime* |
| Large Busy | Type II | Sensor | 0.034 | 0.034 | 0.034 | 0.034 |
| | | Visual | 0.16 | 0.43 | 1.5 | 2.9 |
| | | Visual+Sensor | 0.009 | 0.017 | 0.021 | 0.025 |
| | Type IV | Sensor | 0.003 | 0.003 | 0.003 | 0.003 |
| | | Visual | 0.013 | 0.036 | 0.12 | 0.24 |
| | | Visual+Sensor | 0.001 | 0.001 | 0.002 | 0.002 |
| Small, Long-taxi | Type I | Sensor | 0.87 | 0.87 | 0.87 | 0.87 |
| | | Visual | 6.6 | 14.1 | 29 | 49 |
| | | Visual+Sensor | 0.202 | 0.234 | 0.281 | 0.393 |
| | Type IV | Sensor | 0.0003 | 0.0003 | 0.0003 | 0.0003 |
| | | Visual | 0.0013 | 0.004 | 0.012 | 0.024 |
| | | Visual+Sensor | 0.0001 | 0.0001 | 0.0002 | 0.0002 |
| Small, Short-taxi | Type I | Sensor | 0.23 | 0.23 | 0.23 | 0.23 |
| | | Visual | 1.8 | 3.7 | 7.7 | 13 |
| | | Visual+Sensor | 0.054 | 0.062 | 0.075 | 0.105 |

* Sensor system with two point sensors per wing both located on the leading edge mid-span and towards wing tip (Sections 2L and 4L). Visual inspection with inspection for all take-offs, but with no allowance for HOTs, delays and weather conditions.

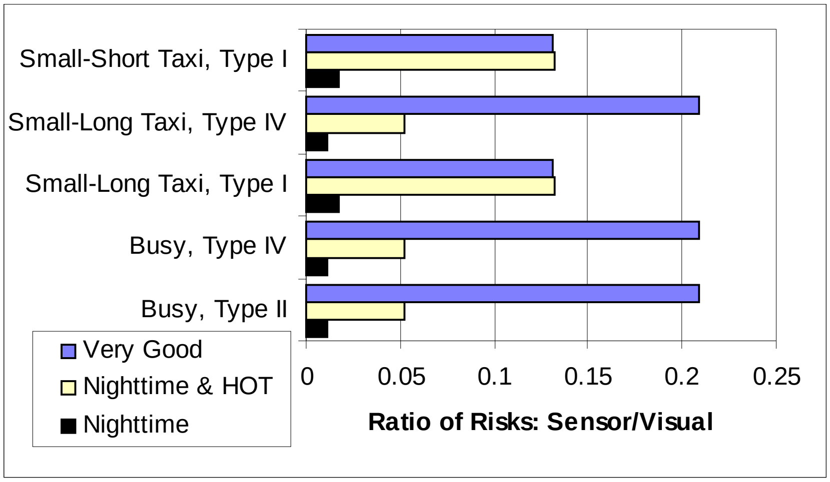

**Figure 5.7 Ratio of Risk Measures, Sensor/Visual, for Two Point Sensor per Wing System and Visual Inspection under *Very Good* and *Nighttime* Viewing Conditions, With and Without Allowance for HOT, Delays and Weather Conditions for Nighttime Viewing**

Despite the much lower risk measures found for the two point sensors per wing system than for visual inspection, the analysis indicates that visual inspection when used in combination with the sensor system, can significantly reduce the risks. When combined visual-sensor inspection is used, there will be a short delay while the visual inspection is conducted. A delay of one minute was used for small short-taxi airports (primarily turboprop aircraft) and two minutes was used for busy airports. The risk measures were estimated both with and without any inspection delay, and are compared in Figure 5.8.

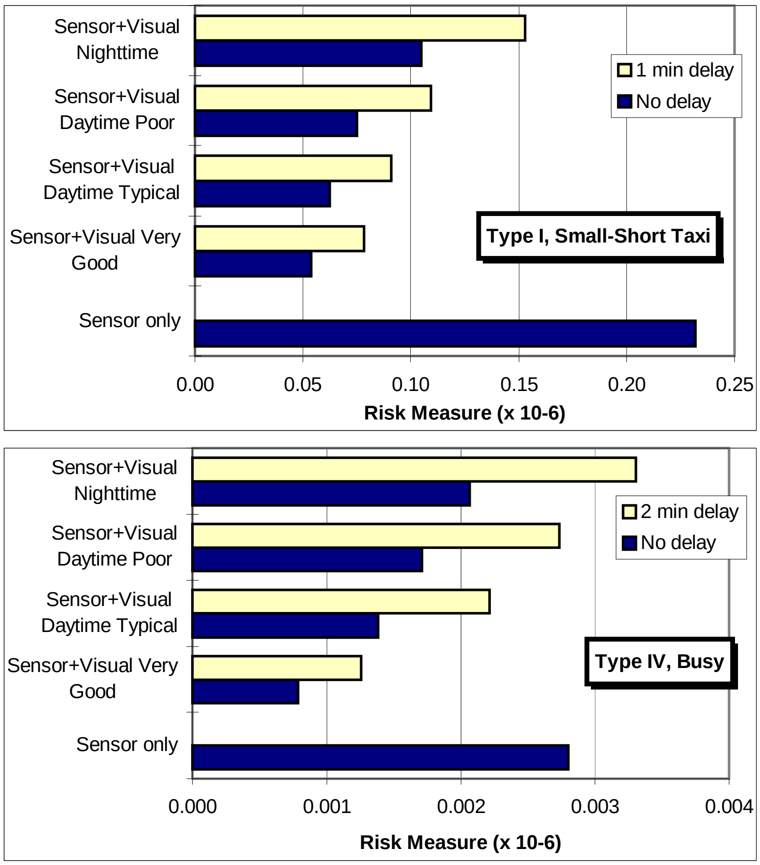

**Figure 5.8 Comparison of Risk Measures for Point Sensor and Combined Visual-Sensor Inspection Under Various Viewing Conditions With and Without a Delay to Conduct the Visual Inspection – Type I Fluid Small Short-taxi Airport and Type IV Busy Airport Cases**

If there is no additional delay due to the visual inspection, reductions in the *risk measures* ranging from around 40% during *nighttime* viewing conditions to 75% during very good viewing conditions were found. This significant reduction in the *risk measures* due to the use of visual inspection appear 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.

With inspection delays of one minute at small short-taxi airports and two minutes at busy airports, the risk measures with combined visual and sensor inspection were still found to be lower than with sensors only in all but one case. In this case, nighttime viewing conditions with Type IV fluid at busy airports, the reduction in risk due to the visual inspection at night did not offset the increased risk due to the additional two-minute delay in the take-off. Thus, with a point sensor system in place, conducting a visual inspection under poor viewing conditions that significantly delays the take-off may actually increase the risks.

### 5.4.2 High-wing Aircraft

The reduction in risk due to the use of point sensor systems is much greater for high-wing than low-wing aircraft. Figure 5.9 shows the estimated risk measures for the two point sensors per wing system and for visual inspection, allowing for HOT, delays and weather conditions, under *daytime typical* viewing conditions. Visual inspection procedures for high-wing aircraft rely heavily on allowing for HOT, delays and weather conditions in determining whether to proceed with take-off. Although the estimation of risks allowing for HOT is only approximate, inclusion of this factor will give a much more realistic comparison of the risks using sensor and visual based inspection. The method used to allow for HOT, delay and weather conditions was the same for both low- and high-wing aircraft and does not account for pilots possibly being more conservative in their use of HOTs when much of the wing is not visible.

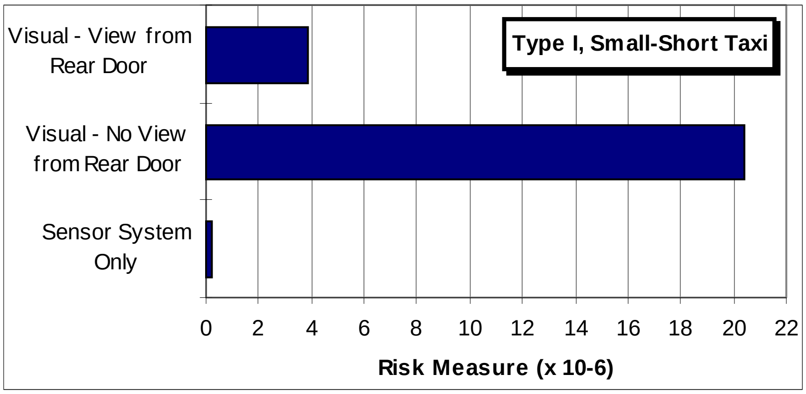

**Figure 5.9 Comparison of Risk Measures for Point Sensor System and Visual Inspection Allowing for HOT, Delays and Weather Conditions for High-wing Aircraft under *Daytime Typical* Viewing Conditions – Type I Fluid, Small Airport Short-taxi Time Case**

Risks for visual inspection depend on whether the rear door can be opened to view the wings and the estimated risk measures for both cases are given. Use of the point sensor system is estimated to reduce risks by a factor of between 15 and 100. For high-wing aircraft there is little added benefit of using visual inspection in conjunction with the sensor system as little of the wing can be viewed from inside the aircraft.

### 5.4.3 Sensitivity to Assumptions and Data Limitations

A number of assumptions were made in deriving these risk measures and a number of the estimated parameters are based on limited data. The sensitivities of the comparative risks to these assumptions and data limitations were examined. The sensitivities use the conditions given in Section 5.4.1 as a base for comparison the risks; i.e., low-wing aircraft, visual inspection under *daytime-typical* viewing conditions with no allowance for HOTs, delays and weather conditions, and a two-sensor-per-wing system. For each assumption/parameter a range in values of the relevant characteristic/parameter was specified that reflected the likely range of that characteristic/parameter based on the available data. Risk measures were then estimated for values of the characteristic/ parameter and used to estimate low and high values of the comparative risks (given by the ratio of risks, sensor/visual). The medium values correspond to the risk ratio under the base case. These assumptions and data limitations, and the sensitivities of the comparative risks, are outlined below and are summarized in Table 5.3.

*Ability of Pilot to Visually Identify Fluid Failure*

The ability of the pilot to identify fluid failure from inside the aircraft under various viewing conditions is a very important factor in the analysis and is modelled based on very limited data. The probability distribution for identifying fluid failure in *daytime-typical* viewing conditions is used to represent the medium cases, while the probability distributions of identifying fluid failure during *very good* and *nighttime* viewing conditions are used for the high and low cases, respectively. The comparative risks were found to be very sensitive to the assumed probabilities of identifying fluid failure, but even for the high case, *risk measures* were 80% less using the sensor system.

*Delay/taxi times*

Delay and taxi times significantly affect 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, 15 and 20 minutes were used. The comparative risks were found to be insensitive to this parameter.

## Table 5.3 Sensitivity of Comparative Risk to Assumptions and Data Limitations*

| Assumption, Parameter or Data Limitation | Risk Ratio: Sensor/Visual[#] | | | Parameter Values Corresponding to Risk Ratio: | | |
|---|---|---|---|---|---|---|
| | Low | Medium | High | Low | Medium | High |
| **Small Short-taxi Airport, Type 1 Fluid** | | | | | | |
| Visual identification of fluid failure | 0.02 | 0.06 | 0.13 | Nighttime | Day-typical | Very good |
| Taxi/delay time | 0.06 | | 0.06 | Mean 5.5 min | | Mean 8 min |
| Time between inspection & take-off | 0.05 | 0.06 | 0.62 | 4 min | 2 min | 0 min |
| Delay due to visual inspection | 0.04 | 0.06 | | 1 min | 0 min | |
| Effect of contamination on aerodynamic performance | 0.03 | 0.06 | 0.15 | Low | Medium | High |
| Time between fluid failure & take-off | 0.06 | 0.06 | 0.07 | 2 min | 3 min | 6 min |
| Consistency of early fluid failure location | | 0.06 | 0.17 | | L.E. High | L.E. Med. |
| Time between visually observed failure and significant aerodynamic affect | | 0.06 | 0.08 | | 0-0.5 min | 1-1.5 min |
| Number of sensors*^ | 0.03 | 0.06 | 0.23 | 3 (2L,4L,2T) | 2 (2L, 4L) | 1 (2L) |
| Location of sensors** | | 0.06 | 0.09 | | 2L, 4L | 2L, 2T |
| Subset of fluid failure progression data | | 0.06 | 0.10 | | All data sets | Sets with all wing sections |
| Variation & limited test data | | 0.06 | 0.07 | | All data sets | Excl. test ID26^ |
| **Busy Airport, Type 1V Fluid** | | | | | | |
| Visual identification of fluid failure | 0.01 | 0.08 | 0.21 | Nighttime | Day-typical | Very good |
| Taxi/delay time | 0.08 | 0.08 | 0.08 | Mean 10 min | Mean 15 min | Mean 20 min |
| Time between inspection & take-off | 0.03 | 0.08 | 0.49 | 5 min | 3 min | 0 min |
| Delay due to visual inspection | 0.05 | 0.08 | | 2 min | 0 min | |
| Effect of contamination on aerodynamic performance | 0.05 | 0.08 | 0.19 | Low | Medium | High |
| Time between fluid failure & take-off | 0.04 | 0.08 | 0.11 | 3 min | 5 min | 10 min |
| Consistency of early fluid failure location | | 0.08 | 0.28 | | L.E. High | L.E. Med. |
| Number of sensors*^ | 0.05 | 0.08 | 0.61 | 3 (2L,4L,2T) | 2 (2L, 4L) | 1 (2L) |
| Location of sensors** | | 0.08 | 0.30 | | 2L, 4L | 2L, 2T |
| Time between visually observed failure and significant aerodynamic affect | | 0.08 | 0.19 | | 0-0.5 min | 5 min |
| Subset of fluid failure progression data | | 0.08 | 0.08 | | All data sets | Sets with all wing sections |
| Variation & limited test data | | 0.08 | 0.10 | | All data sets | Excl. test ID7^ |

* Low value of risk ratio indicates risks lower using sensor system
"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, low and high ratios do not necessarily correspond to low and high values in range of characteristic/parameter.

^ Excluding test most favourable to sensors.

*^ Location of sensor given in brackets, see next footnote for notation

** Sensor locations: 2L=leading edge towards wing tip, 4L=leading edge mid-span, 2T=trailing edge towards wing tip (refer to Figure 3.1)

### *Time Interval Between Pre-take-off Inspection and Take-off*

The time interval between the pre-take-off inspection and take-off is very important for visual inspection as the greater the time interval, the greater the chance of either the fluid failure after the inspection or of an undetected fluid failure spreading.

In the results given above, risks were estimated for set time intervals between pre-take-off inspection and take-off of 2 and 3 minutes for Type I and Types II or IV fluids, respectively (use of these times is discussed in Section 4.3). These time intervals in reality vary and the effect on the risk of using the distribution of the time interval rather than a fixed value was estimated. Using the distribution of the time interval shown in Figure 4.2, the risk measures for visual inspection under *daytime typical* viewing conditions were estimated to be:

| Fluid | Airport | Interval 2 or 3 min. | Distribution | (% change) |
|---|---|---|---|---|
| Type IV | Busy | $0.036 \times 10^{-6}$ | $0.053 \times 10^{-6}$ | (47%) |
| Type I | Small short-taxi | $3.7 \times 10^{-6}$ | $5.9 \times 10^{-6}$ | (59%) |

The comparative risks, sensor/visual, were reduced by a third using the distribution of pre-take-off to take-off time intervals rather than fixed times of 2 and 3 minutes.

The sensitivity of the comparative risk to very low and high time intervals between pre-take-off inspection and take-off was also examined. 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 Type I fluid and five minutes was used for 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.

### *Additional Delay Due to Visual Pre-take-off Inspection*

Conducting a visual pre-take-off inspection increases the time between fluid application and take-off and therefore increases the risk associated with fluid failure in cases where fluid failure is not identified. The effect on the comparative risks of inspection delays of 1 minute for Type I fluid at small airports (typically turboprop aircraft) and 2 minutes for Type IV fluid at busy airports (typically jet aircraft) were examined. Risks with visual inspection increased by roughly 45% in both cases. Risks with the sensor system used as an alternative to visual inspection do not change. Thus, the delay due to visual inspection affects the risks significantly, reducing the risk ratio by 45%.

### *Effect of Amount of Contamination on Aerodynamic Performance and Risk*

The effect of varying amounts of contamination on the aerodynamic performance of the aircraft and the risk was modelled by assuming that for a given amount of contamination, weighted by the criticality of its location, there will be a probability of an accident. The "medium" probability distribution of exceeding a critical loss in maximum lift for various areas contaminated shown in Figure 3.3 was used in the risk analyses above. The sensitivity of the comparative risk was estimated using the "low" and "high curves" in Figure 3.3. The "low curve" could, for example, be more appropriate if the pilot can increase the take-off speed or reduce the climb rate or angle of incidence to reduce the risk of the aircraft stalling. Use of the "low curve" reduced the comparative risk ratio by a factor of two. In the high sensitivity of aerodynamic performance to contamination case, the risk ratio increased by a factor of two, but the risk measure for the sensor system was still found to be one sixth that for visual inspection during *daytime typical* viewing conditions.

### *Time Between Fluid Failure and Take-off*

Average values of the time between fluid failure and take-off of 2.5 minutes for Type I, and 5 minutes for Type IV fluid, used in the analysis were estimated in the earlier study (1). The use of double these times had very little effect on the comparative risks.

### *Consistency of the Location of Initial Fluid Failure*

High consistency in the location of early fluid failure allows sensors to be located in areas that fail first, thus giving a high probability of detecting early fluid failure. The consistency of the location of early fluid failure on the leading edge sections was assumed to be “high” (e.g. with 20% of section contaminated sensor has 0.9 chance of identifying failure – see (1) Figure C1 in Appendix C). For the low case, consistency on the leading edge section was reduced to “medium” (e.g., 0.4 probability of identifying failure with 20% of area contaminated – see (1) 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 much less than those for visual inspection, even under *very good* viewing conditions.

### *Time Interval Between Visually Observed Fluid Failure and Significant Effect on Aerodynamic Performance*

Longer times between visually observed fluid failure and significant effect on aerodynamic performance would 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 to a lesser extent. The comparative risk ratio increases marginally for Type I fluid and doubles for Type IV fluid, but in both cases is still much less than one.

### *Outlying Fluid Failure Progression Test Data*

In a number of field tests the first fluid failure occurred well before the HOT expired, especially for Type IV fluid (see list in Appendix A and for further discussion see APS reports (10), (11), (12)). To test the sensitivity of the estimated comparative risks to data from these tests, the risk analysis was repeated excluding data from the test with the earliest Type I fluid failure and the earliest Type IV failure. Exclusion of these tests had a similar affect on the *risk measures* for visual and sensor inspection and the comparative risks (ratio of sensor/visual) were unaffected.

### *Variation in Location and Time of Fluid Failure*

The risk analysis is based on a relatively small number of tests, 26 tests with Type I fluid and 11 tests with anti-icing fluid, and the comparative risk estimates could be sensitive to variation in the characteristics of the fluid failure. Given the complexity of the analysis, it was not possible to derive confident intervals for the ratio of risks. Empirical estimates of the confidence interval could be derived, but this would be very time-consuming. However, a good feel for the sensitivity of the estimated risk ratio to variation in the test data can be found by excluding the test that is most favourable for sensors. The most favourable test was taken to be the one where the sensor has the highest probability of early identification of fluid failure, and visual inspection has the lowest probability. For Type I fluid, the comparative risks were found to be fairly insensitive to the exclusion of the most favourable test for sensors (one of 26 tests), increasing the risk ratio by only 10%. For Type IV fluid, exclusion of the most favourable test (one of eleven tests) increased the risk ratio by 30%, but the risk measures with sensors were still one tenth those using visual inspection in *daytime-typical* viewing conditions. The probability of obtaining these estimated risk ratios would be extremely small had the risks with the sensor system been greater than or equal to those of visual inspection in *daytime-typical* viewing conditions.

### *Number and Location of Point Sensors*

As shown in Figure 5.1, the risk measures for point sensor systems vary greatly with the number and location of sensors. The comparative risk ratio varies from 0.03 for three sensors per wing, up to 0.6 for one sensor per wing (sensor located on the leading edge). Although the ratio is still less than one, use of only one sensor per wing could result in higher risks for sensor systems if any of the other assumptions or data limitations have led to an underestimate of the risk ratio. Placement of the sensors is also very important; location of one of the two sensors on the trailing edge increased the ratio to 0.3 for Type IV fluid, but had a much smaller effect on the ratio for Type I fluid.

### *Fluid Failure Progression Data on a Limited Number of Wing Sections*

For 8 of the 37 fluid failure progression tests used in the analysis, data were only available for two of the seven sections along the span of the wing and for two representative surfaces. The sensor systems evaluated had sensors located on either the leading or trailing edge of these sections. The effect of any possible biases introduced by using test data with sensors located on the limited sections was examined by estimating the comparative risks excluding these tests. The risk ratio for anti-icing fluid, where one of eleven tests was omitted, was unaffected. For Type I fluid seven of 26 tests were omitted and the risk ratio increased from 0.06 to 0.10. Thus, the inclusion of tests with a limited number of wing sections likely led to an underestimation of the risks with sensor inspection relative to visual inspection. However, the risk measures with sensors were still one tenth those using visual inspection in *daytime-typical* viewing conditions

*Probability of Fluid Failure*

The estimated probabilities of fluid failure have a direct effect of the estimated risk measures. However, comparative risks, measured by the ratio of risks, are insensitive to the values used in the analysis and are not included in Table 5.3.

*Methodology Used to Estimate the Risks Using Visual Inspection*

The risk measures for visual observation were analysed using a different methodology and different relationships for the accuracy of visual observation under different viewing conditions, described in the Volume 1 report, Appendix D (1). The combined risk measure over all viewing conditions using visual inspection was found to be consistent with the values in Table 5.2[10].

The *risk measures* for visual inspection procedures were found to be higher than for the point sensor system in each case examined above. Even in combinations of assumptions favourable for visual inspection, the *risk measures* for visual inspection were higher. However, 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. This clearly demonstrates the sensitivity of the comparative risks to the visual inspection procedures and conditions under which the visual inspection takes place.

### 5.4.4 Other Considerations

The point sensor system analysed, unless otherwise stated, 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.

The analysis assumes that the sensors work properly. The reliability of the equipment, that is the electronics, wiring, power supply, etc., is not considered.

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:

- 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 therefore where no visual inspection is done; and
- buildup of ice on the aircraft in situations where the aircraft is not deiced.

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[10] *Risk measures* estimated to be between $3.1 \times 10^{-6}$ and $5.9 \times 10^{-6}$ for Type I fluid at small airport with short-taxi times

Point sensors would certainly be of benefit if a wing was missed completely. In the case of poor de/anti-icing, the areas affected will usually be small and lead to localized early failures which do not propagate and pose minimal risks depending on the location and areas affected. Point sensor systems would only be of benefit if they were located in the areas missed or where a poor job was done. These areas may not correspond to where early fluid failure occurs. However, since the sensors are located on the leading edge, they would be more likely to detect the failure in the higher risk cases.

### *Possible Differences Between Ethylene-glycol and Propylene-glycol Based Type IV Fluids*

Preliminary results of limited testing of ethylene-glycol and propylene-glycol based Type IV fluids indicate that fluid failure differs in its visual appearance and that frozen contamination present in one of these fluids may be stripped off the aircraft more easily following visually observed fluid failure than the other.

The possible effect of these differences on the comparative risks is considered below:

- Implication of Difference in Visual Appearances
  The sensitivity of the comparative risks to the accuracy of visual identification of fluid failure indicates that very much better viewing conditions would be required before the risk measure for visual inspection even got close to that for the sensor system. In the tests of the ethylene and propylene-glycol based fluids, although there was a difference in the appearance, it was not felt that this had a great effect on the identification of fluid failure.

- Implication of Different Propensity for Contamination Stripping
  (i.e. different times to contamination ‘attachment’ for different fluids with similar times to visual failure)
  Visual fluid failure with Type IV fluid occurs well before the fluid reaches a condition that will cause significant aerodynamic effects. Any difference in the degree to which one of the fluids is stripped from the wing following visually observed fluid failure is closely related to differences in this time interval between failure and significant aerodynamic effects. Given continued exposure following the onset of fluid visual failure, the fluid will eventually fail to the extent where it is not stripped from the wing. This additional exposure time is not known. The time interval between visually observed fluid failure and a significant aerodynamic penalty (due to residual contamination after take-off) is important in the risk comparison due to the incremental risk of conducting pre-take-off visual inspections several minutes before take-off. The sensitivity analysis indicated that with a five minute interval the risk ratio increased by a factor of 2.4 from 0.08 to 0.19.

  Since visual inspections are rarely more than 5 minutes prior to take-off, longer intervals between visual failure and the onset of aerodynamic penalty will not further reduce the incremental risk inherent in the delay between visual inspection and takeoff. Thus, the comparative risk ratio given above will not change for longer intervals between visual failure and the onset of aerodynamic penalty.

Thus, although the possibly different properties of ethylene-glycol and propylene-glycol based Type IV fluids could significantly affect the comparative risks, it is unlikely that the risk measures for sensor-based inspection would exceed those of the visual based inspection.

# 6. FALSE ALARMS

Under the “clean wing concept” the wing must be completely free of contamination and once the fluid has failed the aircraft must be re-deiced. False alarms, or unnecessary turn-backs, occur when pilots opt to re-deice or call for a tactile check when the fluid would not have failed prior to take-off. Using sensor-based systems, fluid failure is only identified once fluid failure has occurred and, thus, false alarms would only occur due to malfunction of the sensor system.

With visual inspection, false alarms occur when the fluid would not have failed prior to take-off, but the pilot either incorrectly identifies the fluid as having failed at the pre-take-off inspection, or returns to re-deice (or call for a tactile check) based on the HOT, weather conditions and delay. The probability of this occurring can be estimated using the approach outline in Section 3.3 for allowing for HOTs with visual inspection and Section 4.3 estimating the frequency of fluid failure[11].

The proportion of false alarms was estimated to be the ratio: $P_{nf} / (P_{nf} + P_f)$

where $P_{nf}$ is the estimated proportion of returns to re-deice when the fluid would not have failed prior to take-off; and

$P_f$ is the estimated proportion of returns to re-deice where the fluid would have failed prior to take-off

*Visual Inspection Procedure*

The estimated probabilities of the pilot returning to re-deice (or call for a tactile check) when fluid failure would not have occurred prior to take-off (i.e., false alarm); and the estimated proportion of returns that are false alarms are given in Table 6.1. These rates are for visual inspection where the pilot may also return based on the HOT, delay and weather conditions[12]. The false alarm rates based solely on visual observation of the wing are approximately equal to the rates under very good viewing conditions given in the table. As expected, the probability of a false alarm is very dependent on the viewing conditions – the worse the conditions the higher the false alarm rate. The false alarm rate decreases as the probability of a fluid failure increases. The proportion of returns to re-dice (or call for a tactile check) which are false alarms is high even in very good viewing conditions. These estimates were confirmed using a rough, more simplistic approach given in Appendix E.

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[11] The detailed description of this procedure is given in Appendix A of the Volume 1 report (1).

[12] An average wind speed was used in determining the proportion of pilots returning due to HOT, delay and weather conditions rather than a distribution of wind speeds. Use of a distribution leads to an overestimation of the probability of pilots returning because the effect of wind speed was not included in the estimation of fluid failure times (due to lack of data).

Considering the distribution of jet and turboprop aircraft departures across airports in Canada, roughly 90% of re-deicings (or delays for tactile inspection) following the pre-take-off inspection are done when the fluid would not have failed prior to take-off.

**Table 6.1 Estimated Proportion of False Alarms Using Visual Inspection with Pilot Allowing for HOT, Delays and Weather Conditions in Decision to Re-deice**

| Viewing Conditions | Small Airport | | | Busy Airport |
| --- | --- | --- | --- | --- |
| | Short-taxi | Long-taxi | | |
| | Type I | Type I | Type IV | Type IV |
| Probability of fluid failure prior to departure | 2.4% | 9.0% | 0.01% | 0.1% |
| Probability of unnecessary return (false alarm) | | | | |
| *Very Good* | 2% | 4% | 0.0% | 0.1% |
| *Day-Typical* | 6% | 12% | 0.1% | 0.3% |
| *Day-Poor* | 7% | 14% | 0.1% | 0.4% |
| *Nighttime* | 10% | 18% | 0.1% | 0.5% |
| Proportion of returns which are false alarms | | | | |
| *Very Good* | 60% | 43% | 77% | 64% |
| *Day-Typical* | 80% | 68% | 95% | 89% |
| *Day-Poor* | 82% | 70% | 96% | 90% |
| *Nighttime* | 85% | 73% | 96% | 91% |

### *Sensor-based Inspection*

As mentioned above, the point sensor systems considered here[13] only identify contamination once it is present. Thus, use of sensor systems as an alternative to visual inspection would eliminate all these unnecessary deicings. However, if the sensor system is used in conjunction with the current visual inspection procedures, false alarms due to the inaccuracy of visual inspection would still occur and the false alarm rate would not change.

Use of a sensor system may lead to an increase in the number of re-deicings where only very small amounts of contamination are present in the least critical areas. To get a feel for the possible extent of this problem with point sensor systems, the probability of the sensor system identifying contamination when contamination is present on less than 1% of the wing, weighted by criticality, was estimated and is given in Table 6.2.

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[13] Point sensors can be calibrated to indicate when fluid failure over the sensor head is imminent, but the analysis in this report assumes that the sensors are calibrated to identify fluid failure, not imminent failure.

**Table 6.2 Estimated Probability of Returning to Re-deice Using Point Sensor System* When Only a Very Small Area of the Wing is Contaminated**

| | Type I Small Airport | Type IV Busy Airport |
|---|---|---|
| Probability of returning due to detecting contamination | 1.4% | 0.049% |
| Probability of returning when < 1% of wing, weighted by criticality, is contaminated | 1.05% | 0.031% |
| Proportion of times that < 1% of wing, weighted by criticality, is contaminated when contamination is detected | 75% | 64% |

* Two sensors per wing located on leading edge of Sections 2 and 4 (refer to Figure 3.1)

*Return on Expiry of HOT*

As discussed in Section 5.3, risks can be reduced by returning to re-deice (or call for a tactile inspection) whenever the lower HOT is exceeded. With this procedure, a false alarm occurs when the HOT expires prior to take-off, but the fluid would not have failed before take-off. The estimated false alarm rate using this procedure, and the proportion of returns that are false alarms are given in Table 6.3. Using Type I fluid, this procedure would lead to a very high percentage of unnecessarily delayed take-offs -- 37% of take-offs at small short-taxi airports and 89% at small long-taxi airports. Using Type IV fluid the false alarm rate is estimated to drop to less than 1% of take-offs, even at busy airports.

**Table 6.3 Estimated Probability of Lower HOT Expiring Prior to Take-off When the Fluid Would Not Have Failed Before Take-off**

| | Small Airport | | | Busy Airport |
|---|---|---|---|---|
| | Short-taxi | Long-taxi | | |
| | Type I | Type I | Type IV | Type IV |
| Probability of unnecessary Return (false alarm) | 37% | 89% | 0% | 0.7% |
| Proportion of returns which are false alarms | 95% | 91% | n.a. | 96% |

The false alarm rates of visual inspection, return on expiry of HOT, and the "very low contamination" rate for the point sensor system examined above, are given in Figure 6.1. Use of sensors as an alternative to visual inspection, assuming that the 1% level would not affect safety, would reduce the false alarm rate by a factor of 3 - 10 under very good viewing conditions and by a factor of 10 - 50 under nighttime viewing conditions. Use of expiry of HOT as the criterion for re-deicing (or calling for a tactile check) rather than visual inspection would greatly increase the number of unnecessary deicing when Type I fluid is used, but would not significantly change the number of unnecessary deicings when Type IV fluid is used.

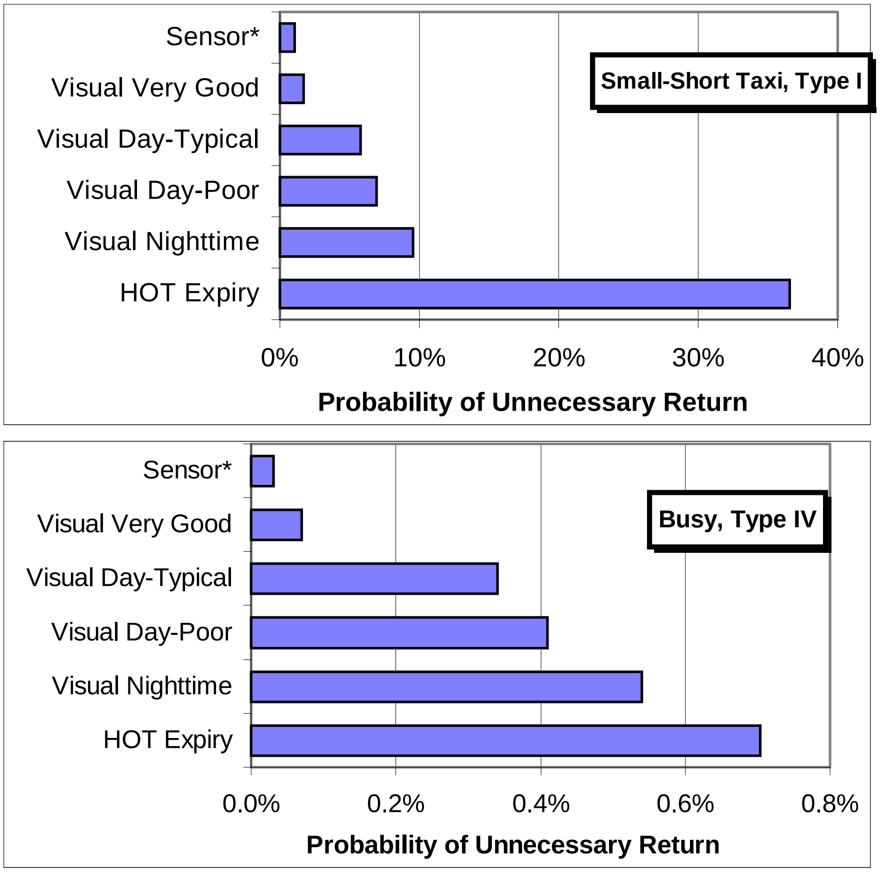

**Figure 6.1 Comparison of Estimated False Alarm Rates for Visual Inspection Under Various Viewing Conditions, Sensor System* and Return on Expiry of HOT**

* False alarm rate with sensor is zero, but could be overly sensitive to very small amounts of contamination – rate given is for less than 1% of wing contaminated, weighted by criticality

# 7. CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Conclusions

*Comparative Risks of Visual and Sensor-based Pre-take-off Inspection*

Based on the risk analysis conducted, and the sensitivity of the risks to assumptions made in the analysis, it can be concluded that the risk associated with a serious aerodynamic performance penalty due to undetected failure of anti-icing fluids can be reduced significantly by the use of a point contamination detection sensor system.

- During aircraft ground operations with commonly experienced time delays between pre-take-off inspection and take-off, the risk when using an inspection system based on two point detection sensors per wing is less than the risk associated with the current visual inspection procedures, even under conditions of good visibility. The risk associated with visual inspection is 1.5 to 50 times greater than the risk associated with the use of point detection sensors, the value depending on the ground operational circumstances and analysis assumptions. This conclusion is valid when the sensors are placed in areas where the onset of fluid failure typically occurs in the areas most critical to aerodynamic performance, or where sensors are placed so that the state of the fluid can be reliably predicted in those areas.
- The use of an inspection system based on three point detection sensors per wing reduces the risk by a further 30% to 50%.
- The risk associated with a point detection sensor system used in conjunction with visual inspection is significantly lower than when either visual or sensor-based inspection is used separately in typical daytime and good viewing conditions. At night, any reduction in risk caused by conducting a visual inspection in addition to a sensor system inspection will be small.
- The risk incurred by using a two sensor per wing system, only (i.e., no visual inspection), for pre-take-off inspection is similar to, or slightly greater than, the risk associated with:
  - visual inspection, only, under very good viewing conditions with no delay between pre-take-off inspection and take-off, and
  - returning to re-deice on expiry of the HOT.

*False Alarm/Unnecessary Turnback Rates*

- Visual Inspection:

  Using visual pre-take-off inspection procedures, the percentage of re-deicings that are unnecessary (where the pilot in command returns for deicing, but the fluid would not in fact have failed prior to take-off) is approximately 90%.

- Point Detection Inspection

  Using point sensor systems, the proportion of returns with only a very small amount of contamination present would be much less than when using visual inspection procedures (except in very good viewing conditions).

- Holdover Time as Decision Criteria

  Use of expiry of the HOT (minimum value in HOT range) as the sole criteria for the decision to return to de-ice would:

  - for Type I fluid, lead to an unworkably high proportion of delayed take-offs.
  - for Type IV fluid, lead to a much lower number of returns. The rate would be only marginally higher than that for visual inspection at night.

*Allowance for HOTs, Delays, and Weather Conditions*

When using visual pre-take-off inspection procedures to decide whether to re-deice (or call for a tactile check), pilots consider the HOT and assess whether the protection time of the fluid is greater than the total of the fluid application, the taxi and the delay times. They estimate the protection time based on the range of HOTs given in the HOT Tables and the prevailing weather conditions.

The study shows that in order to keep risks at similar levels as those experienced in good viewing conditions, pilots *must* consider the HOT in deciding whether to re-deice in poor viewing conditions and must make reasonable estimates of the protection time.

The study also shows that in order to keep risks at similar levels as those applicable to low-wing aircraft, pilots of high-wing aircraft pilots *must* consider the HOT and need to be very conservative in the selection of protection times.

*Area/Scanning Sensors*

- The data is insufficient 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, or would be removed during the take-off run, when the sensors identify fluid failure;
  - the sensitivity of identification of fluid failure to transient contamination accumulation which is subsequently absorbed by the anti-icing fluid;
  - the view of the wing surface from the intended location of the sensor cameras; and
  - demonstrated use of the system for identifying fluid failure in operational conditions.

- Remote area sensors can significantly reduce the risks associated with post-deicing inspection, but this use of area sensors was not considered further in this report.

Other conclusions on this project, such as from the results of the pilot surveys, are given in the previous Volume 1 report (1) and are not repeated here.

## 7.2 Recommendations

- Point sensor systems should be used in conjunction with current pre-take-off inspection procedures to provide additional information to the pilot on the wing condition prior to take-off.
- Work with remote area sensor manufacturers, airports, and air carriers should be continued, to collect the data required for comparisons of the risks of using sensors and current inspection procedures.
- The data required for determining the reliability of tactile inspection should be collected and minimum reliability criteria for use of remote area sensors as an alternative to tactile inspection should be established.
- When the required data is available, the comparative risks of using remote area sensors and current procedures for both post-deicing critical surface inspection and pre-take-off inspection should be evaluated. In the latter case, risks associated with a remote area sensor mounted on a truck, or on a fixed or retractable pole near the runway apron should be considered.

## REFERENCES

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# Appendix A

## Summary of Fluid Failure Progression Test Data

## Summary of Fluid Failure Progression Data from Outdoor Aircraft Tests Collected by APS Used in Analysis

| Test | Date | Aircraft Type | Fluid Type | Precip. Rate g/dm$^2$/h | Precip. Type | Wind Speed km/h | Temp. C | HOT Lower min. | Time Since Applic. | | # of Sections |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Ist. Fluid Failure | Last Time Recorded | |
| A5C | 27 Apr 95 | A32 | 1 | 5 | S | 39 | 0 | 6 | 9 | 30 | 2 |
| B4A | 15 Mar 95 | BAE | 1 | 16 | FD | 37 | -2 | 5 | 47 | 100 | 2 |
| B4B | 15 Mar 95 | BAE | 1 | 22 | FD | 37 | -2 | 5 | 10 | 25 | 2 |
| ID1 | 16 Jan 97 | 737 | 1 | 7 | S | 14 | 0 | 6 | 36 | 55 | 7 |
| ID14 | 28 Jan 97 | 737 | 1 | 21 | S | 11 | -13 | 6 | 4 | 17 | 7 |
| ID15 | 28 Jan 97 | 737 | 1 | 12 | S | 7 | -15 | 6 | 5 | 23 | 7 |
| ID16 | 28 Jan 97 | 737 | 1 | 30 | S | 2 | -17 | 6 | 3 | 15 | 7 |
| ID20 | 5 Feb 97 | F100 | 1 | 17 | S | 7 | -2 | 6 | 4 | 18 | 7 |
| ID21 | 5 Feb 97 | F100 | 1 | 20 | S | 9 | -2 | 6 | 6 | 18 | 7 |
| ID22 | 5 Feb 97 | F100 | 1 | 14 | S | 9 | -1 | 6 | 7 | 33 | 7 |
| ID23 | 5 Feb 97 | F100 | 1 | 14 | S | 9 | -1 | 6 | 6 | 18 | 7 |
| ID25 | 21 Feb 97 | 737 | 1 | 17 | FR | 0 | -4 | 2 | 8 | 35 | 7 |
| ID26 | 21 Feb 97 | 737 | 1 | 25 | FR | 0 | -2 | 2 | 12 | 45 | 7 |
| ID30 | 6 Mar 97 | F100 | 1 | 8 | S | 16 | -3 | 6 | 11 | 35 | 7 |
| ID31 | 6 Mar 97 | F100 | 1 | 6 | S | 17 | -4 | 6 | 6 | 45 | 7 |
| ID32 | 6 Mar 97 | F100 | 1 | 16 | S | 20 | -4 | 6 | 4 | 16 | 7 |
| ID33 | 6 Mar 97 | F100 | 1 | 16 | S | 20 | -4 | 6 | 9 | 22 | 7 |
| ID5 | 22 Jan 97 | 737 | 1 | 7 | IP | 10 | -8 | 2 | 4 | 12 | 7 |
| ID6 | 22 Jan 97 | 737 | 1 | 10 | IP | 9 | -8 | 2 | 7 | 12 | 7 |
| ID8 | 22 Jan 97 | 737 | 1 | 26 | IP | 9 | -9 | 2 | 11 | 20 | 7 |
| L1 | 24 Feb 95 | DC9 | 1 | 11 | S | 2 | 0 | 6 | 9 | 23 | 2 |
| L2 | 6 Mar 95 | DC9 | 1 | 21 | S | 15 | -7 | 6 | 8 | 25 | 7 |
| L5 | 6 Mar 95 | DC9 | 1 | 6 | S | 10 | -7 | 6 | 20 | 90 | 2 |
| L8 | 9 Mar 95 | DC9 | 1 | 9 | S | 12 | -7 | 6 | 5 | 25 | 2 |
| L9 | 9 Mar 95 | DC9 | 1 | 6 | S | 9 | -7 | 6 | 8 | 22 | 2 |
| Q3 | 28 Jan 97 | 737 | 1 | 21 | S | 10 | -7 | 6 | 3 | 15 | 7 |
| L7 | 9 Mar 95 | DC9 | 2 | 9 | S | 8 | -7 | 20 | 20 | 90 | 2 |
| ID13 | 28 Jan 97 | 737 | 4 | 18 | S | 6 | -15 | 30 | 36 | 150 | 7 |
| ID17 | 28 Jan 97 | 737 | 4 | 14 | S | 5 | -17 | 30 | 21 | 80 | 7 |
| ID18 | 5 Feb 97 | F100 | 4 | 19 | S | 11 | -2 | 45 | 24 | 90 | 7 |
| ID19 | 5 Feb 97 | F100 | 4 | 17 | S | 9 | -2 | 45 | 9 | 110 | 7 |
| ID29 | 6 Mar 97 | F100 | 4 | 8 | S | 17 | -4 | 35 | 27 | 100 | 7 |
| ID34 | 6 Mar 97 | F100 | 4 | 33 | S | 20 | -5 | 35 | 12 | 65 | 7 |
| ID35 | 6 Mar 97 | F100 | 4 | 35 | S | 20 | -5 | 35 | 15 | 60 | 7 |
| ID7 | 22 Jan 97 | 737 | 4 | 26 | IP | 9 | -9 | 30 | 7 | 45 | 7 |
| Q1 | 28 Feb 96 | DC9 | 4 | 11 | FR | 9 | -1 | 30 | 50 | 120 | 7 |
| Q2 | 28 Feb 96 | DC9 | 4 | 17 | FR | 11 | -1 | 30 | 50 | 120 | 7 |

Notes:

1. All test numbers except Q1, Q2, and Q3 were those used by APS (4),(14)
2. Precipitation type: S=snow, FD=freezing drizzle, FR=light freezing rain, IP=ice pellets
3. Last time for which the areas of fluid failure were recorded usually corresponded to when most or all of the wing area had failed.
4. When data was only recorded on two sections, data was also recorded on one or two representative sections. In all cases, data was recorded on the leading and trailing edges and each middle section.

# Appendix B

# Rating the View of the Wing for Different Aircraft

## View Rating of Different Sections of The Wing

Ratings assigned based on photographs of the wing from the cabin and cockpit (and rear doorway of ATR 42)

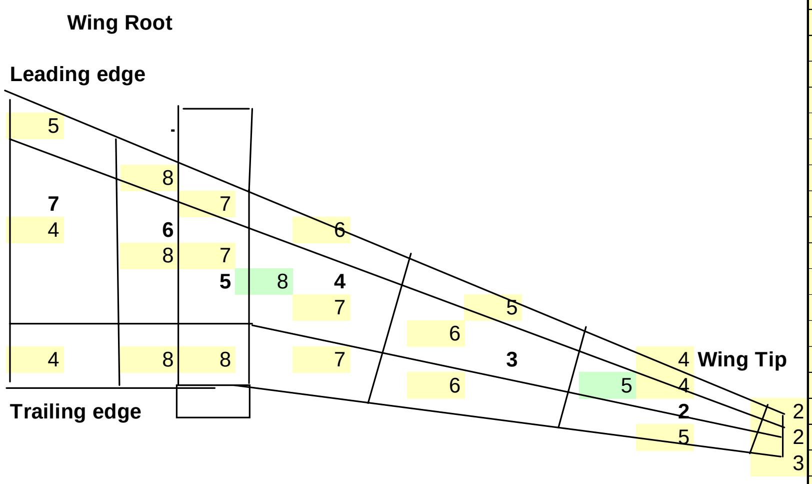
| Wing Section | B737 | DC9 | A320 | B146 | F28 | RJ | DHC8 | ATR42 | J31 | **Low Wing** | **High Wing** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7L | 5 | 5 | 5 | 0 | 4 | 0 | 2 | 3 | 0 | **5** | **2** |
| 7M | 4 | 5 | 5 | 0 | 4 | 0 | 0 | 4 | 0 | **5** | **0** |
| 7T | 4 | 5 | 5 | 0 | 4 | 0 | 0 | 6 | 0 | **5** | **0** |
| 6L | 8 | 8 | 7 | 3 | 8 | 0 | 5 | 6 | 0 | **8** | **5** |
| 6M | 8 | 8 | 8 | 0 | 8 | 0 | 0 | 0 | 0 | **8** | **0** |
| 6T | 8 | 8 | 8 | 0 | 8 | 0 | 0 | 6 | 0 | **8** | **0** |
| 5L | 7 | 7 | 6 | 6 | 7 | 0 | 5 | 4 | 0 | **7** | **5** |
| 5M | 7 | 7 | 7 | 0 | 7 | 0 | 0 | 0 | 0 | **7** | **0** |
| 5T | 8 | 8 | 7 | 0 | 7 | 0 | 4 | 5 | 0 | **8** | **2** |
| 4L | 6 | 6 | 5 | 5 | 6 | 0 | 0 | 0 | 0 | **6** | **2** |
| 4M | 7 | 6 | 6 | 0 | 6 | 0 | 0 | 0 | 0 | **6** | **0** |
| 4T | 7 | 7 | 6 | 0 | 6 | 0 | 0 | 5 | 0 | **7** | **0** |
| 3L | 5 | 5 | 4 | 4 | 5 | 0 | 3 | 3 | 0 | **5** | **3** |
| 3M | 6 | 6 | 5 | 0 | 5 | 0 | 0 | 0 | 0 | **6** | **0** |
| 3T | 6 | 6 | 5 | 0 | 5 | 0 | 3 | 4 | 0 | **6** | **2** |
| 2L | 4 | 4 | 3 | 2 | 4 | 0 | 3 | 3 | 0 | **4** | **3** |
| 2M | 4 | 4 | 3 | 0 | 4 | 0 | 0 | 0 | 0 | **4** | **0** |
| 2T | 5 | 5 | 4 | 0 | 4 | 0 | 3 | 4 | 0 | **5** | **2** |
| 1L | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 0 | **2** | **2** |
| 1M | 2 | 2 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | **2** | **0** |
| 1T | 3 | 3 | 3 | 0 | 2 | 0 | 0 | 3 | 0 | **3** | **0** |
| 2R | 6 | 6 | 5 | 3 | 6 | 0 | 3 | 5 | 0 | **6** | **4** |
| 4R | 8 | 8 | 7 | 5 | 8 | 0 | 5 | 7 | 0 | **8** | **6** |

### View Ratings Used

| | | | |
|---|---|---|---|
| 9 | Extremely good | 4 | Poor |
| 8 | Very good | 3 | Poor-very poor |
| 7 | Good | 2 | Very poor |
| 6 | Fair | 1 | Extremely poor |
| 5 | Fair-poor | 0 | No view |

Comments on the assigning of ratings of each aircraft are given below.

**Aircraft Type: B737**



| Section | Rating | Comment |
|---|---|---|
| 7L | 5 | No view near wing root, slightly more on LE |
| 7M | 4 | slightly distored view at edge of window |
| 7T | 4 | very good view on most parts visible |
| 6L | 8 | Very good view, also good from cockpit with window open (un-obsured by fluid |
| 6M | 8 | Very good view<br>on window) |
| 6T | 8 | Very good view |
| 5L | 7 | Good view |
| 5M | 7 | Very good view, still close to this section |
| 5T | 8 | Downward slope of wing improves view |
| 4L | 6 | Distance and angle of incidence becomes a factor |
| 4M | 7 | |
| 4T | 7 | Slope & shorter distance to trailing section gives better view than LE |
| 3L | 5 | |
| 3M | 6 | |
| 3T | 6 | |
| 2L | 4 | |
| 2M | 4 | |
| 2T | 5 | |
| 1L | 2 | Angle of incidence and distance make view poor |
| 1M | 2 | Middle section similar-slightly better |
| 1T | 3 | View of trailing edge significantly better than leading edge |
| 2R | 6 | |
| 4R | 8 | |

Wing section # is given in bold, ratings assigned for each section are highlighted

| Aircraft Type: | **A320** | |
|---|---|---|
| Section | Rating | Comment |
| 7L | 5 | |
| 7M | 5 | |
| 7T | 5 | |
| 6L | 7 | View of leading edge not as good as middle & trailing sections |
| 6M | 8 | |
| 6T | 8 | |
| 5L | 6 | |
| 5M | 7 | |
| 5T | 7 | |
| 4L | 5 | |
| 4M | 6 | |
| 4T | 6 | |
| 3L | 4 | |
| 3M | 5 | |
| 3T | 5 | View of trailing section remains good due to slope of wing |
| 2L | 3 | |
| 2M | 3 | |
| 2T | 4 | |
| 1L | 2 | |
| 1M | 2 | |
| 1T | 3 | Angle of incidence & distance worse than 737 |
| 2R | 5 | |
| 4R | 7 | |

| Aircraft Type: | **F28** | |
|---|---|---|
| Section | Rating | Comment |
| 7L | 4 | Cannot see near wing root |
| 7M | 4 | |
| 7T | 4 | |
| 6L | 8 | |
| 6M | 8 | |
| 6T | 8 | |
| 5L | 7 | Slope of LE improves view |
| 5M | 7 | |
| 5T | 7 | |
| 4L | 6 | |
| 4M | 6 | |
| 4T | 6 | View of trailing edge no better than leading edge |
| 3L | 5 | |
| 3M | 5 | |
| 3T | 5 | |
| 2L | 4 | |
| 2M | 4 | |
| 2T | 4 | Part of section hidden by aileron |
| 1L | 2 | Angle of incidence is much worse at wing tip |
| 1M | 2 | |
| 1T | 2 | |
| 2R | 6 | |
| 4R | 8 | |

| Aircraft Type: | | **DC9** |
|---|---|---|
| Section | Rating | Comment |
| 7L | 5 | |
| 7M | 5 | |
| 7T | 5 | |
| 6L | 8 | |
| 6M | 8 | |
| 6T | 8 | |
| 5L | 7 | |
| 5M | 7 | |
| 5T | 8 | View remains very good |
| 4L | 6 | |
| 4M | 6 | |
| 4T | 7 | |
| 3L | 5 | Due to angle of incidence remains quite good on LE |
| 3M | 6 | |
| 3T | 6 | |
| 2L | 4 | Due to shorter distance & better angle of incidence view better than most a/c |
| 2M | 4 | |
| 2T | 5 | |
| 1L | 2 | Poor angle of incidence at wing tip |
| 1M | 2 | |
| 1T | 3 | |
| 2R | 6 | |
| 4R | 8 | |

| Aircraft Type: | | **BAe146** |
|---|---|---|
| Section | Rating | Comment |
| 7L | 0 | No view, assumes pilot does **not** open front door to view wing |
| 7M | 0 | |
| 7T | 0 | No view of top edge, assumes pilot does **not** open back door to view wing |
| 6L | 3 | Very good view of lower part of actual LE, but not of LE section |
| 6M | 0 | |
| 6T | 0 | No view of top edge |
| 5L | 6 | Good view of curve near top of engine where fluid is likely to fail |
| 5M | 0 | |
| 5T | 0 | No view of top edge |
| 4L | 5 | Section hidden by engine |
| 4M | 0 | |
| 4T | 0 | No view of top edge |
| 3L | 4 | Good view of actual LE, but not of LE section, part of section hidden by engine |
| 3M | 0 | |
| 3T | 0 | No view of top edge |
| 2L | 2 | Section not hidden by engine, but only view of very front of LE is good |
| 2M | 0 | |
| 2T | 0 | No view of top edge |
| 1L | 2 | Similar to section 2L, but slightly worse |
| 1M | 0 | No view |
| 1T | 0 | No view of top edge |
| 2R | 3 | |
| 4R | 5 | |

| Aircraft Type: | **ATR 42** | |
|---|---|---|
| Section | Rating | Comment |
| 7L | 3 | No view near wing root, excellent view of only actual edge |
| 7M | 4 | Assume Pilot opens back door to view TE and top of a/c |
| 7T | 6 | Excellent view of part of TE section, un-obsured by fluid on window |
| 6L | 6 | Excellent view of actual LE, but not of whole LE section |
| 6M | 0 | No view of this section |
| 6T | 6 | Same of section 7T |
| 5L | 4 | Good view of curve near top of engine where fluid is likely to fail |
| 5M | 0 | No view of this section |
| 5T | 5 | Unobsured view on part of TE sections that typically fail first |
| 4L | 0 | No view of this section |
| 4M | 0 | No view of this section |
| 4T | 5 | Unobsured view on part of TE sections that typically fail first |
| 3L | 3 | Good view of actual LE, but not of LE section, part of section hidden by engine |
| 3M | 0 | No view of this section |
| 3T | 4 | Angle of incidence starting to affect view |
| 2L | 3 | Section not hidden by engine, but only view of very front of LE is good |
| 2M | 0 | No view of this section |
| 2T | 4 | View similar, but slightly worse, than section 3T |
| 1L | 2 | |
| 1M | 0 | No view of this section |
| 1T | 3 | |
| 2R | 5 | |
| 4R | 7 | |

| Aircraft Type: | **DH 8** | |
|---|---|---|
| Section | Rating | Comment |
| 7L | 2 | Most not visible, assumes pilot does **not** open door to view wing |
| 7M | 0 | |
| 7T | 0 | No view of top edge |
| 6L | 5 | Very good view of lower part of actual LE, but not of LE section |
| 6M | 0 | |
| 6T | 0 | No view of top edge |
| 5L | 5 | Good view of curve near top of engine where fluid is likely to fail |
| 5M | 0 | |
| 5T | 4 | View of sides near top of rear part of engine |
| 4L | 0 | Section hidden by engine |
| 4M | 0 | |
| 4T | 0 | No view |
| 3L | 3 | Good view of actual LE, but not of LE section, part of section hidden by engine |
| 3M | 0 | |
| 3T | 3 | Assumes flaps are deployed to view TE |
| 2L | 3 | Section not hidden by engine, but only view of very front of LE is good |
| 2M | 0 | |
| 2T | 3 | Assumes flaps are deployed to view TE |
| 1L | 2 | As for section 2L, but worse |
| 1M | 0 | No view |
| 1T | 0 | No view |
| 2R | 3 | |
| 4R | 5 | |

# Appendix C

# Assumptions

# ASSUMPTIONS

The modelling of any real life process requires assumptions to be made about how the process will proceed in different situations. This is particularly true for human processes such as visual observation of the condition of the wing that rely on qualitative assessments of situations. The lack of complete data on the varying conditions under which the process takes place and on responses to those conditions necessitates further assumptions. Finally, assumptions are required to reduce the complexity of a situation so that it can be modelled.

The assumptions are critical to the accuracy of the final results and it is important to understand what assumptions have been made and their possible affect of the final results. The major assumptions in determining the risks, the reason for the assumption and their likely effect, are given below for the different part of the risk analysis. These assumptions were drawn largely from those given in the previous report (1), but assumptions made in the new aspects of the analysis are also given. Section 5.4.3 considers the sensitivity of the estimates of comparative risk to many of these assumptions.

## *Estimation of Probabilities of HOT Expiry, Fluid Failure and False Alarms*

The assumptions in this section relate to the probabilities of fluid failure, HOT expiring and of false alarms occurring. The sensitivity analysis (Section 5.4.3) indicates that the comparative risks of sensor versus visual based inspection are insensitive to the probabilities of fluid failure.

- Distributions of fluid application, taxi plus delay times for large and small airports follow those given in Section 4.2.
  - ◊ 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 HOT expiry and fluid failures.

- 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 probabilities of fluid failure and HOT expiring 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 in form required 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.

### *Contamination of Wing at Take-off*

- 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 examined in the sensitivity analysis is significant, especially for estimates using Type IV fluid, but is not critical to the overall analysis. Results for specific aircraft types may differ.

- 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 with point sensors 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 of location of sensors and will affect the percentage of wing area with failed fluid, weighted by criticality and, thus, the

estimated risks. Use of higher criticality factor for the middle and trailing edge sections would lower the estimated risks with visual inspection due to the slightly better view of those sections than the leading edge. However, effect is likely small.

- 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 I fluids and 5 minutes for anti-icing fluids.
  - ◊ Reason: Lack of data available for estimating a distribution; 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: small as estimated risks were found to be insensitive to the mean value.

***Estimation of Risks – Point Sensors***

- 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 outside weather conditions.
  - ◊ Effect: may lead to over- or underestimates of the risks – effect likely small.
- Sensors are located on the part of the wing section where early failure of the fluid typically occurs over a range of aircraft types – optimal placement of sensors for a particular aircraft type is not assumed.
  - ◊ Reason: Sensors would be installed, where possible, in areas that minimize the risk. However, it may not be possible to mount sensors in some areas, such as the flaps and slats, due to size and space limitations. Due to lack of data on individual aircraft types, optimal placement of sensors for a particular type could not be analyzed.
  - ◊ Effect: Risks would be overestimated by not optimizing the location of sensors for particular aircraft types. However, it may not be possible to locate the sensors in the areas of earliest fluid failure on a particular wing section. The two effects will offset each other in the analysis. Sensitivity analysis on the consistency of the location of early failure indicates that this assumption likely has a moderate effect on the estimated risks, but is not critical to the analysis.
- The likelihood of a sensor identifying fluid failure on a section is related to the consistency of the location of early fluid failure on that section. The consistency varies over the different sections of the wing and tends to be high on the leading edge sections, medium on the trailing edge sections and low on the middle sections.
  - ◊ Reason: the limited data on fluid failure and data on the depths of fluid indicate these levels of consistency.
  - ◊ Effect: over estimation of consistency will lead to underestimates of the risks with sensors – sensitivity analysis indicated effect is moderate, but not critical to the analysis.

- Risks for a complete aircraft with a sensor system that 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 will likely to be small as the difference in risks between modelling one wing and both wings was found to be small. The comparative risks of visual and sensor-based inspection where the sensor system has sensors on the tail was not considered.

### *Visual Identification of Fluid Failure*

- The ability of the pilot to correctly identify fluid failure from within the aircraft is reflected by the probabilities shown in Figure 3.2.
    - ◊ Reason: lack of good test data on visual identification of fluid failure from the cabin, only limited data under very good viewing conditions is available.
    - ◊ Effect: may lead to under- or overestimates of risks – sensitivity analysis indicates effect is moderate, but not critical to the analysis.
- The view ratings in Table 3.1, together with the hypothetical probabilities shown in Figure 3.2, provide good estimates of the probability of the pilot identifying fluid failure on specified sections of the wing from inside the aircraft during typical daytime viewing conditions.
    - ◊ Reason: Required to analyse risks of combined visual and sensor-based systems and no data available on accuracy of identifying fluid failure on particular wing sections.
    - ◊ Effect: may lead to under- or overestimates of risks – sensitivity analysis indicates effect is moderate, but not critical to the analysis.
- 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 – again, sensitivity analysis indicates effect is moderate, but not critical to the analysis.
- 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 of the fluid).
    - ◊ Reason: As discussed in Section 3.1 (and Sections 4.1 and 6.2 of the previous report (1)), the relationship between initial visual fluid failure and aerodynamic performance is uncertain. Delays between visual failure and adhesion during freezing rain of 1 minute for Type I fluid and 5 minutes for Type IV fluid have been reported (13), but little data is available for other precipitation types and no clear relationships are indicated.

  - ◊ 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. Sensitivity test indicates that for Type I fluid the effect on comparative risk is likely small, but for Type IV fluid effect is moderate but not critical to the analysis.

*Returning to Re-deice Based on HOT, Delay and Weather Conditions*

- Misclassification of fluid failure is closely linked to allowance for HOT, delay and weather conditions. In very good viewing conditions the frequency of returns due to HOT, delay and weather conditions would be minimal and the proportion returning would equal the misclassification rate under very good conditions (25-30%). In worse viewing conditions, the proportion of pilots returning due to premature misclassification of fluid failure would increase in line with the conservatism of pilots in these conditions.
  - ◊ Reason: Lack of data on the exact form of the relationship between visual misclassification of fluid condition and HOT, delay and weather conditions.
  - ◊ Effect: may lead to an under or over estimate of the probability of misclassification. Minor effect on the comparative risk, but significantly affects the false alarm rate using visual inspection.
- The proportion of pilots that will return to re-deice (or call for a tactile check) is assumed to increase as the viewing conditions get worse, the delay in time to take-off increases (in relation to the HOT range); the precipitation rate increases; and the wind speed increases. The relationship between the proportion of pilots returning and HOT, delay and weather conditions are well represented by those given in Figure 3.3.
  - ◊ Reason: Lack of data on the exact form of the relationship between returning to re-deice and HOT, delay and weather conditions.
  - ◊ Effect: may lead to an under or over estimate of the risks with visual inspection when allowing for HOTs. Allowance for HOTs would be expected to have little effect on risks in very good viewing conditions. The risks are very sensitive to this assumption in poor viewing conditions where risks are brought down to comparable levels to good viewing conditions.

# Appendix D

# Assigning Probabilities of Returning Based on HOT, Delay and Weather Conditions

# Assigning Probabilities of Returning Based on HOT, Delay and Weather Conditions

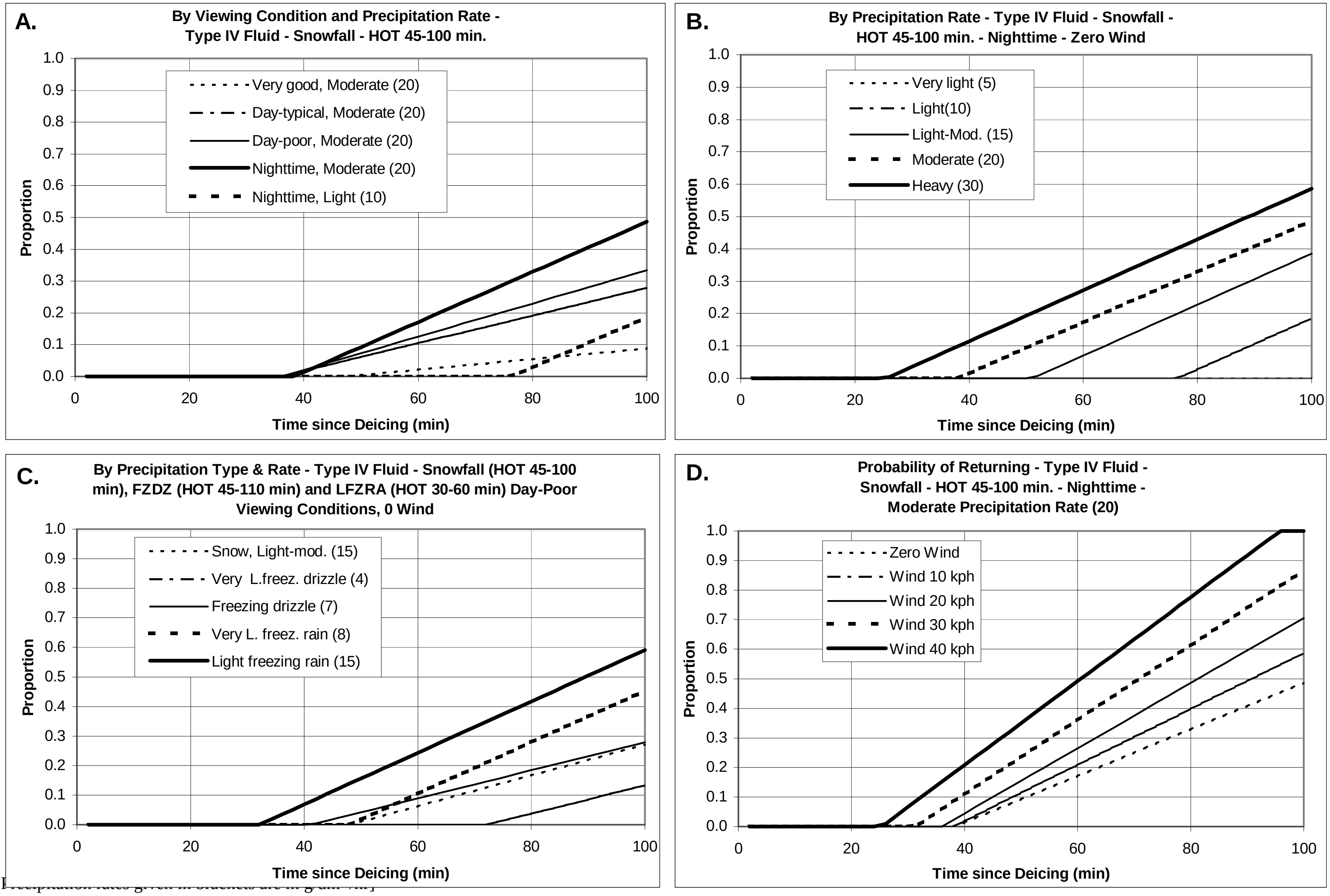
The proportion of pilots that are assumed to return to re-deice (or call for a tactile check) are is estimated using the following expression:

$$P[\text{Return}] = \{ (t - \frac{b \times \text{HOTlow} \times (\text{Precip0}/\text{Precip})}{((1+\text{Wind}/wc)^{e}) / \text{Ptype}) / (c \times \text{HOTup} \times (1+\text{Wind}/wc)} \} ^{\text{DN}}$$

| | |
|---|---|
| where t | is the time since commencement of the final application of fluid; |
| HOTlow | is the lower value of the applicable HOT; |
| HOTup | is the upper value of the applicable HOT; |
| Precip | is the precipitation rate in g/dm$^2$/h; |
| Precip0 | is a constant dependent on the type of precipitation: |
| | = 10 for snowfall |
| | = 6 for freezing drizzle |
| | = 15 for light freezing rain |
| Ptype | is a constant to allow for the effect of precipitation type on the pilots confidence in identifying fluid failure: |
| | = 1.5 for freezing drizzle and light freezing rain |
| | 1.0 otherwise |
| Wind | is the wind speed in km/h; |
| wc | is a constant set equal to 50; |
| e | i s a constant set equal to 3; |
| DN, c and b | are constants dependent on the viewing conditions (see table below); |

| Viewing Condition | Values of Factors Used | | |
|---|---|---|---|
| | DN | c | b |
| Very Good | 0.2 | 1.2 | 2.1 |
| Day-Typical | 0.4 | 0.92 | 1.6 |
| Day-Poor | 0.6 | 1.15 | 1.6 |
| Night | 1 | 1.27 | 1.7 |

The estimated proportions of pilots returning/calling for tactile check under various conditions are shown in Figure 3.3 using Type I fluid and similar estimates using Type IV fluid are given in Figure D1.



[Precipitation rates given in brackets are in g/dm$^2$/hr]

**Figure D1** **Proportions of Pilots that Would Return to Re-deice or Call for a Tactile Check Based on HOT Under Various Conditions Using Type IV Fluid – Hypothetical Relationships Used in Analysis**

# Appendix E

# Alternative Estimation of False Alarm Rate in Very Good Viewing Conditions

# Alternative Estimation of False Alarm Rate in Very Good Viewing Conditions

To confirm that the estimates of the false alarm rate under very good viewing conditions given in Table 6.1 are reasonable, a rough, more simplistic approach was used. This approach is outlined below.

| Probability | Denoted by | Approx. Value |
|---|---|---|
| Probability of pre-take-off inspections taking place | Pin | 15% |
| Error rate in visual inspection in very good viewing conditions (i.e., identifying fluid failure when not failed) | Perr | 25% |
| % of pre-take-off inspections where fluid has failed | Piff | 10% |
| Probability of identifying a fluid that has failed at pre-take-off Inspection given it has failed by that time (very good viewing) | Pid | 45% |
| Given a pre-take-off inspection was done, probability of fluid failing after the inspection and before take-off | Pitff | 15% |
| % of deicings which result in false alarms at time of inspection | Pfai = Pin (1 - Piff) Perr | 3.4% |
| % of deicings that result in false alarms at time of take-off | Pfa = Pfai (1 - Pitff) | 2.9% |
| % of deicings that result in returns due to correct ID of fluid failure | Pcid = Pin Piff Pid | 0.68% |
| % of deicings that result in returns that are false alarms at time of inspection, but where fluid fails between pre-take-off inspection & take-off | Pcfa = Pfai Pitff | 0.51% |
| % of deicings that result in returns where fluid has failed | Pcor = Pcid + Pcfa | 1.2% |
| Estimated False alarm rate under very good viewing conditions | Pfa / (Pfa + Pcor) | 71% |

Using this rough approach a slightly higher false alarm rate was found than in Section 6. The percentages used are only approximate and are used only to demonstrate the expected order of magnitude of the false alarm rate.