# Aviation Safety Issues Investigation Report SII A05-01

**Safety issues investigation report SII A05-01**
Post-impact fires resulting from small-aircraft accidents

## Executive Summary

### Introduction

For aircraft with a maximum certified take-off weight of 5700 kilograms (12 566 pounds) or less, post-impact fire (PIF) contributes significantly to injuries and fatalities in accidents that are otherwise potentially survivable. A potentially survivable accident is one in which the impact forces are within the limits of occupant tolerance, the aircraft structure preserves the required survival space, and the occupant restraint is adequate.

This investigation examined Transportation Safety Board of Canada (TSB) data and the history of PIF safety action to become more informed and to provide discussion material with the intent of mitigating risks surrounding PIF in small aircraft, specifically regarding design certification. The historical incidence of PIF occurrences in aircraft weighing less that 5700 kilograms demonstrates a high probability of future similar occurrences, resulting in adverse human consequences, if current design standards are not addressed.

### Statement of the Problem

PIF continues to contribute to injuries and fatalities in otherwise survivable accidents involving small aircraft. Both the National Transportation Safety Board (NTSB) and the Federal Aviation Administration (FAA) of the United States have attempted to address this issue through special studies and Notices of Proposed Rule Making.

In 1994, amendments to the United States *Federal Aviation Regulations* (FARs) introduced comprehensive fuel system crash resistance certification standards for normal and transport category helicopters to minimize the hazard of fuel fires to occupants following otherwise survivable impacts. Technology and design concepts intended to reduce the incidence of PIF have been demonstrated to be effective in helicopter, race car, and automotive applications. However, there is no requirement to incorporate these countermeasures into new or existing small aeroplane types or into small helicopters certified before November 1994.

### Scope of the Project

The selection criteria for this investigation were accidents that occurred in Canada between 1976 and 2002 inclusive, that involved powered, small aircraft, and that resulted in PIF. The investigation reviewed TSB PIF statistics, the history of PIF, existing certification requirements, currently available PIF prevention technology, survivability thresholds, cost-benefit analysis barriers, retrofitting of existing types, and potential future design requirements.

### Methods

The investigation identified 521 PIF accidents listed in the TSB Aviation Safety Information System (ASIS) database. Cause of death statements were reviewed on available autopsy reports, coroners' reports, and registrations of death to determine if fire had contributed to fatalities. Additional data sources were reviewed to determine if fire had contributed to serious injuries. Of the 521 accidents, 128 were accidents in which fire or smoke inhalation was identified as either partly or solely the cause of death or serious injury. An extensive research of past actions by the FAA, the NTSB, and the TSB regarding PIF safety issues was conducted. As well, a detailed examination of a cost-benefit analysis conducted by the FAA in response to previous NTSB recommendations was reviewed.

## Results

In all 128 accidents in which PIF contributed to serious injuries or fatalities, the aircraft occupants were in close proximity to fire or smoke for some time following the impact. The investigation identified four conditions that were essential for this to occur.

- There was an ignition source in proximity to a combustible material, such as fuel.
- There was combustible material in close proximity to the occupants.
- Occupant egress was compromised.
- The fire was not suppressed in time to prevent fire-related injuries or fatalities.

The data collected and analysed indicate that there is a significant risk for PIF with fire-related injuries and fatalities in small-aircraft accidents. Furthermore, information examined shows that past attempts to change certification requirements have been unsuccessful, largely because of insufficient data, which resulted in cost-benefit analysis conclusions that negated the proposed safety action.

## Conclusions

The defences to prevent PIF and to reduce fire-related injuries should fire occur in otherwise survivable accidents involving aircraft weighing less than 5700 kilograms can and should be improved. PIF presents a great risk to the occupants of small aircraft because of

- the high volatility of aviation fuel;
- the close proximity of fuel to occupants;
- the limited escape time;
- the limited energy-absorption characteristics of small-aircraft airframes in crash conditions;
- the high propensity for immobilizing injuries; and
- the inability of airport firefighters and emergency response personnel to suppress PIFs in sufficient time to prevent fire-related injuries and fatalities.

Volatile liquid fuel is the combustible material of greatest significance in PIF accidents. Considering the propensity for rapid propagation and the catastrophic consequences of fuel-fed PIF, the most effective defence against PIF is to prevent the fire from occurring at impact, either by containing fuel or preventing ignition, or both.

The benefits of PIF-resistant fuel system technology have been proven in land vehicle applications and, recently, in certified civilian helicopter applications. A requirement for similar engineering countermeasures in existing, newly manufactured and newly certified FAR 23 and equivalent small aeroplanes, existing small helicopters, amateur-built aircraft, and basic and advanced ultralights would reduce the incidence of fire-related serious injuries and fatalities in otherwise survivable accidents, and could significantly increase the rate of occupant survival.

The implication of design improvements on new aircraft will be significant, and even more significant on existing designs. Enhancing current design standards will require considerable effort by Transport Canada and the FAA, and cooperation by their international counterparts to ensure harmonization of any new standards and guidelines.

*Ce rapport est également disponible en français.*


Cat. No. TU4-18/1-2006E
ISBN 0-662-43937-6.

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## NOTE

The following documents were prepared for or used in the preparation of this report. All of the listed documents are available upon request from the Transportation Safety Board.

| | |
|---|---|
| Document 1 | *A Review of the Process of Economic Analysis into Risk Control Options for Mitigation of Post-Impact Fire Risks for Aircraft with a Maximum Certified Take-off Weight of 5670 Kilograms or Less* |
| Document 2 | Microsoft Excel spreadsheet of all accident information used to prepare Appendix A |
| Document 3 | Chronology of Typical Post-Impact Fire Accidents |
| Document 4 | Excerpt from Simula Technologies *Small Airplane Crashworthiness Design Guide*, Chapter 10: Post-Crash Factors |
| Document 5 | Excerpt from Simula Technologies *Small Airplane Crashworthiness Design Guide*, Fuel System Design Checklist |

# 1.0 Introduction

## 1.1 Background

On 30 May 2000, the pilot of a Cessna 177B Cardinal was attempting to take off from a grass airstrip at Calling Lake, Alberta. The aircraft struck trees during the initial climb, struck the ground, and burst into flame. The two occupants were exposed to smoke and flame for some time. One occupant was fatally injured due to the effects of fire, and one sustained serious burns. The investigation was completed and a public report issued (A00W0109).

The accident investigation identified fuel system crashworthiness as a small-aircraft[1] safety deficiency. In light of that finding, the Board identified a need to examine the extent to which fuel system crashworthiness and other safety deficiencies contribute to the risks associated with post-impact fire (PIF)[2] in otherwise survivable accidents,[3] and to consider the risk control options available to mitigate those risks.

According to TSB data from 1976 to 2002, PIF occurs in approximately 4 per cent of accidents involving small aircraft; however, these accidents account for approximately 22 per cent of the fatalities and 11 per cent of the serious injuries caused by all accidents. Overall, 6.2 per cent of fatal injuries and 3.8 per cent of serious injuries that resulted from small-aircraft PIF accidents were related to fire. Because small aircraft have a higher accident rate with a correspondingly greater number of PIF accidents, more defences are required to mitigate the risk of PIF. Considering these factors, the Board identified the need to conduct a Safety Issues Investigation.[4]

## 1.2 Objectives and Expected Benefits of the Safety Issues Investigation

The objective of this Safety Issues Investigation is to advance aviation safety by examining TSB data on small-aircraft accidents to identify the safety deficiencies that contribute to PIF and to fire-related injuries and fatalities in otherwise survivable accidents. It is also the objective of this investigation to identify the control options for mitigating risks associated with small-aircraft accidents.

The expected benefits are as follows:

- increased awareness of the incidence and effect of PIF in otherwise survivable accidents;
- increased awareness of the necessity to thoroughly investigate and document the pathological and technical aspects of PIF occurrences;
- increased awareness of the practical methods of reducing the incidence of PIF; and
- proposals to effect industry and/or regulatory changes, as required, to reduce or eliminate the risks associated with PIF in small aircraft.

## 1.3 Methodology - Data Collection and Analysis

### 1.3.1 Procedures

The investigation examined accidents that occurred in Canada from 1976 to 2002 that involved powered, small aircraft and that resulted in PIF. The data sources were the TSB Aviation Safety Information System (ASIS) database and the relevant occurrence files and public reports. The investigation reviewed the history of PIF, existing certification requirements, currently available PIF prevention technology, survivability thresholds, cost-benefit analysis barriers, retrofitting of existing types, and potential future design requirements. It also reviewed related studies by the

United States Federal Aviation Administration (FAA) and National Transportation Safety Board (NTSB), and recently published journal papers (see Appendix B).

Two transportation economists in the Department of Economics at the University of Alberta were contracted to examine the current process of aviation economic analysis, including cost-benefit analysis (CBA). They also assessed the effect of that process on decision making in the application of risk control options that are available to mitigate PIF risks. The report, *A Review of the Process of Economic Analysis into Risk Control Options for Mitigation of Post-Impact Fire Risks for Aircraft with a Maximum Certified Take-off Weight of 5670 Kilograms or Less* (Document 1), reviewed the process of economic analysis followed in the United States to assess aviation safety measures. It also offered a preliminary analysis of the potential benefits of PIF risk control measures in terms of lives saved in Canada.

### 1.3.2 Data Collection

A total of 521 PIF accidents involving small aircraft occurred between 1976 and 2002 inclusive. They were identified by querying the TSB ASIS database, and by word searching and reviewing occurrence summaries and final public reports. The extent to which fire contributed to fatalities was determined solely by reference to cause of death statements on available autopsy reports, coroners' investigation statements, and/or registrations of death.[5]

Fire-related serious injuries were identified by a review of occurrence summaries, final reports, investigator notes, and/or newspaper clippings.

Core data for these 521 PIF accidents were collected (Document 2) and analysed to identify those accidents in which fire had contributed to injuries and fatalities (see Appendix A). Fire was determined to have contributed to injuries or fatalities in 128 of these accidents. Those 128 accident files were assembled into a fire injury/fatality data subset. All the occurrence data in this data subset were reviewed to identify the common unsafe conditions that either did or did not definitely contribute to the fire-related injuries and fatalities. The data were captured by a file-by-file examination and entered onto an Excel spreadsheet. Within occurrences, the contributions of some common unsafe conditions were unknown or could not be determined.

Fourteen out of the 128 occurrence files were randomly selected for examination by each of three investigators, and the results were compared to measure inter-rater reliability. There were no disagreements between the three raters regarding identification of the unsafe conditions in those 14 files; that is, no condition was rated present by one rater and absent by another. The remaining 114 files in the data subset were each examined once, by one investigator, who recorded the data.

### 1.3.3 Data Constraints

The following data collection constraints resulted in incomplete data:

- Some records in the TSB ASIS database lacked any reference to PIF in the Events or Summary fields.
- Some archived occurrence files were incomplete, most notably missing victim autopsies or injury descriptions.
- Some occurrence files were missing from older (pre-1982) archives.
- The TSB does not investigate Class 5[6] occurrences.
- Accident characteristics, and injury and survival information are rarely recorded in the ASIS database.

While the full contribution of PIF to fatalities and serious injuries is likely underestimated, several additional sources of bias likely distort the record of unsafe conditions associated with the accidents in this data subset. Therefore, direct comparisons of the frequency of these conditions should be cautiously interpreted if used to determine the most important contributing unsafe conditions. The following are some sources of bias.

- The unsafe conditions that are easiest to detect or identify will appear to be more prevalent, possibly inflating their importance.
- The contribution of some unsafe conditions may be under-represented relative to other unsafe conditions, precluding direct comparison. If they were known, some unsafe conditions might be "did not contribute" while others might be "contributed."
- The meaning of "did not contribute as an unsafe condition" varies, so those frequencies cannot be directly compared (for example, if hydraulic fluid was not the "primary combustible," should it be designated "did not contribute"?). Because the data subset was assembled from many accident records that were compiled over many years by different investigators, the absence of data regarding an unsafe condition may indicate either that its contribution was unknown or that it was not applicable. Further, it is not clear that the designation "not applicable" is different from "did not contribute."
- Before 1991, air accident investigators used a multi-page, hard copy investigation report form containing unsafe condition check-boxes based on International Civil Aviation Organization definitions (that is, page 14, Survival Data; page 15, Fire Data). Consequently, unsafe conditions associated with PIF were more extensively reported before 1991 (particularly ignition sources). Data recorded before 1991 may over-represent these unsafe conditions because investigators were prompted by the reporting form. Furthermore, data recorded after 1991 may under-represent unsafe conditions because investigators were not prompted to check for additional unsafe conditions that may have been present.
- As noted above, the original data were recorded by many different investigators over a considerable period of time, within the context of their own perceptions of salient unsafe conditions. That context is unavailable to the Safety Issues Investigation team.
- For many accidents, more than one related unsafe condition (ignition sources in particular) was recorded as contributory and ascribed equal causal likelihood in the occurrence, inflating the apparent prevalence of the less likely unsafe condition.

A request was forwarded to the NTSB for statistics about small-aircraft PIF rates and the number of fire-related fatalities in the United States during the past 10 or more years. Five years of limited data were provided. Between 01 January 1998 and 31 December 2002, there were 1368 fatal accidents involving small aircraft in the United States. The number of PIF accidents was not identified. Also, the number of fire-related fatalities could not be fully determined because PIF database files had to be researched individually to determine the cause of death. Furthermore, in many cases, no cause of death information had been recorded. To the extent that the available data were examined, 9 fatal accidents in which fire had caused or contributed to fatalities were identified. There were 16 fatalities in those 9 accidents, including one individual who was on the ground near the impact site at the time of the accident. Because of the incomplete data, these results are considered conservative.

The results of this Safety Issues Investigation are limited because the available data were incomplete, as described above. Therefore, it is highly probable that the full extent of the frequency and consequence of PIF involving small aircraft is under-represented. Li and Baker (1997) also reported that injuries sustained from aviation crashes have not been well documented nationally, and concluded that the full importance of PIF may be underestimated.

## 2.0 Overview of Canadian Post-Impact Fire Experience[7]

## 2.1 TSB Post-Impact Fire Statistics

The ASIS database contains records of 13 806 small-aircraft accidents that occurred in Canada from 1976 to 2002. These accidents involved all types of privately and commercially operated aircraft, including production[8] and amateur-built aeroplanes, production and amateur-built helicopters, and basic and advanced ultralights. As a follow-up to the A00W0109 investigation, the TSB determined that PIF had occurred in 521, or 3.8 per cent, of these accidents.

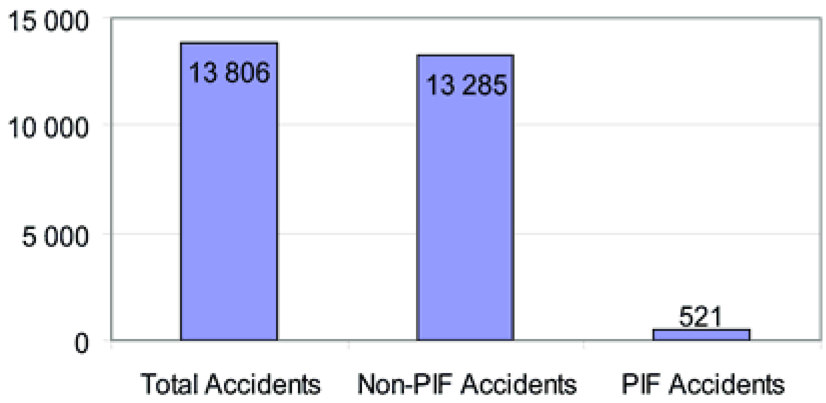


**Figure 1.** Comparison of non-PIF and PIF small-aircraft accidents, 1976-2002

This table contains a graphical comparison of the number of accidents. Total accidents = 13,806. NON-PIF accidents = 13,285. PIF accidents = 521.

The 13 806 accidents had resulted in 3311 fatalities and 2217 serious injuries. The 521 PIF accidents had accounted for 728 fatalities, or 22 per cent of all fatalities, and 231 serious injuries, or 10.4 per cent of all serious injuries. Compared to the fatality rate for all accidents, the fatality rate for PIF accidents was 5½ times greater, and the rate for serious injuries was nearly triple.

**Table 1.** Number of fatal and serious injuries in PIF versus non-PIF small-aircraft accidents, 1976-2002.
Source: TSB (2002) and Lindsey and West (2003).

| (a) All Accidents (total of 13 806) | | |
|---|---|---|
| **Injury Category** | **Number** | **Rates per Accident** |
| Fatalities | 3311 | 0.24 |
| Serious Injuries | 2217 | 0.15 |
| **(b) Accidents Resulting in PIF (total of 521)** | | |
| **Injury Category** | **Number** | **Rates per Accident** |
| Total Fatalities | 728 | 1.4 |
| Total Serious Injuries | 231 | 0.44 |
| Fatalities due to Fire | 205 | 0.39 |
| Serious Injuries due to Fire | 80 | 0.15 |

The 521 PIF accidents were reviewed to differentiate fire and impact injury types. Fire or smoke inhalation was identified as either partly or solely responsible for at least 205 (28 per cent) of the 728 fatalities that occurred in the PIF accidents. This represents 6.2 per cent of all fatalities (3311) for the data range and aircraft weight category. The cause of death was unavailable or undetermined for 129 of the 728 fatalities; therefore, the percentage of fatalities where fire contributed is biased downwards. If it is assumed that fire was responsible for the same proportion of these 129 fatalities as for the fatalities that were explained, then the percentage of fatalities where fire contributed would be increased from 28 per cent to 34 per cent of the 728 fatalities that occurred in PIF accidents (Lindsey and West, 2003). Fire or smoke inhalation was identified as either partly or solely responsible for 80 (3.8 per cent) of all serious injuries resulting from small-aircraft accidents.

The 521 PIF accidents involved 523 aircraft, which included 382 production aeroplanes, 94 production helicopters, 27 amateur-built aeroplanes, 2 amateur-built helicopters, 1 amateur-built gyroplane, 12 basic ultralights, and 5 advanced ultralights. Two of the accidents were mid-air collisions between two aeroplanes.

The extent to which PIF contributes to injury and fatality in small-aircraft accidents has been documented in other studies. Li and Baker (1997) reviewed death certificate data obtained from the National Center for Health Statistics for all aviation-related accidents during the years 1980 to 1990 and determined that burns were recorded as the immediate cause of death in approximately 4 per cent of the fatalities. They noted that the death certificates described only pre-mortem injuries, with the result that the importance of PIFs may have been underestimated. Bensyl, Moran, and Conway (2001) examined work-related aircraft accidents in Alaska between 1990 and 1999 and concluded that PIF was the strongest predictor of fatality. They estimated that the odds of dying were 14 times higher when a fire occurred after a crash than when one did not.

## 2.2 Post-Impact Fire Investigation and Autopsy and Post-Mortem Protocol

A PIF investigation is a complex process requiring a detailed, systematic examination of the wreckage and an objective analysis of the collected data.[9] Because of the destructive nature of fire, the physical evidence necessary to support findings pertinent to ignition, fuel spillage, fire propagation, and impediments to egress may be impossible to obtain. This is especially the case in the absence of survivor or witness reports. In the background discussion of Notice of Proposed Rule Making (NPRM) 85-7A, the FAA reported the following:

The nature of fire damage is such, however, that it is difficult if not impossible to determine where the fire started, how it progressed, or whether the fatality could have been prevented solely by treating either the fuel tanks, fuel lines, or fuel fittings. The data support only the findings that fuel was spilled and that a fatality resulted from thermal injuries.

When a death is unexpected or occurs when an individual is not under the care of a physician, the identification of the decedent and the determination of the manner and cause of death is the responsibility of the province or territory where the death occurred. The medical cause of death constitutes the opinion of a pathologist, based on the pathological examination. TSB Air Investigation Branch guidelines for post-mortem examination can be found in the *Autopsy and Post-Mortem Examination Protocol* (1996). In the case of PIF accidents, a thorough post-mortem examination of all fatally injured occupants, to the extent necessary and to the level permitted by the condition of the remains, is necessary to differentiate fire- and impact-related deaths with certainty. Body x-rays are routine; however, a full autopsy may not be required. This process can contribute to the identification of safety issues related to crashworthiness and survivability.

Whether or not a full autopsy is performed, the medical cause of death must be recorded on the registration of death.

There were many PIF occurrences for which detailed post-mortems were restricted to flight crew. They were performed to determine if pre-existing disease, incapacitation, or toxicology contributed to the accident. Often, there was no record or information in the TSB occurrence file of a post-mortem examination or registration of death for the deceased passengers. As well, there were many instances where the names of the deceased passengers were not entered into the ASIS database, which precluded follow-up requests to the appropriate coroner or medical examiner for historical records.

## 2.3 Geographic Distribution of Post-Impact Fire Accidents and Injuries

The number of PIF accidents varied appreciably among provinces, with British Columbia accounting for approximately 27 per cent of the total. Two factors that appear to influence the number of PIFs in a specific region are the accident rate in that region and the terrain. British Columbia's mountainous terrain contributes to a higher accident rate for small aircraft, due to the increased operational risks that are associated with low-altitude visual flight rules (VFR) flight in mountains. Accidents that occur in mountainous terrain appear to result in a higher incidence of PIF, as well as a higher incidence of impact-related fatalities, regardless of whether PIF occurs. This is likely due to the increased severity of impacts in rough terrain.

The ratios of impact-related injuries to fire-related injuries also varied among provinces, with British Columbia, Yukon, and western Northwest Territories having greater proportions of impact-related injuries in PIF accidents, compared to less mountainous provinces. Factors that may have influenced the ratios of impact injuries to fire injuries are variations in accident dynamics, differences in post-mortem examination protocol among provinces, or varying levels of TSB communication with different coroner and medical examiner jurisdictions.

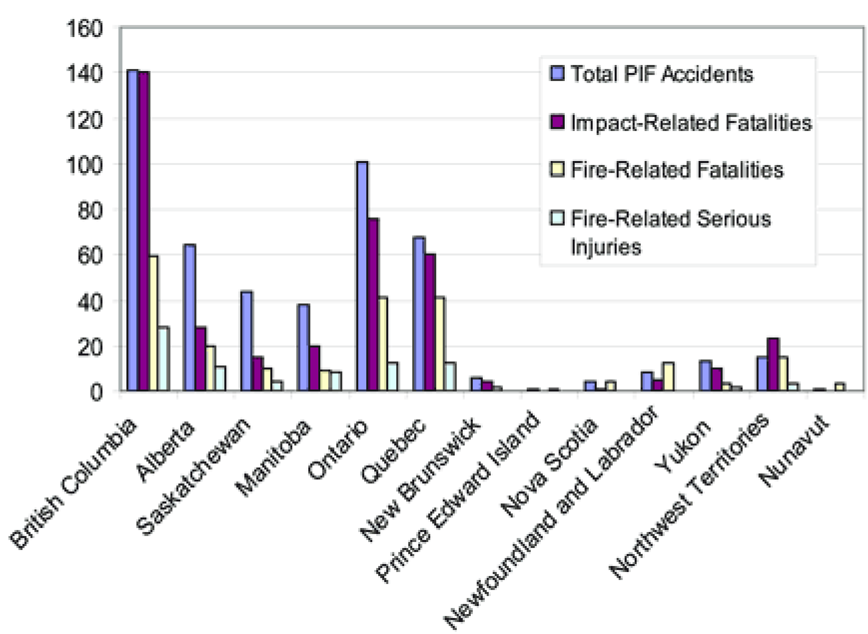


**Figure 2.** Geographic distribution of PIF accidents and injuries[D]f2

This table contains a graphical comparison of the number of PIF accidents and injuries by geographic distribution.

Although mountainous areas are associated with higher small-aircraft accident rates and a greater incidence of PIF, individual aircraft may be operated over a wide variety of terrain, including mountains, during their service life; therefore, certification standards cannot be varied according to anticipated operation in specific geographic areas.

## 2.4 Number of Registered Aircraft

At the end of 2002, there were 28 744 aircraft on the Transport Canada Canadian Civil Aircraft Register, including production aeroplanes and helicopters, amateur-built aircraft, and ultralights, of which 27 374 weighed 5670 kg or less. Transport Canada figures indicate that the average age of Canadian-registered aeroplanes weighing less that 5700 kg is 37 years. Given that many of these aircraft will remain in service until they crash or become uneconomical to maintain, and that few new small aircraft are entering service, the average age of the under-5700 kg Canadian fleet is increasing. There are approximately 220 000 aircraft registered in the United States, of which an estimated 210 000 have a take-off weight of less than 5700 kg. Considering the current low production and retirement rates for small aircraft, most of the under-5700 kg fleet will, for some time into the future, be composed of aircraft that are currently in use.

## 2.5 Accident Rates for Small Aircraft by Operator Type

At the end of 2002, approximately 80 per cent of the small aircraft on the Transport Canada registry were being operated privately, 19 per cent were being operated commercially, and less that 1 per cent were being operated as state aircraft. Aviation operations involving privately and commercially registered small aircraft have significantly higher accident rates than operations using larger aircraft. The generally accepted factors that contribute to these higher accident rates include less stringent aircraft certification standards, reduced pilot training requirements, lower pilot experience, higher instances of single-pilot operations, greater proportions of time spent in low-altitude VFR operations, and more frequent use of small airports and landing strips that are not equipped with navigation and landing aids.

The TSB publishes 10-year accident rate statistics for Canadian aircraft operations. The accident rate trends for air taxi operations have shown a significant downward trend, from 13.2 accidents per 100 000 hours in 1993 to 6.0 accidents per 100 000 hours in 2002. The accident rate for aerial work has also decreased markedly, from 12.7 accidents per 100 000 hours in 1993 to 4.6 accidents per 100 000 hours in 2002. The rates for state and helicopter operations have remained relatively stable during that time. While the accident rate for corporate/private/other has fluctuated, overall, it was down from 31.2 accidents per 100 000 hours in 1993 to 28.4 accidents per 100 000 hours in 2002. While the accident rates for these primarily small-aircraft operations have declined generally, they remain significantly higher than the accident rates for commuter and airline operations that use aircraft weighing more than 5700 kg.

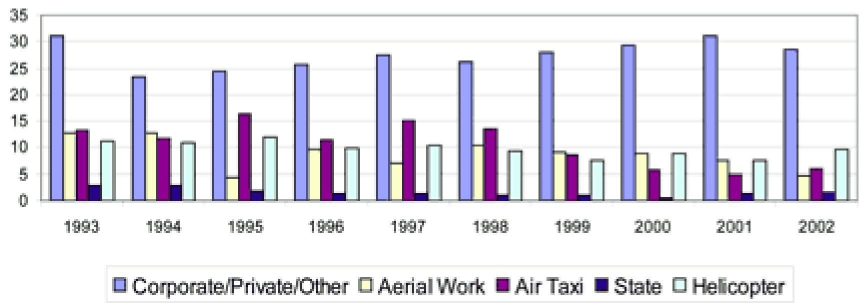


**Figure 3.** Canadian accident rates per 100 000 hours by operator type, 1993-2002[D]f3

This table contains a graphical representation of Canadian accident rates per 100 000 hours by operator type, 1993-2002

The data subset containing 128 accidents with fire-related injuries or fatalities included 98 production aeroplanes, 20 production helicopters, 6 amateur-built aeroplanes, 2 basic ultralights and 2 advanced ultralights.

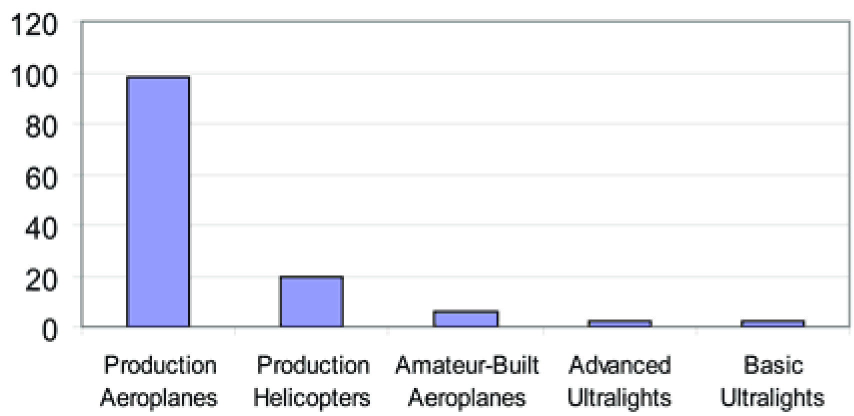


**Figure 4.** Number of aircraft involved in accidents with fire-related injuries or fatalities classified by eligibility for registration[D]f4

This table contains a graphical representation of the number of aircraft involved in accidents with fire-related injuries or fatalities classified by eligibility for registration

Sixty of the aircraft were being operated commercially, 60 were being operated privately, 3 were being operated by a corporation, 2 were being operated by a government agency, and 3 were involved in other operations.

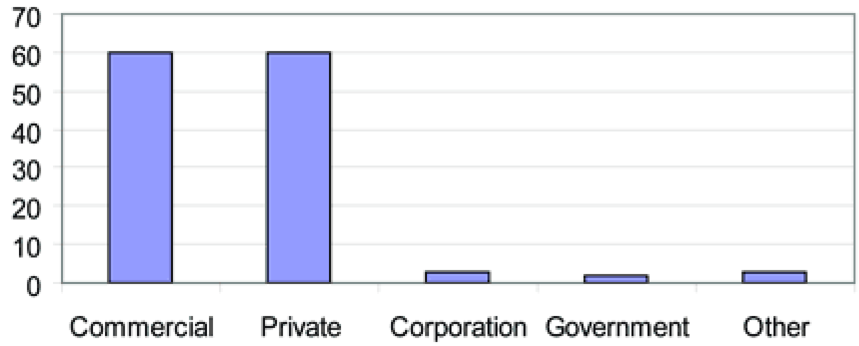


**Figure 5.** Number of aircraft involved in accidents with fire-related injuries or fatalities by type of registration[D]f5

This table contains a graphical representation of the number of aircraft involved in accidents with fire-related injuries or fatalities by type of registration"

## 2.6 Differentiating Post-Impact Fire Rates by Aircraft Type, Model, and Basis for Registration

### 2.6.1 Production Aeroplanes

There were 382 small production aeroplanes in the ASIS database that were involved in PIF accidents. These accidents resulted in 585 fatalities (169 of which were associated with fire or inhalation of smoke) and 175 serious injuries (55 of which were related to fire). The majority of these aircraft were type-certificated under parts 3, 4, 5, 6, 8, or 10 of the *Civil Air Regulations*, or Part 23 of the FARs.

The investigation was able to differentiate PIF rates by certain common models of production aeroplanes; however, their relative safety could not be assessed based on available accident statistics. While certain models of aeroplane were represented more frequently in the statistical summaries, lack of specific information such as numbers in service, number of annual flight hours, and variations in the types of operation precluded valid comparison. Furthermore, even if a differentiation were determined, regulators do not apply airworthiness standards selectively according to specific aeroplane models. A summary of the production aeroplane models with five or more recorded PIF occurrences is provided for reference.

**Table 2.** Summary of production aeroplane models with five or more PIF accidents, 1976-2002

| Manufacturer | Model | Total PIF | Otherwise Survivable PIF |
|---|---|---|---|
| de Havilland | DHC-2 | 15 | 8 |
| de Havilland | DHC-3 | 16 | 5 |
| de Havilland | DHC-6 | 7 | 3 |
| Beech | 15 | 5 | 2 |
| Beech | 90/100 | 8 | 2 |
| Cessna | 150/152 | 17 | 3 |
| Cessna | 172 | 21 | 3 |
| Cessna | 180 | 17 | 5 |

| | | | |
|---|---|---|---|
| Cessna | 182 | 10 | 2 |
| Cessna | 185 | 26 | 5 |
| Cessna | 206 | 14 | 3 |
| Cessna | 210 | 7 | 3 |
| Cessna | 310 | 5 | 2 |
| Piper | PA-12 | 9 | 2 |
| Piper | PA-18 | 11 | 2 |
| Piper | PA-23 | 9 | 4 |
| Piper | PA-24 | 5 | 0 |
| Piper | PA-25 | 18 | 7 |
| Piper | PA-28 | 16 | 6 |
| Piper | PA-31 | 11 | 3 |
| Piper | PA-32 | 9 | 1 |

While valid differentiation of PIF rates by production aeroplane model was beyond the scope of this investigation, the high incidence of otherwise survivable PIF accidents involving the DHC-2 Beaver stands out. Two design factors are believed to contribute. The main fuel tanks in the DHC-2 Beaver (and the DHC-3 Single Otter and DHC-6 Twin Otter) are located immediately below the passenger cabin floor, between the main landing gear attachment points. This location results in the fuel tanks being highly vulnerable to crash damage, such as landing gear penetration, and places the occupants within the flame front of a fuel-fed fire should ignition occur. As well, large, current-carrying direct-current cables, which are routed in the lower .fuselage alongside the fuel tanks, provide an effective electrical ignition source in the event they sustain impact damage. All other aircraft models in this table have the fuel tanks located in the wings.

### 2.6.2 Production Helicopters

There were 94 PIF accidents in the ASIS database that involved production helicopters. Twenty-seven of these accidents were considered otherwise survivable and resulted in 27 fire-related fatalities and 18 fire-related serious injuries. The majority of these accidents involved helicopters that had been certified under Part 27 of the FARs, and that had been manufactured before 1994.

### 2.6.3 Amateur-built Aeroplanes, Helicopters, and Gyroplanes

The airworthiness requirements for Canadian amateur-built aircraft are referenced in Chapter 549 of the *Airworthiness Manual*. Chapter 549 states that aircraft, including those supplied in kit form, will be designated as amateur-built aircraft where the major portion of the aircraft (more than 50 per cent) is fabricated from raw material and assembled by an individual or a group of individuals on a non-commercial, non-production basis for educational or recreational purposes. There are no amateur-built design requirements that are intended to reduce the incidence of PIFs in impact-survivable accidents.

There were 30 PIF accidents in the ASIS database that involved amateur-built aircraft, including 27 aeroplanes, 2 helicopters, and 1 gyroplane. Four of these accidents were considered otherwise survivable, and resulted in four fire-related fatalities and six fire-related serious injuries.

### 2.6.4 Basic and Advanced Ultralights

There were 12 PIF accidents in the ASIS database that involved basic ultralights. These accidents resulted in 3 fire-related fatalities.

There were 5 PIF accidents in the ASIS database that involved advanced ultralights. These accidents resulted in 8 fatalities, 2 of which were fire-related, and 1 fire-related serious injury.

There are no design requirements for ultralights, advanced ultralights, or gyrocopters that are intended to reduce the incidence of PIF in impact-survivable accidents.

### 2.6.5 Gliders

Gliders are non-power-driven heavier-than-air aircraft. They carry no fuel, which is the combustible material of greatest significance in small-aircraft PIF accidents.

The ASIS database contained records of 279 accidents that occurred from 1976 to 2002 involving gliders. There was no record of PIF in these occurrences.

# 3.0 Surviving Post-Impact Fire Accidents

## 3.1 Survival Thresholds

Occupant injuries associated with small-aircraft accidents can be characterized as related to impact or fire. Impact-related injuries can be divided into two groups: contact injuries that occur when a body contacts surrounding structure during impact, and acceleration injuries that occur due to rapid reductions in occupant speed. Contact injuries can be mitigated by better restraint systems, by the use of protective equipment such as helmets, and by enhancements to the interior of the cockpit and cabin areas. Acceleration injuries can be reduced by minimizing the energy transmitted to the occupant through energy-absorbing structure and seats. Both categories of impact injuries can contribute to fire-related injuries and fatalities by immobilizing occupants sufficiently to prevent rapid self-exit from a PIF environment.

Fire-related injuries can be differentiated as burn injuries and respiratory injuries. Occupants exposed to PIF risk skin and flesh thermal injuries, respiratory thermal injuries and/or exposure to toxic gases, all of which can be fatal. References in the Simula Technologies *Small Airplane Crashworthiness Design Guide* (Document 4) indicate that the available tolerance/escape time in a 400ºF environment would be approximately 20 seconds (Hurley and Vandenburg, 2002).

## 3.2 Escape from Small-Aircraft Post-Impact Fires

Several factors can impede occupant escape from small-aircraft PIFs that may not affect occupants escaping from large-aircraft PIFs. Occupants may be subjected to higher impact forces in small aircraft than in large aircraft, at equivalent impact speeds and angles, because of the limited structural dimensions available for energy absorption in small-aircraft airframes. This can result in skeletal fractures that hinder mobility. Occupants are normally seated in closer proximity to fuel in small aircraft than in large aircraft. Also, the aircraft skin burn-through time is less in small aircraft due to reduced skin thicknesses.

The Simula Technologies *Small Airplane Crashworthiness Design Guide* references tests by the National Advisory Committee for Aeronautics (NACA) (a former United States federal agency) to measure ambient and radiant temperatures in crashed and burning large and small fixed-wing aircraft, and to determine escape times. Estimated escape times from large aircraft PIFs, based on aircraft skin burn-through and human tolerance to heat, varied from 53 seconds to

220 seconds, with the average being 135 seconds. The NACA test results identified that the average estimated escape time from fire accidents in small aircraft was 17 seconds (Hurley and Vandenburg, 2002). These data show that, when a PIF occurs and an occupant sustains immobilizing but non-life-threatening injuries, or is otherwise prevented from self-exiting a small aircraft, that occupant is at extremely high risk of sustaining a fire-related injury or fatality.

## 3.3 On-board Hand-held Fire Extinguishers

Section 602.60 of the *Canadian Aviation Regulations* (CARs) requires all power-driven aircraft, other than ultralight aeroplanes, to be fitted with a hand-held fire extinguisher in the cockpit, of a type suitable for extinguishing the fires that are likely to occur. Section 704.83 of the CARs requires that at least one hand-held fire extinguisher be accessible for immediate use and located in the passenger compartment when passengers are on board.

On-board hand-held fire extinguishers are required as a defence against the propagation of in-flight fires, and the data collected in this study demonstrate that they are rarely a defence against PIF. Because of the possibility of rapid fire propagation or explosion, mobile occupants are likely to distance themselves from a PIF rather than attempt to access an on-board portable fire extinguisher and suppress the fire. As well, the fire extinguishers in small aircraft are often mounted in areas that are susceptible to impact damage, such as under a cockpit seat, and may not be readily available to survivors. Moreover, portable extinguishers may not contain a sufficient quantity of chemical to extinguish an intense, fuel-fed PIF. Among the 128 accidents in the data subset, there was no case on record in which an on-board hand-held fire extinguisher had been removed from the mounting bracket and used by the aircraft occupants in an effort to suppress the PIF.

## 3.4 Fire Suppression

Fire suppression is a defence that limits or prevents fire from harming persons or objects. The National Fire Protection Association (NFPA) *Guide for Fire and Explosion Investigations* (NFPA 921) states that the combustion reaction can be characterized by four components: the fuel, the oxidizing agent, the heat, and a self-sustained chemical reaction. NFPA 921 further states that these four components have been classically symbolized by a solid four-sided geometric form called a tetrahedron, and that fires can be prevented or suppressed by controlling or removing one or more of the sides of the tetrahedron.

Operators of airports that serve large numbers of commercial passenger-carrying aircraft are required to provide Aircraft Rescue and Fire Fighting (ARFF) services. Section 303.18 of the CARs requires the operator of an airport to demonstrate that aircraft firefighting vehicles must be able to reach the midpoint of the farthest runway serving commercial passenger-carrying aircraft, or another predetermined point of comparable distance, within three minutes after an alarm is sounded and in a number sufficient for applying the principal extinguishing agent at 50 per cent of the total required discharge capacity. There are presently 28 designated Canadian airports that are required to have firefighters on site, and four more airports that voluntarily meet the requirements of Part 303 of the CARs. Part 308 of the CARs also applies to an additional 25 airports that handle 705 traffic.[10]

For fire suppression to be an effective defence against fire-related injuries or fatalities where occupants are unable to evacuate an aircraft on their own following an accident, the fire must be suppressed or extinguished before the fire-related injuries or fatalities occur. This may not be possible in the case of most post-impact fuel-fed fires involving small aircraft. More often than not, small-aircraft accidents occur at sites other than CARs 303-designated airports. Even when a small-aircraft accident occurs at a CARs 303-designated airport and a fuel-fed PIF erupts at impact, the predictable escape time of 17 seconds is significantly less than the demonstrated ARFF response time of three minutes. This indicates that there is a much greater benefit to taking whatever engineering initiatives are necessary to prevent PIFs than there is to relying on potential rescue actions when fire occurs.

CARs do not address firefighting response time to aircraft crash sites in off-airport locations. Furthermore, the probability of reducing the risks associated with those small-aircraft PIF through enhanced ARFF response requirements is very low.

The increased risks associated with aircraft accidents occurring at non-airport locations have been identified in other studies. Li and Baker (1993), in their examination of pilot survival in crashes of commuter aircraft and air taxis, identified that the most important risk factor for fatality was post-crash fire. They also stated that crashes away from airports, in bad weather and/or at night, also increase the chance of death, probably because they are more likely to involve high-speed, uncontrolled impacts, and because they can severely complicate rescue attempts. In their research into the epidemiology of aircraft fire in commuter and air taxi crashes, Li, Baker, and Dodd (1996) cited non-airport location as one of the factors associated with increased likelihood of fire, and, again, that the high-risk circumstances of night, non-airport location and instrument meteorological conditions often thwart rescue and firefighting efforts.

## 3.5 Fuel Type

Eighty-nine of the aircraft in the fire injury/fatality occurrence set were fuelled with avgas, 13 were fuelled with mogas, 3 were fuelled with Jet A, and 17 were fuelled with Jet B.[11] One aircraft had both avgas and mogas on board in separate tanks. In five occurrences, the type of fuel was not recorded. Avgas has a higher vapour pressure than jet fuel and, therefore, has a greater tendency to vaporize over a wider range of ambient conditions, especially in warmer temperatures and during crash conditions. This suggests that aircraft fuelled with avgas or mogas are at a greater risk for PIF. However, based on available accident statistics, the safety significance of fuel type could not be determined because accident rates for reciprocating-powered aircraft and turbine-powered aircraft could not be conveniently differentiated in the ASIS database.

Other reports have highlighted the more frequent occurrence of PIF in aircraft fuelled with aviation gasoline, compared to aircraft fuelled with aviation kerosene. An FAA report titled *Study of General Aviation Fire Accidents (1974-1983)* (Ludwig, Clarke, and Lawton, 1987) noted that 94.5 per cent of the PIF accidents in the FAA fire database involved aircraft fuelled with aviation gasoline and 5.5 per cent of the PIF accidents involved aircraft fuelled with aviation kerosene. The report noted that, while the fatalities and number of accidents were similar in proportion between the two fuel types, the majority of the general aviation population used aviation gasoline and the kerosene fuel was used only in the larger models typically used in business aviation (Ludwig, Clarke, and Lawton, 1987).

# 4.0 Overview of Aircraft Crashworthy Design Requirements

## 4.1 General

The administrative defences that govern aircraft certification worldwide are found primarily in three regulatory structures: the United States *Federal Aviation Regulations* (FARs), the *Canadian Aviation Regulations* (CARs), and the European Aviation Safety Agency (EASA) requirements. Part 23 of the FARs prescribes the airworthiness standards for aeroplanes in the normal, utility, aerobatic, and commuter categories. The FARs, CARs, and EASA requirements are harmonized;

therefore, type-certificated light aircraft manufactured in the United States, Canada, and Europe all meet basically the same standards. For simplicity in this report, the references to aircraft certification will cite FARs only.

## 4.2 Current FAR 23 Requirements for Production Aircraft

There are three FAR 23 fuel system certification requirements that reduce the risk of PIF in minor crash conditions. Subparagraph 23.967(e)(2)(I) of the FARs requires fuel tanks to be designed, located, and installed so as to retain fuel in a wheels-up landing on a paved runway. Under this requirement, the tearing away of an engine mount must be considered unless all engines are installed above the wing or on the tail or fuselage. Section 23.994 of the FARs also requires fuel system components in an engine nacelle or fuselage to be protected from damage that could result in a fire hazard during a wheels-up[12] landing on a paved runway, and Subparagraph 23.999(b)(2)(vi) of the FARs requires drain valves to be located or protected to prevent fuel spillage in the event of a landing with landing gear retracted. These requirements pertain only to retractable-gear aircraft. At present, there are no additional mandated fuel system crashworthiness standards for retractable-gear FAR 23 aircraft, and none at all for fixed-gear FAR 23 aircraft. Virtually none of the FAR 23 production aeroplanes in service today, with the exception of a small number of new product models that incorporate voluntary improvements such as flexible hoses at major airframe junctures, incorporate crashworthy fuel system technology.

Sections 23.561 and 23.562 of the FARs prescribe basic occupant protection requirements, such as restraint and roll-over criteria, in controlled, emergency landing conditions. Additionally, Subsection 23.787(3) of the FARs identifies the requirements to protect occupants from injury due to contact with dislodged baggage and cargo, to an ultimate forward inertial load factor of 9 g. While these requirements are intended to minimize injuries in minor crash conditions, occupants may not always be mobile following exposure to the dynamic conditions referred to in these FARs.

## 4.3 History of Change in FAR 23 Fuel System Crash-Resistance Certification Requirements

Government agencies have attempted in the past to deal with the issue of PIF in small aircraft, through special studies and Notices of Proposed Rule Making (NPRMs). Many of the concerns related to PIF were addressed in a National Transportation Safety Board (NTSB) special study report, *General Aviation Accidents: Postcrash Fires and How to Prevent or Control Them* (NTSB-AAS-80-2, 1980). The 1980 NTSB special study identified that, from 1974 to 1980, there were 22 002 general aviation accidents in the United States, of which 1764, or 8 per cent, resulted in PIF. Based on the special study, the NTSB made six recommendations to the FAA.

From 1980 to 1996, the FAA established projects to study the recommendations and requested that an informal organization known as the General Aviation Safety Panel (GASP) be established to address questions concerning general aviation safety, including that of crashworthiness. The GASP, consisting of knowledgeable volunteers from the general aviation community, agreed in 1984 to formulate meaningful crashworthiness recommendations to reduce the incidence and effect of PIF in general aviation aeroplanes. An Advanced Notice of Proposed Rule Making (ANPRM), published 05 March 1985, announced the FAA's intent to incorporate airworthiness standards for crash-resistant fuel systems into FAR 23 aircraft. Subsequently, in the response to the ANPRM, the NTSB reported that about 14 per cent of the fatally injured occupants in fire accidents could have survived had there been no fire, and that about 26 per cent of the seriously injured occupants in accidents with fire could have been injured less severely had there been no fire.

The purpose of the ANPRM was to solicit public comment regarding needed regulatory changes and their costs. Following review of the responses, the GASP recommended that

1. aircraft capable of carrying fewer than 10 passengers be designed so that no more than 8.0 ounces of fuel spillage per fitting will occur in specific areas of the aircraft;
2. fuel tanks in defined locations meet specific crashworthiness criteria;
3. the FAA investigate additional means to reduce fuel spillage from fuel tanks in general; and
4. the FAA prepare an Advisory Circular that identifies acceptable means for compliance with regulations pertaining to fire-resistant fuel systems.

NPRM 85-7A, titled *14 CFR Part 23 Airworthiness Standards: Crash-Resistant Fuel Systems*, issued on 28 February 1990, proposed changes to Part 23 of the FARs airworthiness standards to enhance fuel system crash resistance in normal, utility, acrobatic, and commuter category aircraft. The NPRM focused on fuel containment and did not address elimination of crash-induced ignition sources.

NPRM 85-7A was deliberated for nine years, but withdrawn on 30 December 1999. The withdrawal notice stated that the FAA had completed a revised economic evaluation of the safety recommendations as a result of the comments received and concluded that the costs of the proposed changes were not justified by the potential benefits. The withdrawal notice also reported some of the concerns expressed in the comments received, including the need for a definition of a "survivable" crash, the reliability of self-closing devices in fuel lines, the preference for an objective test for fuel tanks rather than mandating the use of flexible bladder tanks, and the inability to apply selective standards based on aircraft types.

The revised calculations that formed the basis for withdrawing the NPRM were not provided, and the document did not state explicitly that the estimated costs exceeded the benefits (Lindsey and West, 2003). Since the withdrawal of NPRM 85-7A, there has been no tangible action by regulators to address the issue of crashworthiness as it relates to PIF in small production aircraft, through certification change.

The concerns relating to the definition of a survivable accident in the comments received for NPRM 85-7A had been addressed in NPRM 90-24. NPRM 90-24, which proposed adding comprehensive crash-resistant fuel system (CRFS) design and test criteria to the airworthiness standards for normal and transport category rotorcraft, provided the following definition for "survivable" crash:

An otherwise survivable crash, as used in this rule making, is defined as one where the survivable human tolerance acceleration limit has not been exceeded in any of the principal rotorcraft axes, where the structure and structural volume surrounding occupants remain sufficiently intact during and after impact to permit survival, and where an item of mass does not become unrestrained and create a hazard to occupants.

If the reference to "rotorcraft axes" is replaced by "aircraft axes," this definition could serve adequately for fixed-wing aircraft as well (Lindsey and West, 2003).

## 4.4 Tests of Crash-Resistant Fuel Systems

A report titled *Tests of Crash-Resistant Fuel System for General Aviation Aircraft* was prepared for the United States Department of Transportation, FAA, in 1978. The report documented testing that was conducted to demonstrate the performance of light-weight, flexible, crash-resistant fuel cells used in combination with break-away fuel line couplings. Included in the report were the results of three Piper Navajo airframe crash tests. The report concluded that light-weight, flexible, crash-resistant fuel cells used in combination with self-sealing break-away fuel-line couplings can effectively reduce PIF in general aviation aircraft equipped with wing tanks (Perrella, 1978). This report has been referenced in previous NTSB recommendations (A-80-90 and A-80-91).

Soltis (1987) evaluated a wide range of aircraft sizes and configurations to estimate the potential impact that the installation of fuel bladder cells might have on aircraft design. He concluded that rework of current small-aircraft designs to install fuel bladder cells would increase an aircraft's empty weight and reduce its fuel volume, payload, and operational range. He also provided a qualitative finding that fuel cell bladders could be, and in some cases are, installed in selected areas such as readily accessible wing box areas in the wing root or in engine nacelles where ignition sources could exist. Those installations would have minimal impact on aircraft design or function (Soltis, 1987).

## 4.5 History of Fuel System Crash Resistance Certification Changes to Parts 27 and 29 of the Federal Aviation Regulations

Part 27 of the FARs prescribes airworthiness standards for normal category rotorcraft with maximum weights of 7000 pounds or less, and 9 or less passenger seats. Part 29 of the FARs prescribes airworthiness standards for transport category rotorcraft.

A significant improvement in civilian helicopter certification requirements occurred in 1994 when the FAA mandated fuel system crash resistance standards for newly certified helicopters, under sections 27.952 and 29.952 of the FARs. Fuel systems in helicopters certified subsequent to 1994 were required to meet drop test criteria, specific load factors, and design features such as self-sealing break-away couplings and frangible or deformable structural attachments. Fuel is required to be located as far as practicable from occupied areas and from potential ignition sources, and rigid or semi-rigid fuel tank or bladder walls are required to be impact and tear resistant.[13]

## 4.6 The Simula Technologies *Small Airplane Crashworthiness Design Guide*

The *Small Airplane Crashworthiness Design Guide*, a comprehensive reference for crashworthy design, was prepared for the Integrated Design and Manufacturing Technical Council of the Advanced General Aviation Transport Experiments (AGATE) alliance and for the National Aeronautics and Space Administration (NASA) Langley Research Center by Simula Technologies, Inc. The design guide was created to assist aircraft designers in understanding the design consideration associated with the development of crashworthy general aviation aircraft and includes information on current state-of-the-art crashworthiness technologies that are applicable to civil general aviation aircraft. The design guide is intended to be the first, best source of information on crashworthiness design of light aeroplanes (Hurley and Vandenburg, 2002). Chapter 10 of the design guide (Document 4) provides an extensive discussion of PIF factors, and Appendix C of the guide (Document 5) offers guidelines in the form of a fuel system design checklist.

## Improvements by Manufacturers to Reduce Post-Impact Fires and Fire-Related Injuries and Fatalities

There are several examples of voluntary action by small aeroplane manufacturers to reduce the risk and consequence of PIF in their newest products. Piper Aircraft has incorporated provisions into the PA46-500TP Meridian, a low-wing, turbine-powered, pressurized, single-engine aircraft to totally eliminate any fuel lines and fittings from the pressurized compartments in the fuselage, thereby reducing the possibility of injury due to PIF. The fuel lines between the fuel tanks and the engine are routed external to the cabin, and the tanks are positioned in the wings outboard of the landing gear, in order to increase the distance between the occupants and the fuel.

Cessna Aircraft Company has incorporated several safety features in its new product line for powered high-wing aircraft, specifically the 172, 182, and 206 models, to reduce the incidence of PIF. A small dry bay has been added between the wing fuel tanks and the fuselage to reduce the probability of fuel spilling into the cabin during accidents, and flexible fuel lines are now installed at the wing-to-fuselage junctures to reduce fuel line breakage at those locations. As well, the gascolator has been relocated on the firewall to make it less vulnerable to impact damage, and the firewall-mounted fuel system and electrical components are better isolated from each other.

The fuel tank on the Diamond DA20 series aircraft is constructed of welded aluminum, with internal reinforcements to withstand fluid inertia forces during a crash. The tank is mounted in the fuselage, and well away from any external fuselage surfaces, to resist potential penetrations. Cessna Aircraft Company also installs 26 g energy-absorbing seats and enhanced padding in the cabin in its new product line of single-engine aircraft to reduce impact injuries.

Several helicopter manufacturers currently install energy-absorbing seats in their products. Any technology that reduces occupant injuries and maintains occupant mobility during crash conditions will reduce the risk of fire-related injuries and fatalities in the event of PIF.

## 4.8 Automotive Improvements to Reduce Post-Impact Fires

Jennings and Mohler (1988), among others, have described how major advances in vehicle occupant protection have been demonstrated in auto racing at the Indianapolis Motor Speedway, where speeds obtained are comparable to the cruising speed of many general aviation aircraft. By 1964, restraint and occupant protection had already been improved considerably; however, post-crash fire accidents continued to claim drivers' lives. New rules in 1965 limited the volume of fuel that cars could carry and specified tank placement. Methanol fuel became mandatory and internal fuel bladders were required to be contained within welded tanks. The benefits of these improvements were demonstrated the following year, when a 17-car pile-up at the start of the Indy 500 resulted in no injuries and no significant fires (Jennings and Mohler, 1988).

Canada and the United States have adopted stringent safety standards for highway motor vehicle design and components. As a result, highway motor vehicle crashworthiness standards have historically surpassed those of small aircraft, especially in control of ignition sources, fuel system integrity, and occupant protection in crash conditions.

Federal Motor Vehicle Safety Standard (FMVSS) 301 (*Fuel System Integrity*) is specifically intended to reduce fire-related injuries and fatalities in motor vehicle crashes. Parsons (1990) reported that FMVSS 301 was effective in reducing the incidence of fire in passenger car accidents; however, there was no reduction in fire-related fatalities, as the force levels in many PIF crashes exceed the 48 km/h fuel containment impact levels set by the standard. The effect on burn injuries was uncertain. For light trucks, no fire reduction was found. As well, the report noted that the contributions of fire and impact forces in causing death and injury could not be separated in crash data files.

Considerably upgraded rear-impact test requirements for FMVSS 301 compliance are currently being phased in (as of March 2006), in an effort to further reduce the incidence of PIF, save lives, and prevent injuries in automotive accidents. Under the new rule, vehicles will have to retain fuel following offset rear impacts of 80 km/h.

Switching technology, such as resettable crash sensors using ball and magnet or pendulum inertial switches or resettable battery cut-off switches, is used on newer automobiles to inert electrical components such as fuel pumps and batteries, and has proven to be highly reliable in crash conditions. This is a mature technology, with no evidence of reliability problems such as false openings and few examples of vehicle recalls involving these products. Similar technology may be adaptable with no reduction in airworthiness (following acceptance in compliance with the processes prescribed for design approvals) to small aircraft to eliminate potential electrical ignition sources in survivable accidents. Automotive technology has been transferred to the aircraft industry in the past. A very recent example is the FAA approval of the AmSafe Aviation Inflatable Restraint system, which is based on mature automotive technology, for use in FAR 23 aircraft.

## 5.0 Cost-Benefit Analysis

This investigation contracted services to review the current process of aviation economic analyses, including cost-benefit analysis (CBA), and to assess the effect of that process on decision making in the application of risk control options that are available to mitigate PIF risks (Document 1).

CBA attempts to put a monetary value on all the incremental costs and benefits of regulatory change (Lindsey and West, 2003). Economic analysis of regulations and the use of CBA are required in the United States under Executive Order 12866 (*Federal Register*, 1993; Lindsey and West, 2003). The guidelines for CBA under Executive Order 12866 are comprehensive; however, they are not strict and analysts are required to use their professional judgment in implementing them (Lindsey and West, 2003). Since 1986, the Treasury Board of Canada has also specified that CBA be used, although until fairly recently, risk regulators in Canada rarely conducted a CBA (Lindsey and West, 2003).

The primary anticipated benefit from tighter PIF risk control measures regulations is a reduction in fatalities due to fire and smoke inhalation (Lindsey and West, 2003). Value of statistical life (VSL) is generally accepted as the appropriate monetary measure of human life. The CBA report concluded that the present United States guidelines on economic analysis are commendable, the only apparent defect being that the VSL of $3 million that is currently used by the Department of Transportation and the FAA is too low by about a factor of two relative to recent empirical estimates (Lindsey and West, 2003).

The expected benefits of PIF risk control measures are directly proportional to the VSL and to the effectiveness rate. The Canadian PIF database that was compiled during this project permitted calculation of the expected benefits in lives saved by preventing PIF. Using these statistics, Lindsey and West (2003) reported that, for a benchmark 100 per cent hypothetical effectiveness rate and plausible values for other parameters, the expected present-discounted benefits over the lifetime of an aircraft are found to be several thousand dollars.

In comments submitted to the FAA in response to NPRM 85-7A, the NTSB reported that about 14 per cent of the fatally injured occupants in accidents resulting in PIF could have survived if there had been no fire. That translated to about a 4 per cent yearly decrease in fatalities in all general aviation aeroplane accidents if PIF were prevented in survivable accidents. The NTSB further reported that about 26 per cent of the seriously injured occupants in accidents resulting in PIF could have been injured less severely had there been no fire, which represents about a 6 per cent yearly reduction in serious injuries.

This Safety Issues Investigation determined that, overall, in small-aircraft accidents that result in fire, fire contributes to 28 per cent of the fatalities. This translates to a potential decrease of up to 6 per cent in yearly fatalities if PIF could be eliminated in impact-survivable accidents. This investigation further identified that about 35 per cent of the seriously injured occupants in accidents resulting in PIF could have been injured less severely had there been no fire. This suggests that PIF has contributed to fire-related injury and fatality to a greater extent than previously identified, and measures to reduce PIF risks could yield greater benefit in Canada, if not also elsewhere, than has heretofore been recognized (Lindsey and West, 2003).

# 6.0 Unsafe Conditions Associated with Post-Impact Fire

## 6.1 General

This Safety Issues Investigation documented the common unsafe conditions[14] that contributed to PIF and the resulting fire-related serious and fatal injuries through a comprehensive review of the 128 occurrence files that were identified as "otherwise survivable" accidents. Several of the common unsafe conditions that were repeatedly catalogued in the analysis of these accidents were fuel system design deficiencies that had been previously addressed in NPRM 85-7A.

In every one of the accidents, the same four distinct groups of unsafe conditions were identified. The elimination of any one of the four unsafe conditions would have reduced or eliminated the fire-related serious injuries or fatalities. The unsafe conditions were

- an ignition source in close proximity to combustible material;
- combustible material such as fuel in close proximity to an occupant;
- compromised occupant egress; and
- inadequate or untimely fire suppression.

The risks associated with the unsafe conditions were examined, the defences against the unsafe conditions were reviewed, and safety deficiencies related to the unsafe conditions were identified.

## 6.2 Ignition Source in Close Proximity to Combustible Material

The probable sources of PIF ignition that were recorded in the occurrence file documents were hot items (87 occurrences), electrical items (66 occurrences), and friction (27 occurrences).[15]

Hot engine exhaust ducts, engine exhaust gases and flames, and hot engine parts were common "hot item" sources of ignition. There were 91 fire-related fatalities in accidents where a hot exhaust duct was the probable source of ignition, 32 fatalities associated with hot exhaust gases and flames and 9 fatalities associated with hot engine parts. The primary defences against hot items becoming sources of ignition in crash conditions are to shield hot engine parts from flammable liquids and prevent fuel spillage onto engines. At present, there are no design requirements that reduce the risk of or defend against hot items becoming an ignition source for PIF in small-aircraft accidents.

Electrical arcing, wires, and batteries were also common electrical sources of ignition. In accidents where electrical arcing was a probable source of ignition, there were 104 fire-related fatalities. Electrical arcing has been identified as a common PIF ignition source in other aviation reports and papers as well, including the NTSB report *General Aviation Accidents: Postcrash Fires and How to Prevent or Control Them* (NTSB-AAS-80-2). There are no regulatory requirements that specifically address the proximity of potential electrical ignition sources to combustible material or the control or suppression of impact-related electrical ignition sources in small-aircraft accidents.

Friction sparking occurs when ferrous metals, such as those used in landing gear components, exhaust pipes or ducts, and engine mounts, come into contact with hard surfaces, such as rocks, concrete, or asphalt. In accidents where friction was a probable source of ignition, there were a total of 58 fire-related fatalities. The primary defence against friction heating and sparking is to insulate spark-producing ferrous metals with non-ferrous materials or otherwise protect the components so as to prevent direct contact with hard surfaces during accidents. There are no design requirements that reduce the risk of or defend against friction becoming an ignition source for PIF in small aircraft.

## 6.3 Combustible Material in Close Proximity to an Occupant

The combustible material of greatest significance in small-aircraft accidents is uncontained fuel. The relationship between fuel and PIF is exemplified by the lack of PIF in accidents involving gliders, which do not carry fuel.

In all, 91 accidents in the fire-related injury/fatality subset involved a PIF associated with fuel tank rupture; 71 of these were associated with a fuel line rupture. Fuel from gascolators, carburetors, and fuel filters was ignited in 11, 9, and 6 accidents, respectively. Engine oil or hydraulic fluid was ignited in 60 accidents, and upholstery, wing/fuselage skin, ground material or cargo provided combustible material in 95 accidents. It is probable that most of the non-fuel combustible materials that were consumed by fire were ignited by a fuel-fed fire, and were not ignited independently by other ignition sources.

Preserving the fuel system integrity in crash conditions is the most effective way to prevent PIF. In a typical small aircraft, critical fuel system components are located in areas that are vulnerable to impact damage. Fuel lines are often routed through the floor or sidewall areas of the fuselage, in close proximity to the occupants, and are subject to breakage at major airframe junctures, such as wing-to-fuselage or fuselage-to-engine, during crashes. Gascolators are located in damage-prone areas such as the lower forward firewall, and fuel tanks are not protected from impact by major structure. Many aircraft are fitted with "wet-wing" fuel tanks, where the wing skin is sealed to the spars and ribs to form an integral fuel tank. Wet-wing fuel cells are not reinforced to withstand the torsional loads and high fuel inertial forces associated with crash episodes, and are not fitted with any sort of high-strength tear or puncture-proof liner; therefore, they are especially vulnerable to leaking large quantities of fuel following an impact.

Physical defences that enhance fuel system crashworthiness include using self-sealing break-away fuel fittings and impact-resistant fuel cells, and locating fuel cells in areas that are not susceptible to impact damage and are remote from the occupied areas of the aircraft. Although the unsafe conditions relating to loss of fuel system integrity during crash conditions are well known, there are no requirements for small aircraft, other than during gear-up landings, that address fuel system integrity and fuel containment in crash conditions or the proximity of combustible material, such as fuel, to an occupant.

## 6.4 Compromised Occupant Egress

Occupant egress was most often compromised by heat, toxic gases, injuries, and obstructions. Other factors that contributed to egress difficulties were related to flight crew or other passengers or ground personnel being unavailable or unable to assist because of fire or injury.

Of the unsafe conditions that compromised occupant egress, the most prevalent was related to the direct physical effects of heat and toxic gases. Less prevalent factors related to obstructions and injuries sustained in the crash. In many accidents, the pilot was the only occupant of the aircraft. Firewalls often proved ineffective in keeping a fire out of the cabin, clothing often ignited, and exits were often blocked by fire.

The direct physical effects of heat compromised occupant egress in at least 113 accidents and toxic gases compromised occupant egress in at least 47 accidents. Burning clothing compromised occupant egress in at least 44 accidents. In those accidents where occupant egress was compromised by heat or toxic gases, there were 175 fire-related fatalities associated with the direct physical effects of heat, 113 fatalities associated with toxic gases, 27 fatalities associated with burning clothing, and 7 fatalities associated with ineffective firewalls.

Occupant egress was obstructed by distorted aircraft structure in at least 17 accidents, by restraints in at least 12 accidents, by damaged exits in at least 9 accidents, by occupants being pinned in the aircraft in at least 9 accidents, and by exits being difficult to locate or access in at least 6 accidents. Exits were blocked by fire in at least 6 accidents.

In those accidents where occupant egress was compromised by obstructions, there were 32 fire-related fatalities associated with the aircraft structure being distorted, 12 fatalities related to egress being obstructed by restraints, 13 fatalities associated with damaged exits that were difficult to open, 12 fatalities associated with an occupant being pinned in the aircraft, 15 fatalities associated with exits being difficult to locate or access, and 13 fatalities associated with exits being blocked by fire.

In many of the accidents, injuries sustained during impact compromised occupant egress, which led to fire-related serious or fatal injuries. Often, defences against impact injuries were not available, were not used, or failed.

Unavailability of shoulder harnesses contributed to injuries that hampered occupant egress in at least 15 accidents. Non-use of a helmet[16] also contributed to injuries that hampered occupant egress in at least 15 accidents. There were 27 fire-related fatalities associated with accidents where the unavailability of a shoulder harness contributed to injuries that compromised occupant egress. Similarly, there were 14 fatalities associated with accidents where a helmet was not used.

Seventeen other types of unsafe conditions that compromised occupant egress in 40 accidents were examined. The type of unsafe condition and the number of accidents in which each applied are as follows: injuries due to restraints not being used (5), injuries due to seats detaching (5), obstruction due to blocked exits (5), obstruction due to cargo (4), injury due to g-load (3), lack of strength to operate exits (3), injury due to projectiles (2), injury due to a failed helmet (2), insufficient number of exits (2), inadequate exit design (2), crushing injuries (1), injury due to restraints not available (1), injury due to restraints failing (1), exits difficult to reach (1), exit orientation (1), exit markings (1), pre-existing mobility problem (1).

Factors relating to the assistance to occupants attempting to egress were examined. In many cases, passengers and crew were unable to assist the occupants due to the fire. Occupant egress was not assisted by ground-based personnel in many cases because there was no one in the area to assist, neither bystanders, airport firefighting personnel, nor other emergency response personnel.

The most effective defence against occupant egress being compromised when PIF occurs is to prevent the PIF. Secondary defences are associated with reducing or preventing impact injuries through aircraft design, so as to maintain occupant mobility, and with providing functional and accessible exits so occupants can egress the aircraft unassisted. Aircraft design concepts that minimize structural distortion of occupied areas at impact, prevent occupant entrapment, provide adequate occupant restraint, reduce deceleration forces applied to occupants, provide mechanisms for rapid egress, and maximize the distance between occupants and fuel will reduce the incidence of fire-related injuries and fatalities when PIF occurs.

## 6.5 Inadequate or Untimely Fire Suppression

Most accidents in the data subset occurred off airport or in locations that precluded a timely or effective ARFF or local Emergency Rescue Services (ERS) response. ARFF (airport fire trucks) responded to 7 accidents. ERS (local fire trucks) responded independently to 27 accidents, and both ARFF and ERS responded to 4 accidents.

ARFF/ERS response time was unknown in 88 accidents. ARFF response was 3 minutes or less in 2 accidents. ARFF/ERS response time ranged from greater than 3 minutes to 3 days in the remaining 38 accidents. Bystanders responded to 39 accidents in 3 minutes or less. Bystander response time was unknown in 50 accidents, and bystander response to the remaining 39 accidents ranged from 4 minutes to 9 days.

The distance to the nearest available firefighting equipment was not recorded for 47 accidents. For the remaining 81 accidents, the distance to the nearest available firefighting equipment varied from nearby on the aerodrome to 122 km from the accident site.

Many of the accidents in the data subset occurred in off-airport locations where local or airport firefighting services were not immediately available. A total of 47 of the 128 accidents occurred at an unknown distance from available firefighting equipment, and 48 occurred at distances greater than 5 km from available firefighting equipment. Six accidents occurred on certified aerodromes, and in only two of these occurrences was firefighting equipment available on the aerodrome.

In the few cases where there was a timely ARFF/ERS response, the time necessary to suppress the fire exceeded the available escape or survival time, and within the data subset, there was no example of ARFF/ERS intervention reducing the level of fire injury or fatality. This demonstrates the greater benefit of preventing PIF in survivable accidents over depending on ARFF/ERS to reduce the incidence of fire-related injuries and fatalities once PIF occurs.

# 7.0 Post-Impact Fire Update: 01 January 2003 to 31 December 2004

The PIF study used data compiled for Canadian PIF accidents that occurred between 01 January 1976 and 31 December 2002. The ASIS database contains records of an additional 40 PIF accidents that occurred between 01 January 2003 and 31 December 2004. Twenty-one of these accidents involved Canadian-registered aircraft, with 2 weighing more than 5700 kg. Nineteen of the accidents were foreign occurrences, involving Canadian-registered or foreign-registered aircraft that had Canadian investigator involvement. Three of these aircraft weighed more than 5700 kg.

Twenty accidents involved Canadian-registered or foreign-registered aircraft, weighing less than 5700 kg, that crashed in Canada. These accidents resulted in 18 fatalities and 6 serious injuries. Seven of these accidents were investigated as Class 3 occurrences, and the remaining 13 were Class 5 occurrences that were not fully investigated. Data specific to fire-related fatalities and serious injuries were not systematically recorded in the ASIS database for these occurrences; therefore, the full extent to which PIF contributed to the injuries and fatalities in these recent PIF accidents was not examined.

The TSB Air Investigation Branch is considering ways to improve the quantity and quality of supplemental accident data that are being recorded in the ASIS database.

## 8.0 Discussion

The problem of post-impact fire (PIF) is not unique to any single model of powered aircraft. Proportionally, more people sustain serious and fatal injuries in accidents that result in PIF compared to accidents where no fire occurs. Between 1976 and 2002 inclusive, there were 521 accidents in Canada that resulted in PIF where the small aircraft involved was Canadian-registered or a foreign aircraft that crashed in Canada. This represents a large sample size of small-aircraft PIF accidents. The accidents comprised approximately 4 per cent of all small-aircraft accidents in the Aviation Safety Information System (ASIS) database for that period, and accounted for approximately 22 per cent of all fatalities and 10 per cent of all serious injuries.

A total of 128 of these accidents were considered otherwise survivable; that is, the impact forces were within the limits of occupant tolerance, the aircraft structure preserved the required survival space, and the occupant restraint was adequate. In these otherwise survivable accidents, some or all of the occupants survived the impact; however, they were in close proximity to fire or smoke for some time following the impact and, as a result, sustained fire-related serious or fatal injuries. The 128 otherwise survivable accidents accounted for, at minimum, 80 (approximately 4 per cent) of all fire-related serious injuries and 205 (approximately 6 per cent) of all fire-related fatal injuries. These statistics are considered conservative due to the incompleteness of the available data; therefore, the full consequence of PIF is probably under-represented.

All four essential groups of unsafe conditions had to be in place for fire-related injuries and fatalities to occur; that is, there was an ignition source in proximity to a combustible material such as fuel, the combustible material was in close proximity to the occupants, occupant egress was compromised, and the fire was not suppressed in time to prevent fire-related injuries or fatalities. In many cases, the defences to alleviate the hazards associated with the unsafe conditions did not exist, or were inadequate and could have been improved.

Past efforts by the National Transportation Safety Board and the Federal Aviation Administration in the United States resulted in comprehensive fuel system crash-resistance certification standards being introduced for normal (FAR 27) and transport category (FAR 29) helicopters in 1994, to minimize the hazard of fuel fires to occupants following otherwise survivable impacts. These standards have proven effective in reducing the risk and incidence of PIF. A Notice of Proposed Rule Making (NPRM) that was intended to introduce similar certification standards for FAR 23 production aircraft was withdrawn following a revised economic evaluation of the NPRM, which concluded that the costs of the proposed change were not justified by the potential benefits. However, the revised economic evaluation may have used fire-related injury data that were under-represented and a low figure for the value of statistical life. There are no design standards for amateur-built or ultralight aircraft that are intended to reduce the risks associated with PIF, and there have been no efforts by regulators to address design deficiencies related to PIF in these types of aircraft.

The data collected and analysed in this investigation identified that there is a continuing significant risk for PIF and PIF-related injuries and fatalities in small-aircraft accidents, and that the defences to prevent PIF and to reduce fire-related injuries should fire occur can be improved significantly. In general, small aircraft are not designed to alleviate damage-induced ignition sources or provide adequate protection against fuel spillage in crash conditions. Factors that increase the risk include the high volatility of aviation fuels, the close proximity of fuel to occupants, the limited escape time, the limited energy-absorption characteristics of small-aircraft airframes in crash conditions, the high propensity for immobilizing injuries and the inability of Aircraft Rescue and Fire Fighting and/or Emergency Rescue Services to suppress PIFs that ignite at impact in sufficient time to prevent fire-related injuries and fatalities. Technology and design concepts intended to reduce the incidence of PIF have been demonstrated to be effective in helicopter and automotive applications. The use of similar countermeasures in production aeroplanes, production helicopters, amateur-built aircraft, and basic and advanced ultralight designs may reduce the incidence of fire-related serious injuries and fatalities in otherwise survivable accidents, and increase the rates of occupant survival.

A large amount of the technical information that already exists, such as that contained in the Simula Technologies *Small Airplane Crashworthiness Design Guide*, documents how to reduce the risks associated with PIF. Voluntary action on the part of certain manufacturers will reduce the incidence of PIF and the level of injury associated with PIF. However, action by regulators is also necessary to ensure that all new-aircraft designs also result in a reduction of PIF. Considering the high number of small aircraft that are already in service and the current low manufacturing rates for new small aircraft, it is unlikely that a significant reduction in PIF rates can be achieved without requiring retrofitting selected crashworthiness technology to aircraft that are already flying.

A fire resulting from an otherwise survivable accident puts the small-aircraft occupants at unnecessarily high risk of fire-related injury and fatality. Although the safety hazards related to PIF are well known and specific, detailed design guidelines exist to reduce the incidence of PIF, the defences to alleviate the hazards in most small aircraft are not adequate in light of the risks associated with the unsafe conditions. While system crash resistance certification standards for normal and transport category production helicopters have been mandated to minimize the hazard of fuel fires to occupants following otherwise survivable impacts, there has been no tangible action to ensure parallel improvements in new or existing production aeroplanes, or in existing helicopters, amateur-built aircraft, or ultralights. Consequently, occupants of small aircraft continue to be at risk of sustaining PIF-related injuries and fatalities. The historical incidence of PIF occurrences in small-aircraft accidents demonstrates a high probability of future similar occurrences if current design standards are not changed.

# 9.0 Safety Action

## 9.1 Recommendations

Fire or smoke inhalation were identified as either partly or solely the cause of death for 205 (nearly 30 per cent) of the 728 fatalities and 80 (nearly 35 per cent) of the 231 serious injuries that occurred in the 521 accidents identified from the Aviation Safety Information System (ASIS) database as involving post-impact fire (PIF). This supports the concern that there is a significant risk for PIF and PIF-related injuries and fatalities in small-aircraft accidents, and that regulators should reconsider ways to reduce the risk and consequences of impact-induced fire in otherwise survivable accidents. While the design principles for crashworthy fuel systems are well known, at present, there are no airworthiness standards that require enhanced technical countermeasures to be fitted to small aircraft to reduce the incidence of PIF in circumstances other than gear-up landings.

PIF and fire-related injuries and fatalities can be mitigated through aircraft design, so as to prevent damage-induced ignition, preserve fuel system integrity, and reduce impact-related injuries in crash conditions. These design concepts, which have been shown to reduce the risk of fire and save lives in the helicopter and automotive industries, could be effectively applied to type-certificated small aircraft and to helicopters certified before November 1994 through improved regulatory standards.

The amateur-built aircraft and ultralight communities could benefit from the dissemination of safety information relevant to PIF risks and defences.

Considering the propensity for rapid propagation and the catastrophic consequences of fuel-fed PIF, the most effective defence against PIF is to prevent the fire from occurring at impact, either by eliminating sources of ignition or by containing fuel sufficiently to prevent contact with ignition sources, or both.

The following recommendations are made to address the safety deficiencies related to common unsafe conditions that contribute to the development of PIF and to fire-related injuries and fatalities, as identified by this investigation. The recommendations apply in general to small production aeroplanes, and where applicable, to small helicopters certified before November 1994. Transport Canada and the Federal Aviation Administration (FAA) may wish to communicate concerns and recommendations regarding PIF to the European Aviation Safety Agency (EASA) and other foreign airworthiness authorities in foreign states of manufacture.

### 9.1.1 Recommendation Regarding Value of Statistical Life

The report submitted to the TSB on the process of economic analysis into risk control options for mitigation of PIF risks identified that the U.S. guidelines on economic analysis and cost-benefit analysis (CBA) are commendable; however, the $3 million value of statistical life (VSL) figure currently used by the Department of Transportation and the FAA is low relative to recent empirical estimates. The original CBA for Notice of Proposed Rule Making (NPRM) 85-7A used a VSL of $1 million. Because numerous cost-effective technological advances to eliminate PIF have been developed, and given that benefits are directly proportional to the value chosen for VSL and to the effectiveness rate of the PIF risk control measures, the calculated benefits may be greater and the costs proportionately lower if recent higher empirical VSLs were applied to the original CBA. Using the comprehensive PIF database assembled during this investigation, it is possible to calculate the expected benefits in lives saved by preventing PIF. Using Canadian PIF statistics, the expected present-discounted benefits over the lifetime of an aircraft are several thousand U.S. dollars, and that value is sufficiently large that a detailed CBA may be warranted for specific PIF risk control option technologies (Lindsey and West, 2003). Therefore, the Board recommends that:

> Transport Canada, together with the Federal Aviation Administration and other foreign regulators, revise the cost-benefit analysis for Notice of Proposed Rule Making 85-7A using Canadian post-impact fire statistics and current value of statistical life rates, and with consideration to the newest advances in post-impact fire prevention technology.
> A06-08
>
> Assessment **Rating: Satisfactory in Part**

### 9.1.2 Recommendation Regarding Design Standards for New Aeroplanes

Aircraft design is fundamentally important to preventing PIF in impact-survivable accidents. There are currently no design standards that specifically address countermeasures to reduce the incidence of PIF in impact-survivable accidents involving newly manufactured small, production aeroplanes, other than during gear-up landings; therefore, occupants remain at risk of fire-related injury and fatality in accidents involving new aeroplane models. There are numerous engineering concepts and products that are known to eliminate potential ignition sources and protect against impact-induced fuel spillage in impact-survivable accidents. Requirements to consider and adapt these countermeasures in new aeroplane designs may significantly reduce the risk and incidence of PIFs in impact-survivable accidents. Therefore, the Board recommends that:

> To reduce the number of post-impact fires in impact-survivable accidents involving new production aeroplanes weighing less than 5700 kg, Transport Canada, the Federal

Aviation Administration, and other foreign regulators include in new aeroplane type design standards:

- methods to reduce the risk of hot items becoming ignition sources;
- technology designed to inert the battery and electrical systems at impact to eliminate high-temperature electrical arcing as a potential ignition source;
- requirements for protective or sacrificial insulating materials in locations that are vulnerable to friction heating and sparking during accidents to eliminate friction sparking as a potential ignition source;
- requirements for fuel system crashworthiness;
- requirements for fuel tanks to be located as far as possible from the occupied areas of the aircraft and for fuel lines to be routed outside the occupied areas of the aircraft to increase the distance between the occupants and the fuel; and
- improved standards for exits, restraint systems, and seats to enhance survivability and opportunities for occupant escape.

A06-09

Assessment **Rating: Unsatisfactory**

### 9.1.3 Recommendation Regarding Existing Production Aircraft

There are a large number of small aircraft already in service and the defences against PIF in impact-survivable accidents involving these aircraft are and will remain inadequate unless countermeasures are introduced to reduce the risk. The most effective ways to prevent PIF in accidents involving existing small aircraft are to eliminate potential ignition sources, such as hot items, high-temperature electrical arcing and friction sparking, and prevent fuel spillage by preserving fuel system integrity in survivable crash conditions. Technology that is known to reduce the incidence of PIF by preventing ignition and containing fuel in crash conditions may be selectively retrofitted to existing small aircraft, including helicopters certified before 1994. Therefore, the Board recommends that:

To reduce the number of post-impact fires in impact-survivable accidents involving existing production aircraft weighing less than 5700 kg, Transport Canada, the Federal Aviation Administration, and other foreign regulators conduct risk assessments to determine the feasibility of retrofitting aircraft with the following:

- selected technology to eliminate hot items as a potential ignition source;
- technology designed to inert the battery and electrical systems at impact to eliminate high-temperature electrical arcing as a potential ignition source;
- protective or sacrificial insulating materials in locations that are vulnerable to friction heating and sparking during accidents to eliminate friction sparking as a potential ignition source; and
- selected fuel system crashworthiness components that retain fuel.

A06-10

Assessment **Rating: Unsatisfactory**

## 9.2 Crashworthiness Technology for Amateur-built Aircraft, and Basic and Advanced Ultralights

There were 30 PIF accidents in the ASIS database that involved amateur-built aircraft, 12 that involved basic ultralights and 5 that involved advanced ultralights. These accidents resulted in 8 fire-related fatalities and 7 fire-related serious injuries.

There are no design requirements for amateur-built aircraft, or basic or advanced ultralights that are intended to reduce the incidence of PIF in impact-survivable accidents. As well, the extent to which amateur-built and ultralight designers include PIF countermeasures in their products is unknown. Therefore, Transport Canada, the Federal Aviation Administration and other foreign regulators may wish to disseminate applicable information to the amateur-built and ultralight communities to reduce the risk of PIFs in accidents involving those types of aircraft.

*This report concludes the Transportation Safety Board's investigation into this subject. Consequently, the Board authorized the release of this report on 13 June 2006.*

**Footnotes**

1. Subsection 101.01(1) of the *Canadian Aviation Regulations* (CARs) defines a small aircraft as an aeroplane having a maximum permissible take-off weight of 5700 kg (12 566 pounds) or less, or a helicopter having a maximum permissible take-off weight of 2730 kg (6018 pounds) or less.

2. See Glossary at Appendix C for all abbreviations and acronyms.

3. An otherwise survivable accident is one in which the impact forces are within the limits of occupant tolerance, the aircraft structure preserves the required survival space, and the occupant restraint is adequate.

4. A Safety Issues Investigation reviews multiple occurrences that the Board deems to be indicative of significant unsafe situations or conditions.

5. Examples of wording in cause of death statements that indicated that a death was related to fire are "smoke inhalation and burns due to or as a consequence of fire," "inhalation of products of combustion and thermal injury," "immolation," "inhalation of hot gases," "shock due to or as a consequence of burns," and "multiple corporal trauma due to incineration." Examples of wording in cause of death statements that indicated that a death was related to impact are "multiple injuries," "multiple blunt force and deceleration injuries," "laceration right ventricle of heart," "lacerated aorta," "blunt force injury of head, trunk, and extremities," and "massive multiple injuries due to or as a consequence of blunt trauma."

6. For all reported occurrences, initial determination of the facts is made to assist in deciding if an investigation is warranted. An investigation will be conducted if it is determined that there is potential to advance transportation safety. If an investigation is not warranted, the occurrence is classified as Class 5. The Board gathers and retains data for statistical and trend analysis, but no public report is prepared.

7. A chronology of PIF occurrences that are typical of the 128 accidents in which fire contributed to serious injury or fatality can be found in Document 3.

8. For the purpose of this report, type-certificated aircraft will be referred to as production aircraft or production helicopters.

9. The National Fire Protection Association (NFPA) is an international, non-profit international standards development agency based in the United States dedicated to fire prevention and other safety issues. Two NFPA technical manuals based on accepted scientific principles and research, NFPA 422 (*Guide for Aircraft Accident Response*) and NFPA 921 (*Guide for Fire and Explosion Investigations*) provide excellent guidance to air safety investigators for fire investigation.

10. 705 traffic refers to aeroplanes operated by a Canadian air operator for air transport service that have a maximum certified take-off weight of more than 8618 kg, or for which a Canadian type certificate has been issued authorizing the transport of 20 or more passengers, or to helicopters that have a seating configuration, excluding pilot seats, of 20 or more.

11. Jet B fuel is a relatively uncommon fuel type that is being phased out voluntarily by the oil refining industry.

12. Wheels-up landing and gear-up landing are used interchangeably in this report.

13. A research article by Mark S. Hayden et al. concluded that "The results of this study suggest a better performance, in terms of post-crash fire prevention, of CRFS-equipped civil helicopters as compared with those without CRFS. More widespread use of CRFS in civil helicopters would undoubtedly prevent some thermal fatalities and serious injuries."

14. An unsafe condition is defined as a situation or condition that has the potential to initiate, exacerbate, or otherwise facilitate an undesirable event.

15. File documents allowed up to three probable ignition sources to be selected for each occurrence.

16. The use of a helmet is voluntary and associated with certain air operations such as firefighting and crop dusting.

## Appendix A - Post-Impact Fire Accident Summary

| | Post-Impact Fire Accidents Involving Canadian-Registered Aircraft or Foreign-Registered Aircraft Under 5700 kg from 01 January 1976 to 31 December 2002 | | | | |
|---|---|---|---|---|---|
| | Type | Amateur | Basic | Advanced | Total |

| | Post-Impact Fire Accidents Involving Canadian-Registered Aircraft or Foreign-Registered Aircraft Under 5700 kg from 01 January 1976 to 31 December 2002 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Certificate | | Built | | Ultralights | | Ultralights | | | |
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| Accidents | 474 | | 30 | | 12 | | 5 | | 521 | |
| Aircraft Involved w/ Post-Impact Fire | 476 | | 30 | | 12 | | 5 | | 523 | |
| Aeroplanes | 382 | 80% | 27 | 90% | 12 | 100% | 5 | 100% | 426 | 81% |
| Helicopters | 94 | 20% | 2 | 7% | n/a | - | n/a | - | 96 | 18% |
| Gyroplanes | 0 | 0% | 1 | 3% | n/a | - | n/a | - | 1 | 0% |
| Fatalities | 686 | | 22 | | 12 | | 8 | | 728 | |
| Fire Footnote 1 | 196 | 29% | 4 | 18% | 3 | 25% | 2 | 25% | 205 | 28% |
| Impact Footnote 2 | 374 | 55% | 14 | 64% | 9 | 75% | 4 | 50% | 401 | 55% |
| Natural Death Footnote 3 | 0 | 0% | 1 | 5% | 0 | 0% | 0 | 0% | 1 | 0% |
| Cause Undetermined | 116 | 17% | 3 | 14% | 0 | 0% | 2 | 25% | 121 | 17% |
| Serious Injuries | 223 | | 7 | | 0 | | 1 | | 231 | |
| Fire Footnote 4 | 73 | 33% | 6 | 86% | 0 | - | 1 | 100% | 80 | 35% |
| Fire (minor) Footnote 5 | 4 | | 0 | | 0 | | 0 | | 4 | |
| Fatal or Serious Injury Accidents | 351 | | 23 | | 8 | | 5 | | 387 | |
| Aircraft Involved | 353 | | 23 | | 8 | | 5 | | 389 | |
| Aeroplanes | 287 | 81% | 21 | 91% | 8 | 100% | 5 | 100% | 321 | 83% |
| Fatalities | 585 | | 20 | | 12 | | 8 | | 625 | |
| | 169 | 29% | 4 | 20% | 3 | 25% | 2 | 25% | 178 | 28% |
| | 328 | 56% | 12 | 60% | 9 | 75% | 4 | 50% | 353 | 56% |
| | 0 | 0% | 1 | 5% | 0 | 0% | 0 | 0% | 1 | 0% |
| Cause Undetermined | 88 | 15% | 3 | 15% | 0 | 0% | 2 | 25% | 93 | 15% |
| Serious Injuries | 175 | | 7 | | 0 | | 1 | | 183 | |
| | 55 | 31% | 6 | 86% | 0 | - | 1 | 100% | 62 | 34% |
| | 3 | | 0 | | 0 | | 0 | | 3 | |
| Helicopters | 66 | 19% | 1 | 4% | n/a | - | n/a | - | 67 | 17% |
| Fatalities | 101 | | 1 | | n/a | | n/a | | 102 | |
| Fire Footnote 1 | 27 | 27% | 0 | 0% | n/a | - | n/a | - | 27 | 26% |
| Impact Footnote 2 | 46 | 46% | 1 | 100% | n/a | - | n/a | - | 47 | 46% |
| Cause Undetermined | 28 | 28% | 0 | 0% | n/a | - | n/a | - | 28 | 27% |
| Serious Injuries | 48 | | 0 | | | | | | 48 | |
| | 18 | 38% | 0 | - | n/a | - | n/a | - | 18 | 38% |
| Fire (minor) Footnote 5 | 1 | | 0 | | | | | | 1 | |

| | Post-Impact Fire Accidents Involving Canadian-Registered Aircraft or Foreign-Registered Aircraft Under 5700 kg from 01 January 1976 to 31 December 2002 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Gyrocopters** | 0 | 0% | 1 | 4% | n/a | - | n/a | - | 1 | 0% |
| **Fatalities** | 0 | | 1 | | n/a | | n/a | | 1 | |
| **Fire** [Footnote 1] | 0 | | 0 | | n/a | | n/a | | 0 | |
| **Impact** [Footnote 2] | 0 | | 1 | | n/a | | n/a | | 1 | |
| **Cause Undetermined** | 0 | | 0 | | n/a | | n/a | | 0 | |
| **Serious Injuries** | 0 | | 0 | | n/a | | n/a | | 0 | |
| | 0 | | 0 | | n/a | | n/a | | 0 | |
| **Fire (minor)** [Footnote 5] | 0 | | 0 | | n/a | | n/a | | 0 | |

Footnote 1: Fire or inhalation of smoke was identified as either partly or solely the cause of death.
Footnote 2: Cause of death was due to impact forces.
Footnote 3: Natural death occurring before the crash, due to aortic valve disease.
Footnote 4: Fire-related injury might not necessarily be the cause of the serious injury.
Footnote 5 : The number of serious injuries accompanied by a minor fire-related injury.

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## Appendix C - Glossary

| | |
|---|---|
| **AGATE** | Advanced General Aviation Transport Experiments |
| **ANPRM** | Advanced Notice of Proposed Rule Making |
| **ARFF** | Aircraft Rescue and Fire Fighting |
| **ASIS** | Aviation Safety Information System |
| **avgas** | aviation gasoline |
| **CARs** | *Canadian Aviation Regulations* |
| **CBA** | cost-benefit analysis |
| **CFR** | *Code of Federal Regulations* |
| **CRFS** | crash-resistant fuel system |
| **EASA** | European Aviation Safety Agency |
| **ERS** | Emergency Rescue Services |
| **FAA** | Federal Aviation Administration (United States) |
| **FARs** | *Federal Aviation Regulations* |
| **FMVSS** | Federal Motor Vehicle Safety Standard |
| **GASP** | General Aviation Safety Panel |
| **g** | load factor |
| **kg** | kilograms |
| **km** | kilometres |
| **km/h** | kilometres per hour |
| **mogas** | motor gasoline |
| **NACA** | National Advisory Committee for Aeronautics |
| **NASA** | National Aeronautics and Space Administration |
| **NFPA** | National Fire Protection Association |
| **NPRM** | Notice of Proposed Rule Making |
| **NTSB** | National Transportation Safety Board (United States) |
| **PIF** | post-impact fire |
| **TSB** | Transportation Safety Board of Canada |
| **U.S.** | United States |
| **VFR** | visual flight rules |
| **VSL** | value of statistical life |
| **°F** | degrees Fahrenheit |