# SMOKE, FIRE AND FUMES IN TRANSPORT AIRCRAFT

## PAST HISTORY, CURRENT RISKS AND RECOMMENDED MITIGATIONS

### Part 1: Reference

Fifth Edition 2018

A Specialist Paper by the **Royal Aeronautical Society** **www.aerosociety.com**

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We seek to i) promote the highest possible standards in aerospace disciplines; ii) provide specialist information and act as a central forum for the exchange of ideas; and iii) play a leading role in influencing opinion on aerospace matters. The RAeS is also working with the Government and industry leaders within the Aerospace Growth Partnership (AGP).

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**Front cover:**
United Parcel Service DC-8-72F in Philadelphia, Pennsylvania 8 February 2006 after an in-flight fire. (NTSB)

THE HONOURABLE COMPANY OF
AIR PILOTS

ROYAL AERONAUTICAL SOCIETY

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# PREFACE

This edition is an update of the Royal Aeronautical Society's specialist document Smoke, Fire and Fumes in Transport Aircraft first published in February 2007. Since then, regulations, checklist, procedures and equipment have changed, and there have also been additional accidents and fatalities due to in-flight fire.

The Second Edition was published in 2013 containing new sections on lithium batteries, composite materials and predictive technologies together with new recommendations to reflect the current risks.

Further updates to the lithium battery research and advice were included in the fourth edition.

This fifth edition expands the lithium battery issue with updated research, procedures, and advice. Referral to Part 2: Training with updated training advice.

The Flight Operations Group has monitored further developments with respect to the handling of Personal Electronic Device fires and lessons from recent cargo aeroplane accidents. As a result, we have conducted another update incorporating the latest risks and recommended mitigating actions in this Edition.

SAFITA Part 2: Training now updated with a Second Edition deals with flight and cabin crew training for handling smoke, fire and fumes in-flight events.

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# 1. Introduction

The purpose of this paper is to serve as a reference document on current risks and proposed mitigations for smoke and fire events on commercial transport aeroplanes. The occurrence of smoke or fire on board commercial aeroplanes during flight is a dangerous situation. If not dealt with effectively by the aeroplane's crew, it can result in disaster.

A statistical analysis of commercial jet aeroplane accident data shows that in-flight fire was responsible for the fourth highest number of on-board fatalities and was the seventh most frequent cause of accidents in 2005 (Boeing, 2005). Using the Commercial Aviation Safety Team (CAST) taxonomy, the number of fatalities is a primary criterion. Since 2005 there have been two B747 freighter fires that resulted in the loss of the aeroplane and flight crews, but no fatal fires aboard passenger aeroplanes. Consequently, the ranking of in-flight fires has decreased since 2005 due to the reduction in passenger fatalities in the annual Boeing statistical summaries. Had the freighter fires occurred in passenger aeroplane causing fatalities, the rankings would certainly have been different.

In addition, data from recent years indicate the probability of passengers experiencing an in-flight smoke event is greater than one in 10,000. In the United States alone, more than one aeroplane a day is diverted due to smoke (Shaw, 1999). According to the FAA, in the event of an in-flight fire:

*"...delaying the aircraft's descent by only two minutes is likely to make the difference between a successful landing and evacuation, and a complete loss of the aircraft and its occupants."* (2004)

Over many years there have been significant improvements to the safety of commercial aeroplanes. However, there is still opportunity for improvements in various areas including:

- Airworthiness requirements;
- Manufacturing and maintenance standards;
- The design of protective and emergency equipment;
- Improved procedures and training for flight crew and cabin crew.

It is a certainty that in-flight fire and smoke events will continue to occur in transport aeroplanes. Further reducing the risk of in-flight fire requires multiple layers of mitigation. The Flight Operations Group believes that adoption of the recommendations made in this document will likely reduce the probability and severity of future in-flight fires.

# 2. Abbreviations

| | |
|---|---|
| AC | FAA Advisory Circular |
| AD | Airworthiness Directive |
| ASR | Air Safety Reports |
| BOAC | British Overseas Airways Corporation |
| CAB | Civil Aeronautics Board |
| CAST | Commercial Aviation Safety Team |
| CFIT | Controlled Flight into Terrain |
| CFR | Code of Federal Regulations |
| COTS | Commercial, Off the Shelf |
| CVR | Cockpit Voice Recorder |
| DC | Direct Current |
| DV | Direct Vision Window |
| E&E | Electronics and equipment |
| EAPAS | FAA Enhanced Airworthiness Program for Airplane Systems |
| EASA | European Aviation Safety Agency |
| EFB | Electronic Flight Bag |
| EFIS | Electronic Flight Information System |
| EICAS | Engine Indication and Crew Alerting System |
| FAA | Federal Aviation Administration |
| FCC | Fire Containment Cover |
| FSF | Flight Safety Foundation |
| GAO | Government Accountability Office |
| GCAA | General Civil Aviation Authority |
| HUD | Head-Up Display |
| IASFPWG | International Aircraft Systems Fire Protection Working Group |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| IFALPA | International Federation of Air Line Pilots' Associations |
| IFE | In-Flight Entertainment |
| IFTC | International Fire Training Centre |
| InFO | Information for Operators |
| LOC | Loss of Control |
| LOFT | Line Oriented Flight Training |
| NPRM | Notice of Proposed Rule Making |
| NTSB | National Transportation Safety Board |
| OEM | Original Equipment Manufacturer |
| PBE | Protective Breathing Equipment |
| PED | Personal Electronic Device |
| QRH | Quick Reference Handbook |
| RAeS | Royal Aeronautical Society |
| RAF | Royal Air Force |
| SAFITA | Smoke, Fire and Fumes in Transport Aircraft |
| SDR | Service Difficulty Report |
| SOP | Standard Operating Procedure |
| STC | Supplemental Type Certificate |
| STEADS | Safety Trend analysis, Evaluation and Data Exchange |

| | |
|---|---|
| TSBC | Transportation Safety Board Canada |
| TWA | Trans World Airlines |
| UK CAA | United Kingdom Civil Aviation Authority |
| ULD | Unit Load Device |
| USAF | United States Air Force |
| VARIG | Vição Aérea Rio Grandense |

# 3. Background

From the beginning of aviation, uncontrolled in-flight fire has been a clearly identified risk. Aviation's first fatal accident occurred due to an uncontrolled in-flight fire. In July 1785, Jean-François Pilâtre de Rozier's hydrogen balloon ignited and burned over the English Channel. Dr Pilâtre de Rozier became aviation's first fatality (Sharp, 2012).

A review of past incidents shows that in-flight fires have continued to occur despite the efforts of manufacturers, regulators and operators. The FAA acknowledges in several documents that this risk will continue to be of concern:

*"We have concluded that we are unlikely to identify and eradicate all possible sources of ignition."* (2007)

*"...the examinations of large transport aircraft ... revealed many anomalies in electrical wiring systems and their components, as well as contamination by dirt and debris."* (2005)

The importance of such statements illustrates the need for several layers of mitigation when addressing smoke and fire issues.

The FAA further acknowledges the inability to eliminate ignition sources in a statement that reads as follows:

*"To address the first part of this comprehensive safety regime, we have taken several steps to reduce the chances of ignition. Since 1996, we have imposed numerous airworthiness requirements (including airworthiness directives) directed at the elimination of fuel tank ignition sources.*

*Special Federal Aviation Regulation No. 88 of 14 Code of Federal Regulations (CFR) Part 21 (SFAR 88; 66 FR 23086, 7 May 2001) requires the detection and correction of potential system failures that can cause ignition. Although these measures should prevent some of the (report's) four forecast explosions, our review of the current transport category airplane designs of all major manufacturers has shown that unanticipated failures and maintenance errors will continue to generate unexpected ignition sources."* (2007)

Additionally, the FAA reports 208 lithium battery fires between March 1991 and May 2018. There is a significant rise in the number, and the rate, of reported fires: 2018 (Jan – May) 16, 2017 – 46, 2016 – 31, 2015 – 16. (FAA 2018)

The FAA recognises that efforts to eliminate ignition sources will not eradicate the in-flight fire risk, since there are three requirements for a fire to occur: fuel, oxygen and a source of ignition.

## 3.1 Accident History

Several in-flight fires in transport aeroplanes have provided insight into the extent of the risk. One example is an uncontrolled fire that caused the crash of a TWA Lockheed Constellation on 11 July 1946, near Reading, Pennsylvania (CAB, 1946). Soon after departure on this training flight, the crew began to smell burning insulation. The flight engineer opened the flight deck door and reported to the Captain:

*"The whole cabin is on fire."* (CAB, 1946).

The flight crew attempted to fight the fire without success. Dense smoke streamed into the flight deck and filled it, obscuring the instruments. The training captain opened the window in an effort to find the airport, but was unable to maintain control. The aeroplane crashed, killing everyone on board, except the training captain. The accident report determined that:

*"The reason for the loss of control of the aircraft immediately prior to impact and therefore the most immediate cause of the accident, was the inability of the pilots to maintain adequate control because of the denseness of the smoke within the crew compartment."* (CAB, 1946)

The CAB determined that the probable cause of the fire was the:

*"...failure of at least one of the generator lead 'through-stud' installations in the fuselage skin of the forward baggage compartment, which resulted in intense local heating due to the electrical arcing, ignition of the fuselage insulation and creation of smoke of such density that sustained control of the aircraft became impossible."* (1946)

A contributing factor was found to be the:

*"...deficiency in the inspection systems, which permitted defects in the aircraft to persist over a long period of time and to reach such proportions as to create a hazardous condition."* (CAB, 1946)

Some of the same concerns raised in this accident, such as electrical arcing, ignition of insulation, and creation of dense smoke, occurred nearly 70 years later in the Swiss Air Flight 111 accident (TSBC, 2003).

## Enter the Jet

BOAC began scheduled transatlantic jet services on 4 October 1958; Pan Am followed on the 26th of that month. With the introduction of jet aeroplanes and the gradual retirement of conventional piston-engine equipment, the accident rate declined. This was due, in part, to the improvements in design and equipment reliability, but especially as gas-turbines replaced piston engines as the means of propulsion. In addition, the regulatory requirements for commercial aeroplanes became more stringent. However, at least two B707s encountered serious fires with severe smoke that resulted in the loss of the aeroplanes. These two accidents in 1973 caused further changes in regulation, design, and procedures for the B707 and future aeroplanes.

## VARIG Flight 860

On 11 July 1973, VARIG Flight 860, operated on a B707 aeroplane, departed Rio de Janeiro for Paris. After a routine flight, it was approaching Paris Orly airport when a fire broke out in the aft cabin. Smoke filled the passenger compartment and began filling the flight deck. Less than three nautical miles from Runway 07, in a smoke-filled flight deck where visibility of the flight instruments was diminishing rapidly, the captain decided to attempt a forced landing short of the runway in a field, which turned into a crash landing after the aeroplane struck trees.

Opening flight deck windows did not provide the pilot with sufficient visibility to continue flight to the runway. Only 70 seconds remained before VARIG Flight 860 would have reached the safety of the runway, where airport rescue and fire-fighting crews were standing by. Unquestionably, there would have been a better landing environment on the runway compared to a field, yet the captain chose the field.

There remains uncertainty whether this was due to smoke or fire. Autopsies of many of the passengers showed that the cause of death was not fire, but smoke inhalation (Secrétariat d'état aux

Transports, Commission d'Enquête, 2005). Conditions in the flight deck may have deteriorated to such a point that there was a question as to the ability to maintain control of the aeroplane for another 70 seconds.

An important clue to the condition of the flight deck is that the surviving crewmembers were not burned but suffered smoke inhalation injuries. It is possible that the captain's decision was based not on fire entering the cockpit, but the amount and density of smoke affecting visibility.

Further evidence that smoke was a more significant issue than the fire itself is that 117 passengers survived the landing, yet all but one succumbed to asphyxiation by poisonous gas and smoke. (Johnson, 1985)

## Pan Am Flight 160

Later in that same year, Pan Am Flight 160 (a B707-321C) departed New York for Prestwick, Scotland, on 3 November 1973. About 30 minutes into the flight of this all-cargo jet, the crew reported smoke on board (NTSB, 1974). The origin of the smoke was established to be improperly packed hazardous cargo. Unfortunately, the aeroplane crashed just short of the runway at the Logan International Airport near Boston, Massachusetts to which it was diverting. The NTSB determined that the probable cause of the accident:

*"...was the presence of smoke in the cockpit which was continuously generated and uncontrollable. The smoke led to an emergency situation that culminated in loss of control of the aircraft during final approach, when the crew in uncoordinated action deactivated the yaw damper which, in conjunction with incompatible positioning of flight spoilers and wing flaps caused loss of control."* (1974)

The NTSB Safety Board further determined that:

*"...the dense smoke in the cockpit seriously impaired the flight crew's vision and ability to function effectively during the emergency."* (1974)

## Commonality of cause

Both of these examples show smoke situations so serious that crew members took drastic actions. VARIG Flight 860 intentionally landed in a field, while Pan American Flight 160's flight engineer selected the essential power selector to the 'external power' position, causing the yaw damper to cease operation. With the flaps set for landing and the spoilers extended (which they had been for the preceding four and a half minutes) the aeroplane became extremely difficult to control.

This action was probably taken without the knowledge or agreement of the captain. In both aeroplanes there was a smoke-filled flight deck; yet, there is no mention of a flight deck fire on either CVR. This demonstrates that not only should fire be considered, but that the effects of smoke in the flight deck are also a safety risk.

The loss of VARIG 860 and Pan Am 160 were instrumental in changing regulations, flight crew procedures and designs for transport aeroplanes. Some of these changes were:

- Improved flight crew procedures for smoke removal;
- Tightened regulation for the shipping of hazardous material;
- Improved design in cabin airflows;
- New requirements that waste towel receptacles be made more fire resistant;
- The banning of smoking in the lavatories.

## 3.2 Technology in Later Generation Aeroplanes

The second generation of jets included wide-bodied aeroplanes such as the B747 jumbos. There were new safety issues for these aeroplanes, but not all were fully anticipated.

An example of this was the airflow pattern within the B747 cabin. In the late 1960s, there was no requirement to predetermine the airflow patterns in transport aeroplanes or standardise them during the design stage. It was subsequently found that, with some airflow settings, smoke could be drawn into the flight deck of the B747SP during a main deck passenger compartment area fire. The FAA proved this in April of 2003 during comprehensive tests (Blake, 2003). The tests showed the complexity of airflow patterns in some wide-bodied aeroplanes, which can allow smoke to accumulate in unexpected places.

Advancing technology provided many operational and safety improvements in this generation of jets. One consequence of the increase in the number of systems was to increase the number of wires routed through the aeroplane. Wire bundles grew in size as the use of electronics to control aeroplane systems increased. Also adding to the growth of wires in aeroplanes was a desire for greater system redundancy. Dispatch reliability was becoming a major selling point for aeroplane manufacturers. Therefore, redundancy was increased to improve reliability, consequently increasing the amount of wiring within the aeroplane.

Additional wiring adds weight to an aeroplane; hence, manufacturers use newer, lighter wire and insulation to mitigate the weight gain. Some of the lighter insulation material was found to be susceptible to cracking, leading in some cases to arcing. Unfortunately arcing can cause a self-sustaining fire in just a few minutes, when combined with combustible material (which can be the wire insulation itself).

Various types of wiring insulation are in use in aeroplanes. Because of the breakdown of different types of insulation over time, the FAA undertook a study in 2008 of the degradation of some common wiring insulation types. As a result of this study, the FAA recommended that:

*"Wire specifications should be revised to incorporate resistance to cut-through, abrasion, hydrolysis, and longer-term heat ageing"* (2008)

Furthermore, requirements for improvement in the maintenance of wiring systems became a regulation in November 2007 (FAA, 2007).

Studies have consistently shown that breakdown or contamination in wiring insulation has resulted in arcing events, even between wiring bundles where different voltages occur. The result can be high voltage being introduced into low voltage wire with the resultant failure of the low voltage wire insulation.

One well-known example of a wiring caused fire that spread rapidly is an MD-11 that was lost on 2 September 1998, Swissair Flight 111. The MD-11 departed New York on a flight to Geneva, Switzerland. Cruising at 33,000ft, unusual odours were noticed by the crew 52 minutes after take-off. The pilots reported smoke in the flight deck four minutes later and began to divert to Halifax, Nova Scotia descending to 10,000ft and dumping fuel. Soon after levelling at 10,000ft both pilots simultaneously declared an emergency, saying that they needed to land immediately. The last radio transmission from the aeroplane was received 14 minutes after the initial declaration of the emergency. Approximately one minute before the final transmission, the flight data recorder began to record multiple system failures. The

TSBC determined that:

*"the fire most likely started from a wire arcing event."* (2003).

Many of the findings in the report are consistent with recommendations in this document.

Of significant importance was the cascade of multiple failures as the fire affected electrical wiring throughout the forward fuselage overhead areas of the MD-11. This caused multiple simultaneous system failures including the primary flight instruments, resulting in the flight crew's workload increasing dramatically.

Severity of the damage caused by fire and its potential for rapid growth are reasons why minimising ignition sources are necessary. Examinations of in-service transport aeroplanes have shown that many had ignition risks on board (Sadeghi, 2003). In consideration of risk mitigation, it must be assumed that every transport aeroplane in service also has a risk of electrical fire. This is consistent with the FAA statements previously cited that ignition sources cannot be fully eliminated (2007).

Another example of an accident caused by a wiring fault is TWA Flight 800. The B747 took off from JFK on 17 July 1996 and exploded while climbing through 13,000ft. The NTSB found the cause to be an explosion of the centre fuel tank. There was evidence of arcing in the wiring in the recovered wreckage, which could have allowed high voltage electricity into the fuel quantity wiring, causing an explosion of the centre fuel tank (NTSB, 2000).

During the investigation, the NTSB examined the wiring in 25 transport aeroplanes. Only one of the aeroplanes (a new B737 not yet in service) did not have metal shavings on or near wiring bundles. Five of the aeroplanes showed signs of fire or heat damage in wiring. Many of the aeroplanes had foreign material between wires or wiring bundles, including:

- Lint;
- Metal shavings;
- Washers;
- Screws;
- Rivets;
- Corrosion prevention compound.

In some instances, wire insulation was damaged or cut by the metal debris and there were examples of the core conductor being exposed (NTSB, 2000).

The TWA Flight 800 in-flight explosion resulted in an investigation on fuel tank safety and also included ageing aeroplane electrical systems. It produced a number of ADs and ACs etc., including a comprehensive programme of inspection. The fuel-tank inerting requirements now in effect are a direct result of aviation recognising that arcing can be a hazard that could not be completely eliminated.

## 3.4 Recent Accidents

On 3 September 2010 a B747-400F departed Dubai, UAE for Cologne, Germany operating as UPS Flight 006. Nearing their cruise altitude of 32,000ft and 22 minutes after departure the fire warning bell activated, and the crew received a warning indicating a main deck cargo fire. The flight turned back toward Dubai, which was less than 150 nautical miles away.

During the descent to 10,000ft the aeroplane depressurised due to a fault in pack 1 and an automatic feature in packs 2 and 3. During the descent, and five minutes after the activation of the fire bell, the pilots reported to air traffic control that the flight deck was "full of smoke." The visibility in the flight deck degraded until the flight crew was unable to effectively monitor the flight instruments.

Due to lack of oxygen the captain delegated the first officer to be the flying pilot while he retrieved portable oxygen aft of the flight deck. The captain never returned to the flight deck. Soon after the captain left the flight deck, the first officer again advised air traffic of the density of the smoke in the flight deck and that he was unable to set radio frequencies.

The first officer attempted to slow the aeroplane to landing speed by extending the landing gear; however, it did not extend. The aeroplane overflew Dubai, entered a descending right turn and impacted the desert nine nautical miles south of Dubai. (GCAA, 2010)

The density of the continuous smoke, lack of sufficient oxygen, and the inability to successfully fight the fire were significant issues. Due to the location of the initial fire and the contents of some of the shipping containers near that location, the possibility that lithium batteries could have been the source was considered.

Several safety recommendations were included in the interim accident report to reduce risks associated with lithium batteries. The interim report included GCAA, FAA, EASA and ICAO recommendations and guidance. The final report, issued in 2013, expanded on the recommendations.

Another B747 freighter experienced a catastrophic in-flight fire less than a year later. On 28 July 2011, the Boeing 747-400F operating as Asiana Flight 991 departed Incheon, South Korea bound for Shanghai, China. After 50 minutes, the first officer reported a cargo fire, requested an emergency descent and a diversion to Jeju.

The crew reported flight control problems and that *"Rudder control…flight control, all not working"* some 15 minutes after the initial report of the fire. Shortly after this transmission the B747 impacted the sea.

Sooting was found on several pieces of wreckage, including near the outflow valves and smoke evacuation shutter, showing evidence of a serious in-flight fire. Sooting patterns and fire damage were consistent with a cargo fire in the aft portion of the aeroplane. There was evidence of an explosion likely caused by the fire.

Similar to UPS Flight 006 there were lithium batteries in the cargo of Asiana 991 listed among the dangerous goods. Also similar to the UPS Flight 006 accident there is clear evidence of smoke in the flight deck. Sixteen minutes after advising air traffic control of the fire warning, the captain remarks that they must *"open the hatch"*; this is in reference to the smoke evacuation shutter, which was found with soot stains. The location of the smoke evacuation shutter is in the overhead of the flight deck.

Unlike the GCAA report, there were no safety recommendations in the South Korean final report. (South Korean Aircraft and Railway Accident Investigation Board, 2012).

# 4. Current Risk of Smoke and Fire

From 1990 to 2010 there were 18 major accidents involving in-flight fire (FSF, 2014). These accidents resulted in 423 fatalities. (Note: these accidents include some Russian manufactured aeroplanes).

This summary does not include the UPS DC-8 in Philadelphia, Pennsylvania on 8 February 2006 because, although the aeroplane was destroyed, there were no fatalities. A review of the FSF's Aviation Safety Network database finds six accidents listed during the same period. The FSF does not include the UPS DC-8 either due to the fact that there were no fatalities or, because it was a cargo aeroplane. This data shows the need for increased attention to all transport category air crashes relating to in-flight cabin fire or smoke and that the use of a raw number of fatalities does not truly represent the entirety of fire/smoke related incidents and accidents.

Data from several sources indicate the probability of passengers experiencing an in-flight smoke event is greater than one in 10,000. In the late 1990s the rate of diversion in the US on average was more than one aeroplane each day diverted due to smoke (Shaw, 1999). Fortunately, it is rare for a smoke event to become an uncontrolled in-flight fire. Later data collected by IATA estimates that more than 1,000 in-flight smoke events occur annually, resulting in more than 350 unscheduled or precautionary landings (2005). In-flight smoke events are estimated at a rate of one in 5,000 flights, while in-flight smoke diversions are estimated to occur on one in 15,000 flights (Halfpenny, 2002).

The FAA found in their research that:

*"Reports to air traffic, submission of Service Difficulty Reports (SDR), and several focused surveys reveal that approximately 900 smoke or fumes events in the flight deck or passenger compartment occur annually in transport category airplanes. Many of these incidents prompted the flight crew to declare an emergency and either divert, turn back or request priority handling to their destination."* (2011)

Over 36 months (from January 2002 to December 2004), IATA conducted a study of ASRs filed in their STEADES database from 50 commercial operators (2005). Over the three years 2,596 smoke events were recorded. Of the 2,596 events, 1,701 were in-flight occurrences of smoke. The highest number of these events occurred within the cruise phase of flight and resulted in an operational impact on the flight (e.g. a diversion and unscheduled landing). The fleet analysis illustrated that both Boeing and Airbus aeroplanes are equally affected by smoke events. The location of smoke events most frequently occurred in passenger compartments and these were in (in descending order of frequency): lavatory compartments, flight deck, cargo compartments and galleys.

In response to a February 2011 Freedom of Information Act request by the Association of Flight Attendants, the FAA reported 1,250 smoke/fume events in 2010 and 1,035 in 2009 in SDRs. Furthermore, they reported 16 accidents/incidents in 2010 and 9 accidents in 2009 attributed to smoke/fumes (FAA, 2011).

The data supports the conclusion that there continues to be in-flight smoke events that result in diversions. There has not been a decrease in in-flight smoke events since the 1990s. The data also indicates the probability of continued in-flight smoke events in the future if no major changes are put into practice.

To evaluate the potential severity of an in-flight fire using accepted definitions could be useful. AC 25-1309-1a, an AC published by the FAA relating to Certification Maintenance Requirements, contains definitions for identifying the severity of events and relating them to the frequency of occurrence. Using these definitions, an in-flight fire can be characterised as a potentially catastrophic event because it has the potential to be a *"condition that would prevent continued safe flight and landing"* (FAA, 1988).

According to AC 25-1309-1a, a catastrophic event must be *"extremely improbable"* (defined as conditions having a probability less than 10-9, or once in a billion). Analysis of in-flight fire events by Captain Jim Shaw shows a greater likelihood of occurrence than that of *"extremely improbable"* (1999). The Shaw study is consistent with the IATA study where during the 36 months examined, an average of two and a half smoke events occurred each day. Paul Halfpenny suggests that the probability of a diversion due to flight deck smoke could be a *"reasonably probable event (10-3 to 10-5)"* (2002).

More recent data shows consistency with the Shaw and IATA studies. In January 2011, the FAA InFO 11002 identified that there were over 900 smoke or fume events annually in the US (FAA, 2011). While the rate is less frequent than the FAA SDR data, it reinforces the conclusion that smoke and fumes occur more frequently than one in a billion flights. These references show that the risk of a smoke or fume event is not sufficiently low, although thee mitigations applied thus far by the Industry are important improvements. That being said, the accident data reviewed shows a much greater rate of occurrence of catastrophic in-flight smoke/fire/fume events than the definition of "extremely improbable", or once in a billion flights. In some rare cases, an in-flight fire can become a catastrophic event. There is a definite need for improved mitigations to reduce the likelihood of such events.

# 5. Potential Sources of Smoke and Fire

This section discusses the potential sources of smoke and fire. These include:

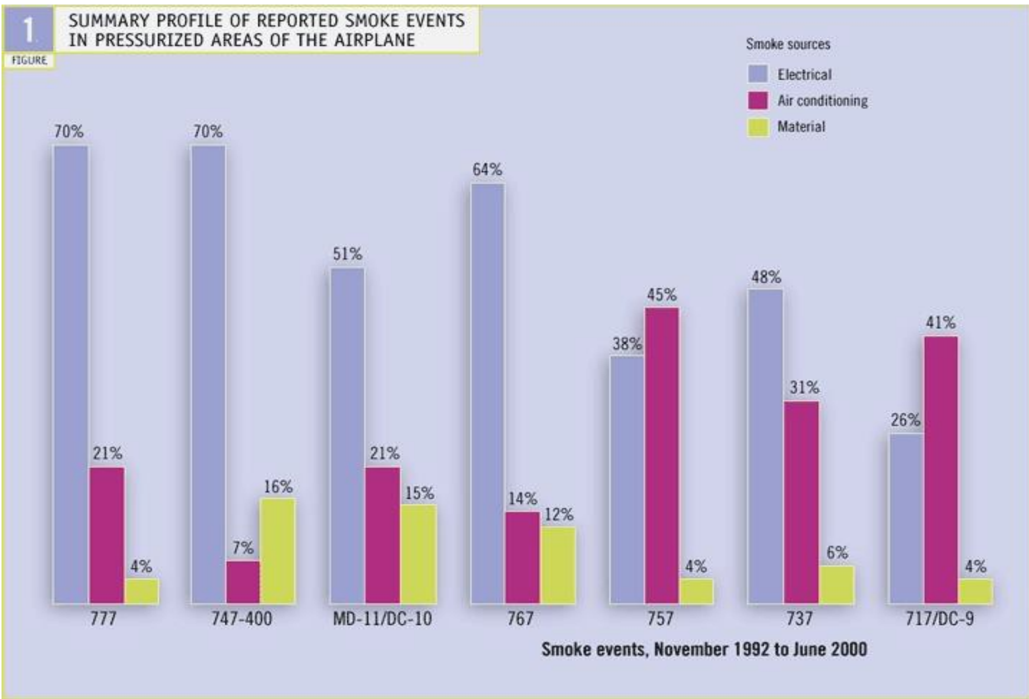
- Electrical systems and wiring;
- Equipment failures;
- Insulation blankets;
- Lithium batteries;
- Hot Components/Powerplants;
- Oxygen Systems.

## 5.1 Electrical Systems and Wiring

The FAA has recognised that electrical systems are, and will continue to be, potential sources of ignition. In the final rule for fuel tanks, the FAA stated:

*"…we have concluded that we are unlikely to identify and eradicate all possible sources of ignition."* (2007)

The most frequent source of fire in transport aeroplanes is electrical. A Boeing study showed that between November 1992 and June 2000 that over two thirds of the in-flight fires on Boeing aeroplanes were electrical (Boeing, 2000). One major ignition source for electrical fires is aeroplane wiring. In modern large transport aeroplanes there are over 500,000ft (150km) of wire. (Potter, 2003)




As the complexity and diversity of systems have grown in transport jets, so has the amount of wire. The addition of more wire has increased the probability of wiring related problems and fires, leading the industry to recognising that the wiring does not last the life of the aeroplane (Teal, 2001). The increasing complexity of electrical installations, especially on larger aeroplanes with premium class cabins, will result in further issues. Such installations include, but are not limited to, IFE Systems, electrically operated seats and charging systems for computers or other electronic devices. Each system installed in an operator's aeroplane can require unique procedures to deal with a failure or a problem that might result in an in-flight fire. Another issue is the addition of new systems to aeroplanes using existing circuit breakers to power the new equipment. The FAA Technical Center found this to be the case in a study of 316 circuit breakers. They found that:

*"...many of the lugs contained two wires and had two different size conductors."* (Air Safety Week, 2003)

This is in violation of 14 CFR § 25.1357. It can cause overloading of the circuit and the circuit breaker will not provide proper protection and additionally would not meet the current standard. Electrical fires can grow rapidly, as happened in the Air Canada Flight 797 accident. Boeing stated:

*"Review of historical data on the rare fire events that resulted in hull loss indicates that the time from first indication of smoke to an out-of-control situation may be very short — a matter of minutes."* (Boeing, 2000)

## 5.2 Equipment Failures - Cascading Effects

When a fire ignites it can spread and affect numerous independent systems. The ability to involve several independent systems defeats the risk mitigation provided by redundant systems.

Wiring failures in particular can be catastrophic, as the loss of an RAF Nimrod proved in May 1995 (RAF, 1995). The Nimrod was forced to ditch in the sea following a severe in-flight fire.

The investigation found that:

1. The DC wiring loom for the number one engine had an arcing event caused by an undetermined defect;
2. This arcing caused the wiring loom to fail and for several wires to melt together;
3. The resultant joining of wires caused an un-commanded signal to the number four-engine starter valve, causing it to open while the engine was operating;
4. As this valve opened, the turbine starter quickly over-sped;
5. The over-speeding starter turbine wheel flew out of its housing and punctured a wing fuel tank.

The ensuing fire was catastrophic, requiring the aeroplane to be ditched immediately. The investigators concluded that chafing of a nearby steel braid hose caused the initial wiring loom fault. Inspection of other Nimrods in the fleet found that 25% of the engines had defects in the wiring looms.

The loss of this Nimrod shows the potential for a fire to cause multiple or cascading problems. The fire, started by melting wires, caused the un-commanded opening of the starter valve, defeating all of the protection features that were intended to prevent it from opening during engine operation. This one event acted as a single point-of-failure as the fire defeated all the redundancies that were designed to protect the aeroplane.

The proximity of wires within wire bundles can cause seemingly unrelated systems to fail due to arcing and burning of wires within a single wire bundle. The need to carefully maintain wiring bundles is made apparent by the criticality of the consequences of wiring arcing, or other failure modes. As shown in Swissair Flight 111, the shorting, arcing and burning of wire can cause melting and provide a conductive path for electric power to other wires.

There is no regulatory requirement to evaluate the potential effect of an arcing wire that might cause the failure of multiple aeroplane systems. The regulatory requirements, met by the IFE system installation on Swissair Flight 111, proved to be inadequate. The system was de-certified after the accident.

This installation did not consider the proximity of the IFE power wires to critical wires powering the flight instruments. In addition, the STC did not show the routing of the power wires for the IFE (TSBC, 2003). Therefore, there was no consideration to the location of the IFE power wires contained in the STC.

This lack of specific wire routing standards applied to the implementation of the IFE system allowed for wire chafing and permitted the bypassing of the CABIN BUS switch. The CABIN BUS switch was intended to give the flight crew the ability to switch-off electrical power to the cabin. However, in the case of Swissair 111, electrical power to the IFE bypassed the CABIN BUS switch. Furthermore, the overall health of the wires within the bundle of the MD11 was not evaluated during the installation of the IFE (TSBC, 2003).

A common design feature of modern transport aeroplanes is to physically separate critical wires so that arcing in one wire cannot cause failure of another critical system.

## 5.3 Insulation

A developing fire needs a source of fuel for combustion. Insulation blankets, which are often located in inaccessible areas, can provide that source. The FAA has given specifications regarding the flammability of insulation blankets for initial certification of aircraft (FAA, 2005). However, as the aeroplane ages, flammable contaminates such as lubricants, corrosion inhibitors, hydraulic fluid and dust can coat the insulation blankets. As shown in NTSB investigations (Keegan, 2001) and FAA tests, (Blake, 1991) these contaminated blankets can burn and provide the fuel necessary for a fire to become self-sustaining.

In September 2005, the flammability requirements of thermal acoustic blankets were upgraded (FAA, 2005). This upgrade was the result of major work done by the FAA Technical Center in flammability testing and material flammability resistance.

In some electrical fires, the panel material or wiring insulation can provide the fuel for combustion (Keegan, 2001). The requirements for the flammability of wiring insulation material are specified in 14 CFR § 25.869 and AC 25.869-2A (FAA, 2008). These requirements have been improved over the years, but there are some aeroplane fires, such as on AirTran Flight 913, which involved wiring that met the standards of the initial type certificate issuance date but did not meet the current standard.

Due to the breakdown of wiring insulation over time, continued improvement and increasingly stringent regulations are necessary. The FAA found that:

*"Current wire specifications do not include qualification requirements for various wire characteristics that would better define wire performance in a multi-stressor aircraft environment. Wire specifications should be revised to incorporate resistance to cut-through, abrasion, hydrolysis, and longer-term heat aging, as applicable."* (FAA, 2008)

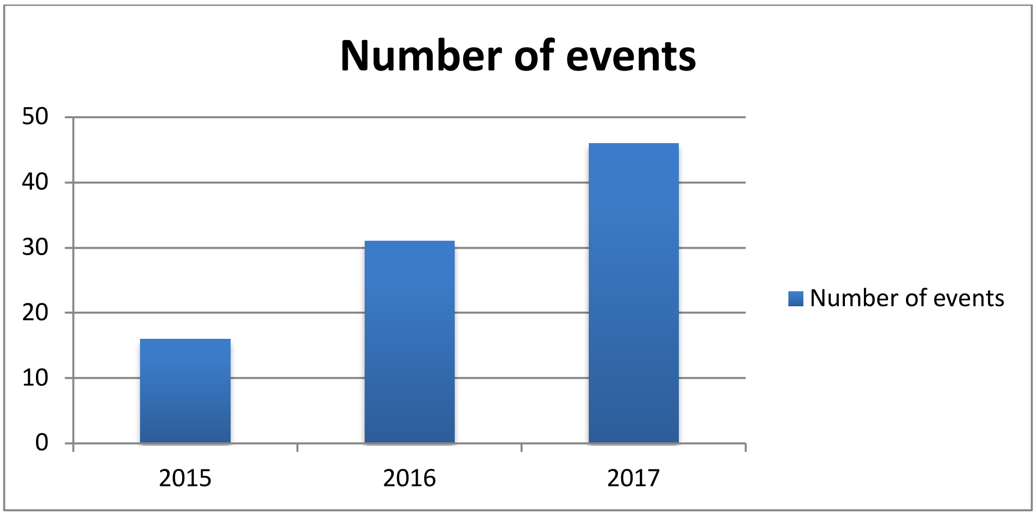
In some fires the surrounding material and location combine to create a serious hazard. AirTran Flight 913 experienced an electrical fire in the electrical power centre located just forward of the flight attendant jump-seat and directly behind the captain. The flight attendants did not attempt to find the source of the smoke nor did they attempt to discharge a fire extinguisher. The source of the smoke was uncertain, and the flight attendants had not been trained to remove interior panels when searching for smoke sources.

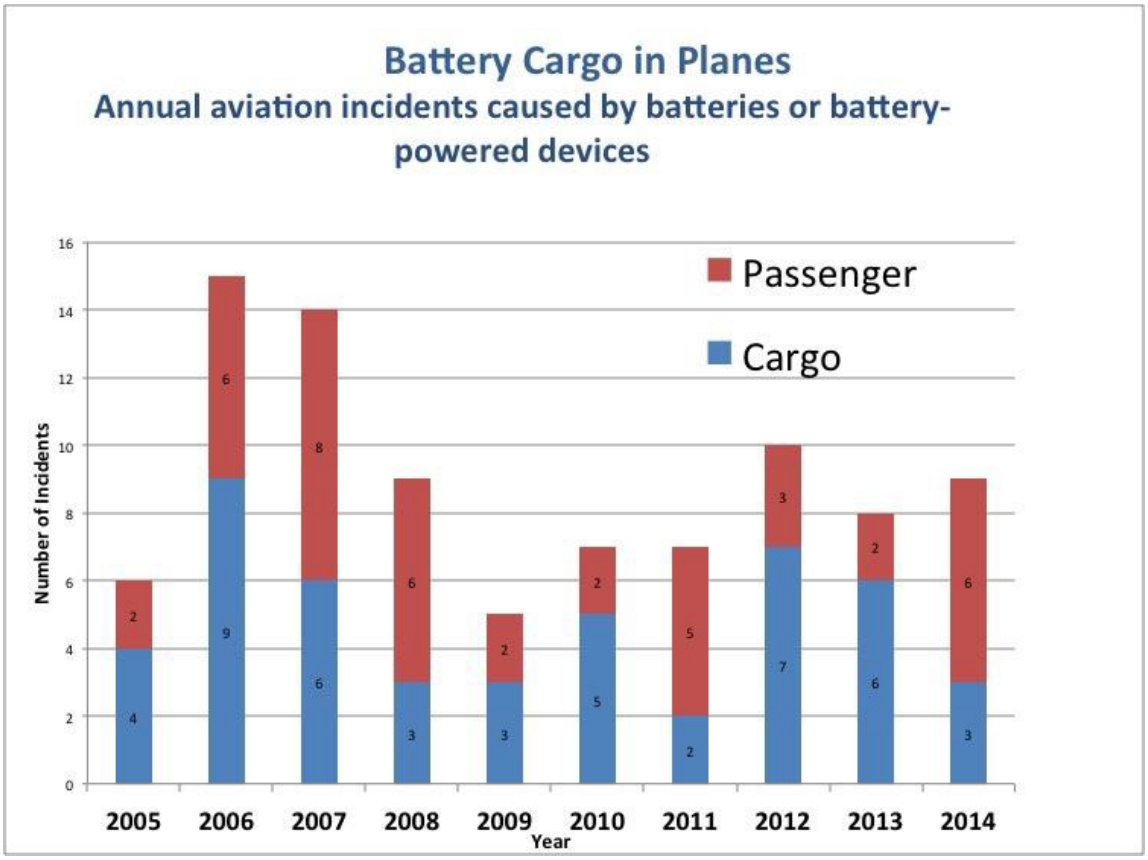
The location of the electrical fault and the lack of proper training prevented fire-fighting from occurring. The fuel for the fire was wiring insulation as well as the panel material. The NTSB determined the probable cause as:

*"A phase-to-phase arc in the left heat exchanger cooling fan relay, which ignited the surrounding wire insulation and other combustible materials within the electrical power center panel…"* (2000)

## 5.4 Lithium Batteries

One of the largest trends in the growth of in-flight fires is due to the transportation of lithium batteries. From March 1991 to August 2018, the FAA office of Security and Hazardous Materials Safety recorded 225 cases of aviation incidents involving smoke, fire, extreme heat or explosion involving batteries and battery powered devices (FAA, 2018). Lithium batteries were the majority of battery types in the incidents. Of particular concern is the increasing number of lithium battery fires onboard aeroplanes. In 2018 between January and August there were 34 events, in 2017 there were 46 events, in 2016 there were 31, and in 2015 there were 16 (FAA 2018).




(FAA, 2015)

Lithium ion batteries (Li-ion) are used to power portable electronic devices such as cellular phones, portable tablets, EFBs and digital cameras; Li-ion batteries are rechargeable. Non-rechargeable lithium batteries (Li-metal) are similar to Li-ion, but use a different electrode material - metallic lithium. New generation lithium batteries include other materials such as cobalt, and polymers causing unique by-products of combustion.

All lithium batteries present a potential fire hazard. These batteries are carried on aeroplanes as cargo, within passenger baggage, and by passengers directly. Like some other batteries, lithium batteries are capable of delivering sufficient energy to start an in-flight fire (Kolly). Lithium batteries present a greater risk of an in-flight fire than some other battery types because they are also unable to contain their own energy in the event of a catastrophic failure (Kolly).

Only a small heat source is needed to start a lithium battery fire. Manufacturing defects or damage sustained during shipping can initiate the ignition process, sometimes spontaneously. The material around lithium battery powered devices (often plastic) melts easily and ignites adjacent cells or batteries, contributing to higher fire intensity (Webster, 2004). When shipped as cargo, batteries are packed on pallets, and several thousand batteries can be shipped on an aeroplane without being declared as HAZMAT when they are shipped using Section II shipping regulations (IATA 2015).

Several aviation accidents and incidents, believed to have been caused by Li-ion battery-initiated fire, have occurred when battery shipments were placed next to other cargo on the aeroplane. One accident occurred on 3 September 2010, when UPS Flight 006, a cargo flight from Dubai, United Arab Emirates, to Cologne, Germany, crashed off-airport near Dubai, resulting in the deaths of the two crewmembers. The B747-400F departed Dubai, but returned due to smoke in the cockpit and the indication of major fire on the main deck

The investigation revealed that a large quantity (over 81,000) of lithium batteries were on the flight. Following the accident, the FAA issued a SAFO stating that Halon was inefficient in fighting fires involving a large quantity of lithium batteries. A restriction was also put in place to restrict the carriage of lithium batteries carried in bulk as cargo on passenger flights (FAA, 2010). Additionally, in July 2015, Boeing published a recommendation that lithium ion batteries no longer be carried as cargo on passenger airplanes until "…safer methods of packaging and transport are established and implemented." Boeing also recommended that those carriers who choose to continue to carry lithium ion batteries as cargo on either passenger or freighter aeroplanes do so only after a comprehensive safety assessment. (Boeing Multi Operator Message, 2015)

Further, a study sponsored by the FAA predicts six US-registered cargo aeroplane accidents will occur between 2012 and 2021 as the result of fire from all forms of cargo including bulk shipments of lithium batteries (R.G.W. Cherry & Associates Limited, 2013).

Additionally, IATA modified the Dangerous Goods Regulations to improve risk reduction for the shipment of lithium batteries (IATA, 2012, 2015).

Batteries travelling in passenger baggage can also start an in-flight fire. The FAA recommends that lithium batteries should not be packed in checked luggage but kept in hand luggage and stowed in the aeroplane's overhead compartments during flight. On 17 April 2012, an in-flight battery fire incident occurred on Pinnacle Flight 4290 from Toronto, Canada to Minneapolis/Saint Paul, Minnesota (Hradecky, 2012). While at 28,000ft, a passenger's personal electronic device (an air purifier) caught fire.

Photo of Mini Air Purifying Device after lithium-ion battery fire on flight from Toronto, Canada, to Minneapolis/Saint Paul, Minnesota, 17 April 2012.

During the in-flight service, the cabin crew noted that the device was on fire on the floor; its battery was burning several feet from the device. Using water from the service cart, the cabin crew put out the fire using wet paper towels. One of the cabin crew then submerged the battery in a cup of water because the battery was still smouldering. On the flight deck, the captain sensed a very strong burning electrical odour coming from the cabin. An emergency was declared and the flight diverted and landed safely at Traverse City, Michigan.

Li-Ion batteries such as the one described in the incident above do not need to be operating in an active circuit to catch fire and do not require an electrical short circuit to overheat. Similar incidents are becoming more common as the number of PEDs increase as shown in the FAA office of Security and Hazardous Materials Safety data. There was a 288% increase between 2015 and 2017 (16 events increased to 46) (FAA 2018).

From the Aviation Herald: “A British Airways Boeing 787-800, registration G-ZBJG performing flight BA-18 from Seoul (South Korea) to London Heathrow, EN (UK) with 205 passengers, was en route at FL380 about 25nm southwest of Irkutsk (Russia) when the battery of a passenger's smartphone suffered a thermal runaway and emitted smoke. The flight crew declared an emergency, reporting smoke in the cabin and the aeroplane diverted to Irkutsk while cabin crew began to cool the device down and brought the fire under control. The aeroplane landed safely in Irkutsk about 15 minutes after leaving FL380.

“The aircraft remained on the ground for almost three hours then was able to continue the journey and is estimated to reach London with a delay of three hours.”

“Russian Authorities reported that a passenger accidentally dropped his smartphone between the seats, where it was subsequently exposed to large pressure resulting in the battery being squashed and suffering a thermal runaway”. (Hradecky, 21 August 2015)

It is not uncommon for a passenger to carry several devices with lithium batteries. Devices include, but are not limited to, laptop computers, tablet computers, mobile phones, electronic watches, flashlights, EFBs, and e-readers.

On a typical flight, a single aisle jet carrying 100 passengers could have over 500 lithium batteries on board. These devices are not tested or certified nor are they necessarily maintained to manufacturers’ recommendations. Replacement batteries from questionable sources, the ‘grey’ market, can be contained within devices. Furthermore, a damaged device that is more prone to thermal runaway can be brought onboard without the crew being aware of the increased risk.

‘Grey’ market batteries may not be manufactured in accordance with international standards. It is possible that they have a greater probability than original equipment to overheat and cause a fire.

Lithium battery distributors do not always adhere to Dangerous Goods regulations and some may attempt to ship significant quantities of batteries via checked baggage. Operators should develop educational material to warn passengers of the dangers of carrying unsecured or improperly packaged lithium batteries and should include batteries as a specific question to be raised during the check-in process. In addition, operators, regulators and manufactures should recognize that the number of lithium batteries onboard will continue to rise. It is imperative that improved mitigations for thermal runaways be implemented.

In addition to the 'grey' market batteries, there is an increasing market for non-original chargers. These 'grey' market chargers may not have the protections for over-charging and charging rate found in original equipment. Over-charging is one way to cause a thermal runaway in rechargeable lithium batteries. These chargers are a growing concern, as the number of them increase so does the likelihood that a battery onboard, OEM or "Grey Market" could have been charged by a charger other than the OEM thereby increasing the possibility of a thermal runaway.

The FAA Fire Safety Branch through cooperation with the International Aircraft Systems Fire Protection Working Group conducted several tests using standard Li-Ion batteries, including flight deck smoke obscuration tests. The tests used a standard air exchange rate of one cabin air exchange every 60 seconds using one air conditioning pack (system) with the gasper fans operating; the flight deck door was closed for all tests. The results for the first test showed that there was no visible smoke or audible warning prior to the battery event. After the battery went into thermal runaway the smoke percentage was greater than 10% light obscuration per foot for a period of approximately 90 seconds (Summer, 2012). The second test performed outlined similar results. In conclusion, the outcome of the tests proves that even in a high ventilation rate a typical Li-Ion battery could pose a *"significant hazard within the flight deck environment and could potentially present a catastrophic risk"* (Summer, 2012). The FAA also determined that smoke from a battery fire possesses different properties than the "theatrical smoke" used for aircraft certification. This difference could account for many of the incidents where smoke penetrated the cockpit to the point of obscuring pilot vision.

One type of electronic device that is rapidly gaining use in all forms of aviation is the EFB. These devices are used by pilots to replace paper materials found inside the flight deck. EASA defines EFBs as either installed or portable; whereas, the FAA divides EFBs into groups by Classes (EASA AMC 20-25; FAA AC 120-76C):

1. Class I: Portable Electronic Devices (PEDs), Commercial off-the-shelf equipment (COTS), used as loose equipment and stowed during portions of flight (equivalent to EASA portable EFB);
2. Class II: PEDs can be COTS equipment, mounted and connected via aeroplane power supply for use in flight and for charging (equivalent to EASA portable EFB);
3. Class III: Not PEDs or COTS (equivalent to EASA installed EFB).

Class III is considered 'installed aeroplane equipment'. These are built and tested specifically for aeroplane EFB use (Summer, 2012). Class I and II are not subject to FAA airworthiness standards. However, Class II mounting and charging connections are subject to FAA airworthiness standards. Class III are subject to airworthiness standards for all aspects of their operation. Because Class I and II are not subject to FAA airworthiness standards, they bring potential hazards when used as EFBs. All classes of EFBs utilise Lithium batteries as their primary power source.

As the number of Class I and II devices increase in their use inside the flight deck, the number of potential hazards also increases.

The FAA Technical Centre conducted research on all classes of EFBs. They cited the primary concern as thermal runway of Lithium batteries.

*"The primary concern is the resulting fire/smoke hazards should one of the lithium-ion (Li-ion) batteries installed in these units fail and experience thermal runaway, a failure causing rapid increases in temperature, significant smoke production and at times, explosion and/or rocketing of the battery cell."* (2012)

Furthermore, the FAA tests found that:
*"The testing showed that even with a very high ventilation rate of one air exchange per minute within the cockpit, a typical COTS Li-ion battery could pose a significant smoke hazard within the flight deck environment. The initial battery event occurred, at times, without warning (i.e. no visible smoke or audible event prior to failure). The battery cells failed in a very vigorous manner, at one point with enough pressure to forcefully push open the unlatched cockpit door. The most striking safety hazard however, was the volume and density of smoke that emanated from the failed battery cells. During one test in which only four of the nine battery cells went into thermal runaway, the installed smoke meter recorded greater than 10% light obscuration/ft for a period of greater than 5 minutes and a peak value of greater than 50% light obscuration/ft, resulting in severe lack of visibility within the flight deck."* (2012)

This testing further supports the recommendation to equip cockpits with both vision assurance technology and PED extinguishing/containment technology referenced elsewhere in this document. It is important that pilots be trained to maintain control of the aeroplane during a smoke event, regardless of the source.

PEDs are becoming powerful, requiring more powerful batteries. This trend will probably increase as consumer demand for more devices continues to rise. The increasing energy densities of the batteries will also increase the likelihood of producing an uncontrollable in-flight fire. The proliferation of PEDs will also increase the risk of battery failure incidents (Keegan, 2001).

Technologies are available that are able to contain and extinguish portable electronic devices which are actively involved in a lithium-ion battery failure. While there have been several of these containment devices on the market, few have featured both adequate protection for the crewmember/firefighter attempting to contain the device and a method for suppressing a fire after containment. New technology now can adequately protect the crewmember/firefighter moving the device, extinguish the fire, and contain it safely. Incorporation of this technology is recommended in all aeroplanes, especially where crewmembers are using EFBs. Protecting the crewmember/firefighter must be the paramount concern. The FAA in AC 20-42D warns "Crew members should be trained not to use fire resistant bum bags to isolate burning Lithium batteries. Transferring a burning appliance into a burn bag may be extremely hazardous." (FAA 2011, January 11) This warning is reiterated in SAFO 09013 (FAA 2009). A review of PED overheating incidents reveals that many crewmembers are not following this guidance. Therefore, the guidance to crewmembers and operators should be updated and improved.

Technologies are also available to lessen the spread of Li-Ion battery-fuelled fires. The International Organization for Standardization (ISO) has developed a standard for Fire Containment Covers (FCCs) following a series of FAA tests determining their effectiveness on palletized cargo. The FAA has also conducted testing of intumescent paint, which acts as a thermal barrier, when used in the packaging of lithium batteries (Pennetta, 2012). Additionally, the FAA is actively testing cargo containers made of new materials much more resistant to heat energy than existing materials. They are also testing the efficacy of in-container suppression systems to control Li-Ion battery fires.

Testing conducted by the FAA in April 2014 created a thermal runway in a Unit Load Device (ULD) with 5000 Li-Ion batteries. This test resulted in an explosion and fire that destroyed the ULD. (The number of batteries which had actually experienced thermal runaway prior to the explosion was substantially less than 5,000.) A build-up of hydrogen created an explosive environment resulting in some of the contents of the ULD being expelled. In an aeroplane the violence of such an explosion could result in damage to the surrounding structure. This is the possible cause of the explosion of Asiana 991.

By-products of combustion of all types of lithium batteries include oxygen, ether, and hydrogen, among others. The organic vapour produced is highly flammable and is an irritant to mucous membranes. The chemical composition of the vapour creates a hazard to anyone in proximity to an overheated lithium battery, including crewmembers attempting to fight the fire. Crewmember protection must be considered when developing procedures to address lithium battery fires. Crewmember incapacitation is a serious concern due to the potential of burns received from the hot contents of a venting battery and/or vapour ingestion.

A review of lithium battery fire incidents also reveals that panic can result when a lithium battery thermal runaway occurs. In June 2014 a London Underground passenger's laptop began to emit smoke; panic quickly ensued as other passengers evacuated the subway at the Chancery Lane station, some thinking it was a terrorist attack. Such an event in an aeroplane could result in similar panic amongst the passengers. Therefore, consideration must be given to methods of safe containment of an over-heating electronic device as part of a range of measures to control the development of panic amongst passengers. Thermal extinguishing and containment technology is available and should be considered for carriage in the cabin by all operators.

The current FAA guidance states "Do not attempt to pick up and move a smoking or burning device! Bodily injury may result." (FAA 2009) there can, however, be times when moving the device will be necessary. An example would be a PED in thermal runaway in the flight deck or atop of an Inflight Entertainment System or other electronic device. Following FAA guidance, attempting to pour water or a non-alcoholic liquid could cause serious unintended consequences. The guidance does not address such situations. Improvement in the guidance to flight crews and operators is needed with updated and improved recommendations to address likely scenarios.

It should be noted that the use of burn bags is not recommended by the FAA in SAFO 09013 (Supplement) (FAA 2009) and Advisory Circular 20-42D (FAA 2014) due to the risk of serious injury to crew when inserting an overheating device into a bag. Other extinguishing agents (dry) and containment devices that adequately protect crew should be used. Furthermore, the adequate protection of firefighter/crewmembers is essential. New technology is available that protects crewmember/firefighters and extinguishes the PED fire without the potential issues of large amounts of water being dispersed in areas of the aeroplane where unintended damage could occur.

The use and transport of lithium batteries will continue to proliferate, even as the energy levels within the batteries increase. Adopting new technologies, restrictions and procedures to deal with this challenge will be necessary to maintain an adequate level of safety when carrying lithium batteries.

Unlike most safety issues in aviation, the risk posed by lithium battery thermal runaway and fire is rising. Only when multiple layers of mitigation are implemented will the risk decrease to an acceptable. The mitigations must include:

1. Guidance
    a. Regulators should update the guidance available to flight crews
    b. Regulators should improve the guidance available to flight crews to include scenarios being faced by the crews (e.g. overheating devices in the flight deck or in a cabin overhead bin where access is restricted)
    c. Regulators should include other extinguishing agents other than water in the guidance (preferably dry) due to water resistance of newer devices and the potential damage in the flight deck or other areas with electronics

2. Training
    a. Regulators should improve and standardize training recommendations
    b. Flight crew should be trained in the proper way to flight a lithium battery fire and the differences from a traditional fire
    c. Flight crew should be trained in the importance of properly using Personal Protective Equipment when fighting a lithium battery fire

3. Aeroplane Control
    a. Due to the large amount of organic vapour (smoke) produced by a lithium battery fire, pilots must be trained how to maintain control in a dense smoke environment
    b. Vision Assurance Technology, if installed, should be used if necessary
    c. The vapour produced by lithium batteries can incapacitate a pilot, therefore it is essential that oxygen masks with full face masks or goggles be utilized by pilots at the first sign of a thermal runaway

4. Capture/Extinguish/Contain
    a. Once a device has entered into thermal runaway only cooling will stop further progression. Therefore, flight crew must determine if the safer course of action is to fight the fire in the present location or to capture the device. Capturing the device can be extremely dangerous. It is essential that a barrier or shield be available to the crewmember. When approaching the device with the barrier in place it possible to deploy new technology dry extinguishing systems or to use water to cool the device.
    b. With the barrier in place it may be possible to move the device into a containment system to eliminate the possibility of explosive shrapnel. Once in the containment device additional cooling or extinguishing can be applied
    c. The device once contained should pose no additional threat. This requires that the containment system be fully capable of withstanding venting or exploding batteries.

Due to the complexity of lithium battery issues simple solutions are not available. By using the aforementioned multiple layers, the risk be mitigated to acceptable level.

# 6. Mitigations during Flight Operations Detection, Prevention and Fire Fighting

Fire detection and protection exist in the engines, auxiliary power unit (if installed) and cargo compartments of modern transport aeroplanes. Smoke detectors are installed in lavatories, with automatic fire extinguishers in the waste bins. Other parts of the aeroplane are unprotected. In the unprotected areas, fire detection depends upon flight crew and the cabin crew involvement.

Prevention of a fire, while desirable, is not possible in all cases. Consequently, consideration of detecting and fighting fire must be included in the mitigations.

Smell is usually the first sensory indication of a fire or potential fire. Once the particular odour is detected, locating the source can be difficult; finding the source can be made more difficult by the high air exchange rate in the passenger cabin area of an aeroplane. On average, the air is exchanged once every two or three minutes, with all air-conditioning packs operating. This can cause dilution of the smoke and dispersal throughout the cabin. Flight crew following the appropriate Smoke/Fire/Fume checklist may change the airflow rate as fans and/or air conditioning packs are shutdown. Action to maintain positive pressure in the cockpit by maintaining sufficient airflow may be necessary. Increasing the number and location of detectors would help in the early detection of smoke/fire/fumes and help pinpoint the location of the smoke.

Boeing states that more than two-thirds of fires are electrical in origin (Boeing, 2000). This means that there is a significant risk that an electrical fire might start in an unmonitored area of the aeroplane, because there is much more wire in unmonitored parts of the aeroplane (between the passenger cabin and the exterior skin of the aeroplane as well as in unmonitored compartments separate from the cabin, flight deck, and cargo areas), than there is in monitored areas.

## 6.1 False Alarms and Diversions

During a 36-month study from January 2002 to December 2004, IATA found 2,596 reports (including jets, turbo props and helicopters) of fire/sparks/smoke/fume occurrences. Of the 2,596 reports, 525 (20%) were false warnings resulting in 11% of in-flight diversions due to such false warnings. Approximately 50% of cargo compartment fire warnings were also false (IATA, 2005).

Following the May 1996 accident of ValuJet Flight 592, the FAA required the installation of fire detection and suppression systems for Class D cargo compartments (thus converting them to Class C compartments) in commercial air transport aeroplanes by 19 March 2001. Approximately 3,000 aeroplanes required retrofitting. (Blake, 2000). This requirement, as expected, resulted in a significant number of false cargo compartment fire warnings (Schmoetzer, 2003). The 14 CFR § 25.858 (a) (and EASA) requires that detection systems must provide a visual indication to the flight crew within one minute after the start of the fire. There is a compromise in speed of the warning and the probability of false warnings.

The FAA Technical Center studied the ratio of false warnings in cargo compartments to actual smoke or fire events in 2000. They found that the false alarm rate was increasing at that time. (Blake, 2000). The rate of false warning is too high and improvements in the reliability of smoke and/or fire detectors are required.

## Multi-source sensors as a mitigation for false alarms

False engine fire warnings plagued pilots in the past. Modern aeroplanes now use a dual-loop system to provide redundancy and reduce the potential for false fire warnings. Dual-loop systems require fire to be sensed on both systems before illuminating the fire warning on the flight deck. This improved system also has the benefit of improving the dispatch reliability by having a redundant system. The idea of redundancy demonstrated by dual-loop systems could be used in cargo compartments and other fixed detection systems.

Another technology to reduce false warnings, while still providing rapid warning, is using two different types of sensors (e.g. smoke and thermal) with an algorithm to interpret inputs in order to distinguish a nuisance input from a real fire.

Cargo compartments on aeroplanes manufactured up to 2005 have only single source fire detectors. Some manufacturers have proposed using multi-source sensors in new aeroplanes (Schmoetzer, 2003). Airbus had proposed using multisource sensors in the A380, but instead installed a compensated optical system. Multi-source technology dramatically reduces the possibility of false fire warnings. Using similar technology, now that it is proven, should be considered for application in other areas of the aeroplane. Detection of a fire in the vast inaccessible areas of the aeroplane should use multi-source sensors.

Since the Swiss Air Flight 111 accident, flight crews have shown an increasing willingness to divert at the first indication of a potential smoke/fire/fume event. Additionally, the FSF industry-standard checklist includes the potential need to divert near the top of the checklist. As a result of this approach to a potential event, the number of diversions due to non-fire events has increased. These diversions are expensive for the operators and, if they are caused by false warnings, they can eventually de-sensitise flight crews.

The causes of these non-fire events are numerous, including overheated fans, bleed air odours, galley ovens, and many more. Of the three diversions that occur daily, (over 900 annually) many are caused by non-fire events (IATA, 2005).

## Predictive technologies to reduce diversions

Predictive technologies are desired to avoid simply reacting to accidents. Examples include predictive flight path monitoring in Terrain Awareness Warning Systems and predictive windshear monitoring. These applications of predictive technologies warn flight crews of pending dangers in time for them to react and avoid an accident.

The development and introduction of technology that can predict and actively intervene to stop a smoke-producing component (e.g. fans) before the smoke begins has significant potential benefit. By shutting down components such as air cycle machines, fans, or other rotating components, the cases of diversions due to odour and smoke of undetermined origin would decrease.

An example of the significance of component-caused smoke odours is the Boeing data showing that the number one most common cause of smoke in the B757 is fans in the air conditioning system (Boeing, 2000). Operators using predictive technology on these fans have fewer in-flight smoke events resulting in a lower number of diversions (Rosenkrans, 2011). There are safety, financial, and operational benefits as a result of improved reliability.

## 6.2 Fire Location

Experience shows that fires can start in inaccessible locations, making it difficult or impossible to extinguish the fire. The fire in the roof space of Swissair Flight 111 spread rapidly without the ability of the crew to extinguish it due to its location. There was no means to direct a fire-extinguishing agent at the source of the fire in the area above the interior ceiling.

The inability to access the source of the fire is a serious limitation that significantly reduces the likelihood of successfully extinguishing it. All fire extinguishers work best when they are discharged at the base of the fire. The flight attendants on Air Canada flight 797 observed the increase of smoke as the fire progressed behind the lavatory wall, but recognised that the fire was inaccessible.

The NTSB stated in the accident report:

*"...in order for the extinguishing agent to be effective it must be applied to the base of the flames."* (1986)

Consequently, in inaccessible locations the inability to reach the base of the fire raises the risk that the fire will spread and intensify.

The FAA in AC120-80A made the following statement:

*"For aircraft with hidden fires, an approximate assessment is that only one third will reach an airfield before the fire becomes uncontrollable" (FAA, 2014)*

This clearly identifies the risk and the urgency of the required flight crew and cabin crew actions.

## 6.3 Pilot Procedures

Standard operating procedures (SOPs) and emergency/abnormal checklists are vital tools for crew members to use for successfully managing an in-flight fire or smoke event; therefore, the quality of the design of these procedures and checklists is extremely important. Manufacturers and operators should ensure that human factors issues such as workload and checklist complexity are considered, as well as evaluating the technical aspects of the procedures and checklists. The investigation of Federal Express Flight 1406 reported that:

*"...during post-accident interviews, the flight engineer said that he felt rushed with the workload during the descent."* It also appeared that he inadvertently skipped an item on the checklist and did not complete another item correctly (NTSB, 1998).

The NTSB report concluded that the failure of the flight engineer to complete the 'Fire and Smoke' checklist correctly caused the aeroplane to remain pressurised on the ground after landing, making it difficult to open doors and emergency exits, thereby delaying the evacuation (NTSB, 1998).

Fire or smoke events with an associated alert will normally have an associated checklist that crew members can follow. It is important that these checklists and associated SOPs do not focus purely on the technical aspects of the event, but also remind crew members of other considerations, such as the need to consider early diversion/emergency landing and how to manage multiple checklists, normal as well as emergency and abnormal. A noteworthy example is a regional jet that landed without accomplishing the pre-landing checklist. As described by the pilot:

*"I feel that I became too focused on finding the circuit breakers and that communications between me and the captain broke down. I found myself unaware of our location and when I realised where we were, we were already on short final."* (Air Safety Week, 2003)

The priority for this first officer was completion of the Quick Reference Handbook checklist, but other critical items in the pre-landing checklist were not accomplished and there was a loss of situational awareness.

The challenges presented by non-alerted fire or smoke events can be even greater. The early cues for non-alerted conditions, such as air conditioning smoke or an electrical fire, are often ambiguous and elusive. In a study of 15 in-flight fires that occurred between January 1967 and September 1998, the TSB of Canada determined that the amount of time between the detection of an on-board fire and when the aeroplane ditched, conducted a forced landing, or crashed ranged between 5 and 35 minutes (TSBC, 2003). These findings indicate that crews may have precious little time to complete various checklist actions before an emergency landing needs to be completed and, hence, the checklist guidance to initiate such a diversion should be provided and should appear early in a checklist.

The FSF sponsored an international safety initiative to improve checklist procedures for pilots confronting fire or smoke events (FSF, 2005). The initiative included a selection of manufacturers, operators and crew representatives from around the world. This initiative resulted in the publication of the Smoke/Fire/Fumes Checklist Template to specifically address flight crew responses to non-alerted smoke/fire/fumes events (FSF, 2005). The template includes the following considerations:

- At the beginning of a smoke/fire/fumes event, the crew should consider all of the following:
  - Protecting themselves;
  - Communication;
  - Diversion;
  - Assessing the smoke/fire/fumes situation and available resources.

- The entire crew must be part of the solution;
- For any smoke event, time is critical;
- Checklist authors should consider a large font for legibility of checklist text in smoke conditions and when goggles are worn;
- Rapid extinguishing/elimination of the source is the key to prevent escalation of the event.

The template is included in Appendix 1.

Currently, when crews wish to complete a checklist for a non-alerted smoke/fire/fumes situation, they typically access a checklist that has been developed for a specific type of smoke, fire, or fumes, (e.g., Air Conditioning Smoke, Electrical Smoke, Fire, or Fumes, etc.). Thus, crews are presented with a list of several different smoke/fire/fumes checklists and they must first determine what type of smoke/fire/fumes they have in order to select the proper checklist from the list. However, some cues for non-alerted events are often quite ambiguous and making a distinction between air conditioning, electrical, materials, florescent light ballast, dangerous goods (i.e., hazardous materials), or some other type of smoke/fire/fumes can be quite difficult. Precious time is wasted if a crew completes a checklist for the wrong type of smoke/fire/fumes. The FSF checklist template proposes the use of an integrated non-alerted smoke/fire/fumes checklist that includes items for all or most types of un-alerted smoke/fire/fumes events that might occur on the aeroplane.

For over-water flights a ditching may be preferable to emergency landing in some circumstances, and checklist guidance should be provided accordingly.

In many earlier non-alerted smoke/fire/fumes checklists, a number of items were devoted to identifying the specific source of smoke/fire/fumes and concurrently isolating and eliminating it. When using a checklist designed according to the FSF template, crews will eliminate the most likely sources of smoke/fire/fumes early on during checklist completion without making a determination first as to whether one of these sources is in fact causing the smoke, fire, or fumes; this step involves source isolation/elimination but not source identification. Hence, a crew may complete the checklist successfully (i.e., fire is extinguished, smoke is dissipating) without ever having to positively identify the source of the smoke/fire/fumes.

The construction and design of checklists to be used for non-alerted smoke/fire/fumes events is very challenging; the types of events for which they might be needed vary widely, but, at their extreme, are highly time-critical and life threatening. Additionally, the cues available to crew may not be very helpful in determining their situation and at times may actually be misleading (Burian, 2005). The use of the FSF template to provide an integrated checklist for non-alerted smoke/fire/fumes is strongly recommended. Since the initial publication of this document most aeroplane manufacturers have revised their checklists to conform to the FSF template. This is a positive step for aviation safety.

## Smoke removal

Once smoke enters the flight deck, its effects can be significant. Aeroplane manufacturers provide procedures for a flight crew to evacuate or remove flight deck smoke. Different methods have been chosen by different manufacturers to remove smoke from the aeroplane.

The procedure for opening flight deck windows continues to be part of some manufacturers' smoke removal checklist, despite the examples of the ineffectiveness of this procedure. Unfortunately, there are flight crews who continue to believe that opening a flight deck window will help vent the flight deck of smoke. Smoke needs to be moved aft, or to an outflow valve, and vented overboard. Another negative result of attempting to open a flight deck window is the requirement to slow the aeroplane before it can be opened, which delays the landing. With the flight deck window open, the increased noise level may have a severe impact on intra-flight deck communication. The inability of a flight crew to communicate during an emergency is a serious hazard that should be avoided. Orderly communication is necessary to complete complex procedures contained in abnormal and emergency checklists.

## Maintaining Smoke Barriers

Smoke migration is a result of a spreading fire. As a fire burns, heat is released, and the products of combustion begin to migrate. Minimising the spreading of smoke and fumes into the flight deck is critical for the continued safe operation of the aeroplane.

In most modern aeroplanes, the flight deck door is a major part of the smoke barrier. A review of several accidents found that the flight deck door was opened on at least one occasion, which allowed smoke to enter the flight deck. Once the flight deck door is opened, it is no longer a barrier.

One example occurred when a cabin crewmember aboard a Cubana DC-8 opened the locked door when the cabin was full of smoke, prompting the captain to shout: “Close the door! Close the door!” (Commission of Enquiry, 1977). However, the entry of smoke and fumes continued (the report is unclear if the door was closed at the captain’s command). The aeroplane crashed into the water.

Another example was AirTran Flight 913, when the flight attendants opened the flight deck door while smoke was pouring into the forward galley area. Although there was already smoke in the flight deck, the flight attendant could not have known this and might have allowed more smoke in. Unfortunately, opening a flight deck door during a smoke event is not a rare occurrence. This tendency to open a flight deck door shows that crew training does not effectively address the importance of maintaining the smoke barrier (NTSB, 2000). The flight deck security requirements introduced post- 9/11 reflect the need for the flight deck door to remain closed during an in-flight fire and that primary means for communication between the flight crew and the cabin crew is via the interphone system. Other flights have lost an effective smoke barrier even before take-off. In Air Canada Flight 797,

*“a 30-inch-long by 6-inch-wide louvered panel at the bottom of the cockpit door was kicked accidentally from its mounts and fell to the floor.”* (NTSB, 1986)

This compromised the door as a barrier and allowed smoke to enter regardless of flight crew action. However, the door was kept open throughout most of the fire so that the cabin condition could be observed. The importance of the barrier was not considered.

Smoke barriers are one part of the defences pilots have in case of smoke/fire/fumes. When they fail, or are ineffective, the ability to successfully fight the fire/smoke is compromised.

## Pilot Actions Related to Ventilation, Open Windows and Visibility

Adequate ventilation of the aeroplane passenger cabin is essential. The exchange rate of air is carefully regulated. During times of smoke contamination, this exchange rate is especially important. Greater amounts of fresh air introduced into the passenger cabin area dilute the smoke at a faster rate. If the smoke production overwhelms the ability of the ventilation system to send it overboard, this smoke will begin to accumulate in the cabin, usually near the outflow valve (or the main outflow valve for aeroplanes with more than one outflow valve). This accumulation then begins to spread throughout the cabin.

A solution for assisting a ventilation system to manage heavy cabin smoke is to use fresh air from outside the aeroplane via a ram air system. To use ram air, the aeroplane must be at an altitude where it can be depressurised; once the depressurisation is complete, opening ram air valves, when fitted, allows uncontaminated air into the passenger cabin at a high rate of flow. Some manufacturers do not utilise ram air, but instead have high volumes of fresh air available through the aeroplane air conditioning systems. Regardless of the method, controlling airflow is essential to mitigating the effect of smoke in the aeroplane.

Most aeroplanes use the principle of positive pressure to keep smoke out of the flight deck. Having a slight positive pressure from the flight deck to the cabin can act as a barrier to smoke migration into the flight deck; although in some aeroplanes this positive pressure does not work as well as initially intended. The FAA Technical Center found that during tests, smoke could migrate into the flight deck in a B747SP, because there was no positive pressure to prevent it. (Blake, 2003).

The UPS Flight 006 investigation found that:

*"The crew further informed BAH-C (Bahrain Control) that there was smoke in the cockpit and that the ability to view the primary flight instruments and radio frequency selection controls had become degraded."* (GCAA, 2010).

The designed barrier had failed and the flight deck filled with smoke due to the lack of airflow from the air conditioning packs.

The flight deck of the B747 should have had positive air pressure to resist smoke ingress from the rear of the aeroplane. As the air conditioning system was compromised during the event, it did not provide the necessary pressure on the flight deck to hold back the smoke from the cargo area (GCAA, 2010).

Another consideration in smoke migration patterns is the buoyancy of the smoke. Very buoyant smoke tends to remain on the ceiling, where it will disperse as it follows the contours of the ceiling Cooler, less buoyant smoke will interact differently with the airflow pattern, making its distribution more homogeneous throughout the passenger cabin area.

During the investigation of Air Canada Flight 797's fire, the procedure to open a flight deck window or cabin door was reviewed. One member of the Structures Group testified:

*"There's a very strong potential that (the forward airflow) would have pulled the fire out of the lavatory area into the passenger cabin and certainly would have moved the smoke forward and faster over the passengers' heads."*

He stated that it would have endangered the passengers and also the safety of the aircraft. (NTSB, 1986)

Boeing's 737 Smoke Removal Checklist, notes that opening a flight deck window may not be possible at speeds greater than holding speeds (Boeing, 2012) and Airbus's Smoke/Fumes Removal checklist for A319/A320/A321 requires that the aeroplane is decelerated to 200 knots before opening the flight deck window (Airbus, 2012). This requires slowing the aeroplane during a time when landing as quickly as possible should be the main concern.

There is a conflict between the need for maximum speed to minimise the time to the airport and slowing to holding speed to open a flight deck window.

An example of the ineffectiveness of opening a flight deck window is shown in the VARIG Flight 860 report. Pictures show the left flight deck window open, soot stains above the window, yet the smoke was so dense the captain landed in a field instead of flying another 70 seconds to the runway.

Additionally, opening a flight deck window has effects and consequences. A review of some incidents shows that the effectiveness is variable. During the Air Canada Flight 797 in-flight fire the first officer's flight deck window was opened and closed several times, making the noise level so high that no communication could take place between the flight crew. The venting was unsuccessful as both the passenger cabin and the flight deck remained full of smoke. The effects of opening the flight deck window were ineffective in respect of smoke removal, while the consequence was a significant reduction in ability of the flight deck crew to communicate.

In cases of continuous cabin smoke, no major manufacturer suggests opening a flight deck window, because it can cause the fire to spread. Several serious in-flight fires show that the flight crew opened the flight deck window without improving the visibility significantly and, in some cases, made it worse.

An open flight deck window creates high wind noise, which prevents effective communication between the crew. The high noise level prevents checklist accomplishment and also prevents a crewmember from assisting the flying pilot during the landing with callouts (which may be vital in limited visibility of a smoke-filled flight deck).

The effectiveness of an opened Direct View (DV) window (also known as a "Clearview Window" by some manufacturers) as a means of smoke removal has decreased, as experience has shown that this is not the most effective way of removing smoke from the flight deck.

The primary purpose of incorporating a DV window into a flight deck design was for egress; more recent aeroplanes, such as the B787, no longer have DV windows, but instead provide escape hatches or other means of egress. Some large older aeroplanes (e.g. such as the DC-10, MD-11, B767) have DV windows, but these were not included in smoke removal procedures.

Aeroplanes that have DV windows, and whose manufacturer recommends opening of these in the event of flight deck smoke, have produced later types of aeroplanes without DV windows (Boeing).

In general, the concept of opening any device in the cockpit to vent smoke to the outside atmosphere, whether a DV window or smoke evacuation vent or shutter, should be limited to removing smoke originating in the cockpit and only then as directed by the appropriate checklist, if used at all. No successful case of opening a window to evacuate smoke was found during research for this document. Investigations of both Asiana 991 and UPS 006 determined the cockpit smoke evacuation shutters of both aircraft had been opened in spite of no checklist guidance to do so. (South Korean Aircraft and Railway Accident Investigation Board, 2012; GCAA, 2010)

## Resetting Circuit Breakers

Any system with circuit breakers requires training regarding restrictions for the resetting of circuit breakers. Cabin and flight crew need to know the location of circuit breakers and the restrictions on the resetting of circuit breakers consistent with recommendations of the aeroplane manufacturer.

The UK CAA has issued the following guidance in CAP 789 "Requirements and Guidance Material for Operators":

*"In-flight operation use of CBs will usually involve the action of resetting a CB which has tripped because of an electrical overload or fault. Clearly, the re-establishment of electrical power to a circuit which is at fault does involve an element of risk, however slight. The following instructions should be included in the Operations Manual and included in flight and cabin crew training:*

*Flight crews should not attempt to reset CBs in flight for other than essential service and, even then, only when allowed by the AFM and there is clearly no associated condition of smoke or fumes. 'Essential services' should be regarded as 'essential for safety or for safe flight'. Fuel pump CBs must not be reset. A second reset should not be attempted.*

*A Technical Log entry should be made whenever any CB trips when the aircraft is in operation and a thorough investigation should subsequently be undertaken including a visual inspection of the appropriate electrical wiring and cable harness."* (UK CAA, 2011)

This warning is especially true for modern fly by wire aeroplanes where the interrelationship between onboard computers is highly complex.

Additionally, the flammability, brittleness and longevity of different types of wire insulation vary dramatically. The risk of an electrical fire expanding may depend on the type of insulation used. This risk cannot be mitigated easily, because rewiring an aeroplane is very expensive. Furthermore, replacing only part of the wiring can cause stress on the remaining wire, which can initiate breakdown in brittle insulation. Once this brittle insulation is broken, there is an increase in the possibility of arcing. Arcing can provide the ignition source for a fire

The US Navy found that between 1995 and 1997 their fleet of transport aeroplanes experienced an average of just over two fires per month, most of which would have been prevented by arc fault circuit interruption protection (Potter, 2003). This higher technology circuit breaker can be a very effective mitigation for wiring insulation breakdown. However, there are extremely few aeroplanes with arc-fault circuit-interrupting circuit breakers installed. This relatively low-cost mitigation has not been effectively utilised to date but could be very effective in the future. Arc fault circuit breaker usage should be increased on current and future aeroplanes.

## Auto-flight Considerations

The first priority in a smoke/fire event is for one of the pilots to fly the aeroplane. The use of the auto-flight system (if functioning and not affected by the smoke/fire) can provide an important reduction in pilot workload. Engaging the auto-flight system during smoke/fire/fumes conditions while accomplishing the complex checklists provided by some manufacturers, allows both pilots to be involved in diagnosing the type of event that is occurring, thereby improving the accuracy, the speed of the analysis and the accomplishment of necessary procedures.

Additionally, any necessary reprogramming of the Flight Management System (FMS), if appropriate for the aeroplane type and the operational circumstances, can be done more effectively. Similarly, reconfiguration of the air conditioning/pressurisation system, electrical system and/or other necessary system adjustments can be done more readily if the pilots are not overloaded.

However, as previously shown, there is the possibility of multiple system failures or cascading failures that, which could degrade or eliminate the auto-flight system and should be considered in procedure design. The flight crew procedures should include provisions for the failure or un-serviceability of the auto-flight system.

Some in-flight fire events (Asiana 991, UPS 006) were accompanied by manual flight control difficulties. Many aeroplane control designs include different routings for manual and auto-flight controls. If manual flight control has been compromised an attempt to use auto-flight should be considered. (South Korean Aircraft and Railway Accident Investigation Board, 2012; GCAA, 2010)

## 6.4 Protective Equipment

### Oxygen Systems

Flight crews must be protected from toxic fumes to safely fly and land their aeroplane. Protecting the crew primarily consists of oxygen masks and smoke goggles. Providing an independent oxygen source and protection for the eyes of the crew is essential. In the past smoke goggles have been found to be ill-fitting and therefore unable to provide a complete seal around the face of some wearers. As noted by the NTSB in the report of Pan American Flight 160:

*"...examination disclosed that if a crewmember wore corrective glasses, the smoke goggles would not fit properly at the temples and, therefore would not provide the needed protection against smoke."* (NTSB, 1974)

These goggles were improved after a one-time inspection of the air carrier fleet. Yet, problems with goggles continued such as the limited ability to purge smoke from the smoke goggles.

NTSB noted in their investigation of Federal Express Flight 1406 that the captain did not don his smoke goggles. The Board expressed their concern that this failure to don the goggles could have exposed the captain to toxic smoke (NTSB, 1998). Masks that cover the entire face, known as full-face oxygen masks, alleviate this concern, as they are a single, integrated unit. These single unit masks and goggles allow a better, tighter fit and more effective purging in the mask.

Full-face oxygen masks for pilots should be required on all transport aeroplanes. Many newer aeroplanes already have full-face masks installed. The need to refit older aeroplanes that are more susceptible to fires caused by electric loom-wiring is clear. The pilots of UPS Flight 006 did not have full-face masks available to them (GCAA, 2010).

Additionally, one carrier which compared the two mask types for speed and ease of use found that the average time to don a mask and separate smoke goggles was more than 20 seconds and required both hands to do so; the average time for the full-face mask was 5 seconds, and required only one hand to don.

Cargo carriers who operate aeroplanes using Class E cargo compartments have additional concerns regarding oxygen quantity. Applicable regulations generally require carriage of sufficient oxygen to comply with passenger-carrying regulations. These aeroplanes, however, in the event of a fire in a Class E compartment, may need to fly for extended distances with continuing smoke and fumes in the flight deck, and may also need to be depressurised to an intermediate altitude (e.g. 20,000ft - 25,000ft) depending on manufacturer requirements. Aeroplanes should therefore carry with enough oxygen to sustain all occupants for the maximum distance or time envisioned. This requirement should correspond to the areas of operation for those aeroplanes. When determining the oxygen quantity required, the oxygen flow rate per occupant should be calculated using the 100%/Emergency mask setting.

The investigation into the loss of UPS 006 revealed that the captain's oxygen mask became unusable after only 8 minutes of use. The crew oxygen distribution line in the B747-400F was routed through an area above the main deck ceiling that, in spite of the protection designed to be provided by the cargo liner material, was exposed to extreme heat resulting from the rapid and extreme energy release from the main deck fire. These distribution manifolds should be routed through an area not likely to be exposed in the event of a main deck fire (GCAA, 2013).

Cargo carriers operating aeroplanes using Class E cargo compartments should replace all "Dixie- Cup" style oxygen masks (generally a yellow, soft, silicone facial cup with white elastic bands for securing the mask to the person's face), with standard crew masks. The facial-cup masks are not designed to provide adequate oxygen at higher altitudes (above 20,000ft) for extended periods of time nor do they provide any acceptable protection in the presence of either smoke or fumes.

## Vision assurance technology

One of the significant issues during an in-flight fire event is the smoke caused by the fire. Smoke in the flight deck can adversely affect the flight crew's ability to perform the necessary tasks. These tasks can include manually flying the aeroplane, performing the appropriate checklists, navigating to an airport and landing. Adequate vision is essential to accomplishing these tasks. A pilot without adequate visual capability is essentially incapacitated.

IFALPA recognised this fact and passed a policy in 2005 to address it:

*"Flight crews should be provided with a system, whose elements are complementary and optimised to provide the maximum probability of detecting and suppressing any in-flight fire.*

*The fire-fighting policy should consist of procedures, training, equipment, and design requirements in order to access and effectively fight any source of fire in any critical location, for example attic areas, cargo holds and galleys. This will ensure that flight crews are prepared and able to respond immediately, effectively and in a coordinated manner to any in-flight fire.*

*In any case of possible fire or smoke in the aircraft, the smoke and fire fighting operating procedures should reflect the need to prepare to land the aircraft expeditiously, within a time frame that will minimise the possibility of an in-flight fire being ignited or sustained.*

*The flight crew should be provided with equipment, systems or procedures to assure their ability to see and perform their emergency and normal checklists, and be assured of their ability to see-to-land the aircraft.*

*Flight crew should be provided with sufficient breathable air for the duration of the flight after a fire or smoke has been detected.*

*Flight crews are considered incapacitated if their vision is impaired to a point where they can no longer see primary instruments, checklist, or outside in the direction of flight.*

*Flight crews are also considered incapacitated if they do not have sufficient breathable air to sustain operation."*

Technologies exists that can improve pilot visibility during a smoke/fire event. They provide the pilot with the ability to see critical flight instruments regardless of the density of smoke.

Several of the accidents cited in this document experienced dense smoke in the flight deck (e.g. Air Canada Flight 797, Swiss Air Flight 111 and UPS Flight 006). The interim report of the investigation of UPS Flight 006 included the statement:

*"...based on the information available to date, it is likely that less than 5 minutes after the fire indication on the main deck, smoke had entered the flight deck and intermittently degraded the visibility to the extent that the flight instruments could not effectively be monitored by the crew."* (GCAA, 2010)

Utilising existing technology to improve visibility when there is smoke in the flight deck would likely increase the effectiveness of the pilots, not only with the pilot flying task, but also with the pilot monitoring tasks. The fundamental concept of the multi-pilot crew could be maintained, instead of breaking down due to smoke, such as in the case of an Air Europe Fokker 100 that experienced dense flight deck smoke when landing in Copenhagen. (ICAO, 1989)

# 7. Aeroplane Wiring Insulation and Debris

Wire insulation breakdown can result in multiple simultaneous failures that may be confusing to the flight crew. An example occurred in United Airlines Flight 95, a B767 accident on 9 January 1998. (UK AAIB, 1998). After take-off and while climbing, the Engine Indication and Crew Alerting System (EICAS) displayed abnormalities with several systems. Circuit breakers were pulled and reset with no effect. Other circuit breakers tripped and the first officer's EFIS flickered, along with both the engine and systems screen.

Investigation found that there was evidence of arcing and heat damage to a wire loom and heat damage to another wire loom in the Electronic and Equipment (E&E) bay. Investigators saw arcing and hot spots in these wiring looms, when power was applied to the aeroplane. Further investigation found that there was evidence of heat as the copper wire had melted and spattered. Nearby wires were found to have nicks in the insulation and areas of abrasion.

As the investigators looked for causes for the nicks, they learned that a galley chiller had been replaced the day before the incident. The replacement should have been accomplished according to the Boeing maintenance manual, but the mechanics involved with the installation had no experience replacing a B767 chiller.

There were some deviations from the recommended work method, resulting in misalignment of the chiller unit. This resulted in pressure on the wiring bundles or looms and was a contributing factor to the initial arcing event.

Another issue discovered during the investigation was the presence of conductive debris in the E&E bay. Items such as coins stainless steel locking wire and copper wire were found. Non-conductive wire cable ties made of plastic were also found. In addition, a puddle of water one inch deep was seen on top of a thermal acoustic insulation blanket.

These findings raised questions of the amount of debris found in other in-service aeroplanes and led to a general investigation of wiring conditions. A review of significant service difficulty reports supported the need for further inspection to determine the significance of failures of wire looms caused by wire damage, chafing, damage caused by objects, or mishandling.

- Several aeroplanes were examined and in almost all, there was conductive and non-conductive debris;
- One aeroplane had its wiring looms covered in grime, dirt and dust;

- Metal shavings were found on many aeroplanes wire and wiring looms, where these shavings were located between the wires, the insulation was cut;
- Some of the lint-like debris was almost an inch thick and is known to be flammable;
- There was residue that was black and sticky on some wires, which attracted lint onto the wires.

Cracked insulation was found both in sunlit areas and in darker areas, showing that the aging process was occurring throughout the aeroplane. (UK AAIB, 1998).

Wiring insulation breakdown, and the potential for debris to be nearby, provides the setting for an ignition source and a combustible material. Improved wiring inspection is needed as noted by the FAA in their NPRM of 6 October 2005 (2007) and the final rule of 21 July 2008 Reduction of Fuel Tank Flammability in Transport Category Airplanes (2005).

## 7.1 Wiring Health

Good wiring health requires a comprehensive wiring inspection programme. It is known that in the areas where maintenance activities contact wiring bundles, there is an increase in wear. This wear can lead to abrasion and chafing, which can cause arcing events to occur. There is a need for improvements in maintenance practices and inspections of wiring.

From 1995 to 2002 the FAA received reports of 397 wiring failures. Only two thirds would have been detectable using current means. Of these failures, 84% were burned, loose, damaged, shorted, failed, chafed or broken wires. The FAA noted that such wiring failures caused over 22 flight delays per year and over 27 unscheduled landings per year on average (2005). The number of reports should be considered to be well below the actual number of events, as it is widely believed that this type of finding is under-reported by the industry.

Additionally, investigation of the in-flight explosion of TWA Flight 800 and the in-flight fire on Swissair Flight 111 led to examination of other aeroplanes where examples of wire deterioration, improperly installed wires and contamination of wire bundles with dust, fluids and metal shavings were found. The FAA realised that today's maintenance practices do not address the condition of wires to a satisfactory level and that improvements need to be made (2005). In 2003, MITRE issued a report on inspection efforts to evaluate the state of wiring in transport aeroplanes (Sadeghi, 2003). The non-intrusive inspections of electrical wiring on large transport aeroplanes found that of the 81 aeroplanes inspected, there was an average of 40 wiring anomalies per aeroplane. These findings resulted in the issuance of 23 ADs. On small transport aeroplanes, 39 aeroplanes were inspected with an average of 58 anomalies found per aeroplane (Sadeghi, 2003). This led to the FAA issuing a NPRM on 6 October 2005, to *"improve the design, installation and maintenance of their electrical wiring systems as well as by aligning those requirements as closely as possible with the requirements for fuel tank system safety"* (2005)

and the following final rule: "Reduction of Fuel Tank Flammability in Transport Category Airplanes" in 2007. (FAA, 2007)

The FAA final rule addresses type certificate holders, applicants and supplemental type certificates. In this final rule, focus on the health of the wiring in the aeroplane was specifically required for the first time. The EASA and FAA requirements have been harmonised.

## 7.2 Wiring Inspection Programme

Regular inspection of wiring is an essential check of the overall health of the aeroplane. Wiring bundles should be inspected particularly for conductive material that can chafe the insulation and allow arcing. Inspection of remote or hidden areas of the aeroplane should be scheduled regularly for wiring that can be covered in dust, grease and other contaminates. All nearby thermal acoustic insulation blankets should also be carefully inspected. Cleaning or removal of contaminates should be a priority so that the source of fuel for a fire can be reduced.

The breakdown of insulation over time is well documented. This breakdown is another compelling reason to improve wiring inspection programmes. The FAA found in a January 2008 study:

*"The continued safe operation of aircraft beyond their expected service life depends on the safe and effective transfer of power and electrical signals between aircraft electrical components. This in turn requires that the physical integrity of electrical wire and its insulation be maintained. As aircraft increase in age and cycle time, the wire insulation may be degraded to the point that it is no longer capable of ensuring the safe transfer of electrical current."* (2008)

Visual inspection of wiring has proven inadequate in some cases. In a test by Letromec, visual inspection located two potential breaks in a test wire-bundle in a recently retired transport aeroplane. Higher technology inspection found over 60 breaks. This finding of damage to the loom wiring was later verified in a laboratory (Lectromec, 2005).

# 8. Composite Materials Used in Aeroplane Construction - Potential Fire Related Issues

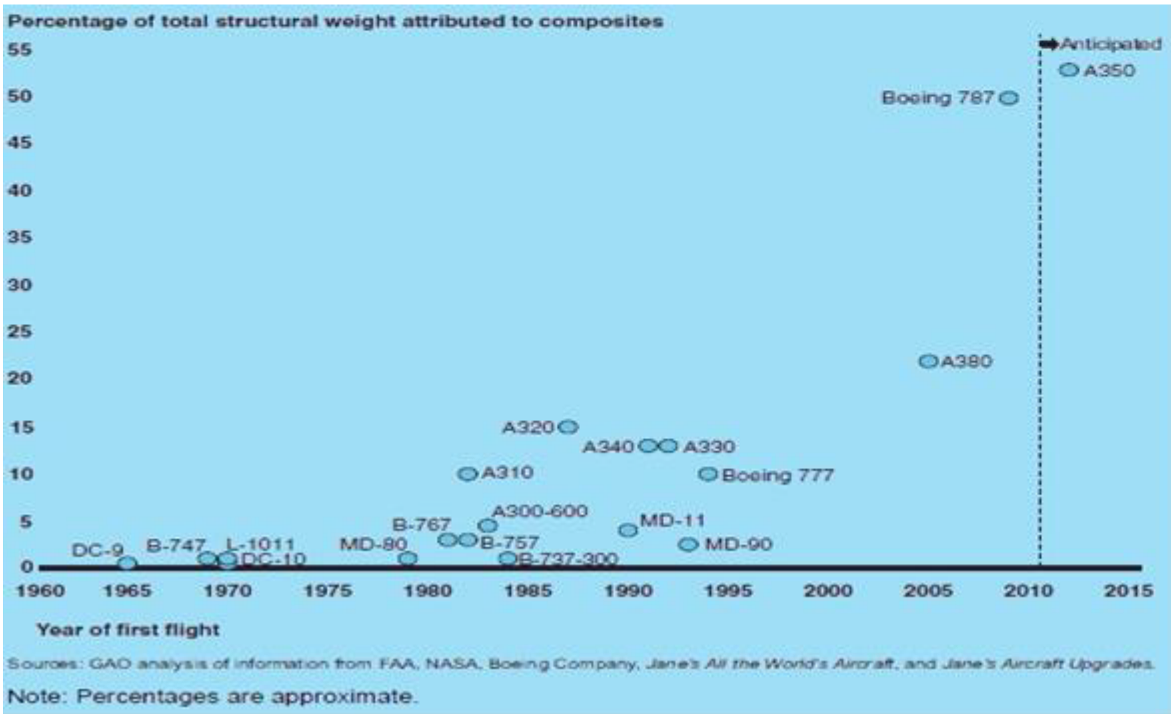
With the increasing use of composite (non-metal) material as a primary component of aeroplanes, additional factors must be considered with respect to smoke/fire events. Toxic fumes produced in the event of burning composite materials are of concern to passengers, flight crew and first responders. Propagation of a fire and considerations for fighting fires are important issues discussed below.

## 8.1 The Use of Composite Materials in Aeroplane Construction

Composite structures are produced by laying composite materials into a mould and curing the combination of fibres and plastic matrix, often in an auto-clave. Many carbon-fibre composites use thermo-setting plastics as the matrix. Thermoplastics may also be used for some components such as flight controls and fuselage sections.

For many years aeroplane manufacturers have used composite materials for certain structures (e.g. B737 rudder). One of the earliest uses of carbon-fibre composites to manufacture commercial aeroplane structure was by Airbus in the A300 in 1972 (Airbus, 2012). Many military aeroplanes have composite materials used in their construction; for example, the Northrop Grumman B-2 stealth bomber which has a structure largely constructed from composite materials. Both Boeing and Airbus are now using composite materials as the primary method of construction for the fuselage of the B787 and the A350, as well as other associated parts.

The following figure shows the percentage of total structural weight attributed to composite materials used in aeroplane construction since the mid-1980s:




(United States Government General Accountablity Office, 2011)

The advantages of using composite materials in the construction of modern aeroplanes include a number of factors, not least that they are demonstrably stronger and lighter than aluminium. Aeroplane structures are not designed on a strength basis alone; buckling and other constraints are required considerations. Composite structures do not suffer from fatigue in the same way as metals, but they are sensitive to impacts and may suffer from de-lamination growth.

Due to the nature of the fibres and resins involved and due to the fact that resins used in composite materials are combustible, potential difficulties may arise with a post-accident fire involving an aeroplane fuselage constructed primarily with composite materials. Both the FAA and EASA required Boeing to show an equivalent level of safety for the B787 related to the flame penetration properties of the composite fuselage compared to a metal fuselage. The FAA approved the equivalent level of safety finding subject to the condition that the results of the Boeing fire testing show that the B787 fuselage skin and structural components provide a survivable cabin environment for five minutes or equivalent to that of a traditional aluminium fuselage with compliant insulation. For the B787, EASA made a Special Conditions during the certification process in respect of composite materials. (EASA, 2010)

## 8.2 Dealing with Composite Fires

In 2003, the IFTC, at Teeside in the UK, issued Training Notes that detailed the problems of dealing with composite fires:

*"The risk to personnel arises from the decomposition of the material both during and after the fire. The intense heat usually found at an accident site will decompose the resins bonding*

*the fibres liberating toxic isocyanate fumes. The fibres within the composite will break into shorter and smaller lengths increasing their respirability and transportability. There is the possibility that the material may plume following a crash and be carried considerable distances downwind. In addition to the respiratory risk, fibres can easily cause needle stick injuries and traumatic dermatitis. Carbon fibres are capable of absorbing all the products of a post-crash fire and if touched will act as an infection carrier enabling such products to enter the body."*

As the proportion of composites in aeroplane structures grows, so does the risk because of the possibility of increase in severity identified by the IFTC.

The IFTC notes also address three major areas of danger from composite materials as follows:

*"Toxic vapours and dust released through the incineration of composite fibres."*

*"Sharp filaments or splinters of material distributed or exposed by impact."*

*"Gases released by burning resins."*

The IFTC notes also state that:

*"Firefighters must follow the safety measures which reduce the possibility of contamination not only to Firefighters but to other emergency service personnel who may be involved in rescue operations within the crash zone. This must include the wearing of full firefighting kit with breathing apparatus during any firefighting operations."*

Flight crew members involved in an in-flight or post-impact fire may need to utilise full face masks to minimise the effects if the composite structure is ignited. (IFTC, 2003)

Boeing has addressed this issue in a document published in February 2012 titled "Firefighting Practices for New Generation Commercial Composite Structures". Boeing is not recommending any major changes to the standard way of fighting an aeroplane fire involving a composite fuselage.

Boeing states that:

*"Gaining access to the 787 for rescue purposes should be in accordance with the local rescue fire service procedures. Our testing concludes that cutting the composite structure is much easier than cutting the aluminium fuselage."*

Boeing also states that:

*"All aircraft accidents involving fire should be considered a hazardous materials incident whether the situation involves an aluminium fuselage or a composite fuselage."*

## 8.3 Boeing 787 Type Certificate - Review of Composite Materials Considerations

The B787 has received EASA and FAA Type Certificates. The FAA, EASA (seen in TCDS No. EASA.IM.A.115), and Boeing have determined that passengers and crew of a B787 would be at no greater risk than an occupant of a more conventionally constructed aluminium fuselage.

The US GAO conducted a comprehensive review of the FAA and EASA certification and came to the conclusion that both the FAA and EASA had correctly conducted due process and oversight of the certification of the B787 in respect of composite materials used in the construction of the B787. (United States Government General Accountability Office, 2011)

# 9. Regulatory Standards for Transport Aeroplanes

The FAA, EASA and other aviation authorities have responded to events, incidents and accidents improving applicable regulations and ACs. Examples of direct improvements of the regulations due to accidents and the resultant safety recommendations include the two B707 accidents previously discussed. One observation of the NTSB during the Pan American Flt 160 investigation was:

*"Although the cockpit voice recorder indicates that crewmembers were wearing smoke goggles during the final phases of the flight, the Board's investigation indicates that the captain may have had difficulty seeing because of smoke."* (1974)

Like the accident to VARIG Flight 860, smoke was a significant contributing factor. As a result, the FAA revised the approved procedures for pilots in smoke or fire conditions.

Ten years after the two B707 accidents, Air Canada 797 experienced a serious fire. On 2 June 1983 Air Canada Flight 797 landed in Cincinnati, Ohio, after the DC-9-30 experienced an uncontrollable in-flight fire that began in the single aft toilet. There were 23 fatalities. This accident resulted in several safety improvements including:

- Detection methods for lavatory fires;
- Full-face mask portable oxygen bottles for cabin crewmembers;
- Methods to identify smoke sources and requirements for aircraft certified under CAR Part 4b to comply with 14 CFR § 25.1439 (NTSB, 1983).

These steps made in-flight fire less likely and provided the aeroplane crew with better means of detecting and fighting fires. The NTSB identified that multiple layers of mitigation would be necessary to reduce the risk and the effects of smoke/fire/fumes.

In 1975, the FAA proposed to amend the regulations (specifically 14 CFR § 25.1439) to include new standards for oxygen masks, but withdrew the proposal to allow further testing to establish the data on which to base standards (NTSB, 1986).

In 1981, the FAA advised the NTSB that they intended to update TSO C99 that would provide a minimum standard for emergency equipment for "protection of flight crew members from toxic atmospheres" (NTSB, 1986). The FAA used an AC to define an acceptable means of upgrading protective breathing equipment to the new TSO standards.

AC are not regulatory; they only describe an acceptable means of compliance with specific regulations. However, a change in an AC often results in applicants adopting the standards.

Much of the protective equipment in use at that time did not meet the updated TSO standard (NTSB, 1986). It should be noted that neither a TSO nor an AC can provide a regulatory requirement for protective breathing equipment (PBE). Only a change in the aviation regulations could make the change mandatory and retroactive. The NTSB did not believe the FAA's action was sufficient to *"assure passenger safety"* (1986).

The FAA did not immediately implement earlier NTSB recommendations regarding lavatory area smoke detectors until after the Air Canada Flight 797 accident in June 1983. Additionally, other safety enhancements resulted from NTSB recommendations contained in the Air Canada Flight 797 accident report. These included new emergency lighting standards and recommendations for tactile aisle-markers and floor proximity escape-path lighting, so that people inside a smoke-filled passenger compartment could more easily locate an emergency exit.

The recommended improvements in fire blocking material to slow fire propagation (which required the retrofit of 650,000 seats) and the installation of emergency exit lighting became requirements in 1986 (Duquette, 2005). Lavatory fires continued to occur, causing the NTSB to recommend smoke detectors and automatic-discharge fire extinguishers in the waste receptacles. The FAA finally implemented the NTSB's 1974 recommendation (A74-98) to mandate automatic-discharge fire extinguishers in the toilet waste receptacle, after Air Canada Flt 797's fire in 1987 (Duquette, 2005). This followed the 1986 FAA requirement for at least two Halon fire extinguishers to be located in the cabin (Duquette, 2005). On 29 July 1986, the FAA issued AC 25-9 to provide guidelines for aeroplane certification tests of smoke detection, penetration, evacuation tests and flight manual emergency procedures (FAA, 1986). The AC specifically cited continuous smoke as a condition that should be considered in the formulation of smoke and fire procedures. It further said that accident statistics showed there are conditions of continuous fire and smoke in-flight.

Surprisingly, the test procedure for flight deck smoke evacuation in AC 25-9 states that the smoke generation should be terminated after the flight instruments are obscured. However, other tests cited in AC 25-9 require continuous smoke to be used (FAA, 1986). The ventilation systems are allowed three minutes to clear the smoke so that a pilot can see the instruments.

This test does not accurately represent conditions where smoke continues to be produced. There is a contradiction in the acknowledgement of continuous smoke being a condition for consideration in the development of procedures in relation to the necessity of the ventilation system to be able to terminate flight deck smoke when it is continually being produced.

Air Canada Flight 797 experienced continuous smoke, causing the captain to land with his oxygen mask and smoke goggles on, with his face pressed against the windshield (Johnson, 1985). Other cases of continuous smoke in the flight deck include:

- Air Europe Fokker 100 landing at Copenhagen on 17 December 1989;
- VARIG Flight 860;
- Pan American Flight 160;
- AirTran Flight 913;
- UPS Flight 006;
- Asiana B747-400 /HL7604.

These flights experienced dense smoke, so thick that the some of the pilots could not see each other, and several resulted in an accident.

It is interesting to note that to further expand the scope of smoke testing; a draft of an update to AC 25-9 began to circulate the industry for comment in July 1992. The revision included recommendations for:

- Addition of regulatory amendments for improved smoke clearance procedures;
- Adherence to updated Part 25 requirements;
- Fire protection;
- Lavatory fire protection;
- Addition of crew rest area smoke detector certification test;
- Use of helium smoke generator in testing;
- Continuous smoke generation in the cockpit smoke evacuation tests (FAA, 1992).

The final version of AC 25-9a was published on 6 January 1994. While most of the issues and testing criteria were similar, there were changes from the initial draft. The revision from the original AC included:

- Recommendations for additional regulatory amendments for improved smoke clearance procedures;
- Adherence to updated Part 25 requirements;
- Fire protection;
- Lavatory fire protection;
- Addition of crew rest area smoke detector certification test;
- Use of helium smoke generator in testing and paper towel burn box smoke generator, but not continuous smoke in the flight deck testing.

Continuous smoke in the flight deck was referred to in Paragraph 6c. It reads:

*"Although the FAR does not require the consideration of continuous smoke generation/evacuation, the FAA recommends that the airframe design address this situation. Accordingly, paragraphs 12a (1) and 12e (3) recommend addressing continuous smoke generation/evacuation in the cockpit."* (FAA, 1994)

The previous test procedure, which terminates the generation of smoke, remained. Rationale for the return to the previous method of testing was not explained in the revised AC, so the previously mentioned contradiction remains in the updated 9a document. No aeroplane manufacturer has applied continuous smoke testing as recommended by the FAA in the AC since 1994.

The FAA testified before Congress on 8 November 1993 just before the final version of the AC was released. During that testimony, the FAA stated:

*"The evacuation of smoke from a cockpit is needed to enable the crew to operate the aircraft. Our standards provide for the effective evacuation of smoke. An aircraft's equipment and procedures are considered to meet FAA requirements if smoke concentration is reduced within three minutes, so that any residual smoke neither distracts the flight crew nor interferes with operations under either instrument meteorological conditions, IMC or visual meteorological conditions, VMC. We believe these standards provide sufficient reserve for a*

*flight crew to retain adequate visibility of the flight instruments and controls and outside the aircraft, to continue safe flight and landing even when a reasonably probable continuous smoke source is present."* (FAA, 1993)

However, this was not consistent with the experience of Federal Express Flight 1406 (NTSB, 1998), AirTran Flight 913 (NTSB, 2000), Swissair Flight 111 (TSBC, 2003), UPS Flight 1307 (NTSB, 2007), UPS Flight 006 (GCAA, 2010), or Asiana Flight 991 (South Korean Aircraft and Railway Accident Investigation Board, 2012). The fires on these aeroplanes burned fiercely. The crews could not extinguish or evacuate the smoke, so it spread creating a life- threatening event.

## 9.1 Interior Material Toxicity and Flammability

The flammability of material in the interior of the passenger cabin became a concern as toxic fumes were found to be released during cabin fires.

Improvements to flammability standards were therefore proposed.

The FAA, working with safety recommendations from the NTSB, began a major improvement in cabin interiors following the fires aboard VARIG Flight 860 and Pan American Flight 160.

In 1972 a United Air Lines B737 crashed near Chicago's Midway airport, some of the victims of the accident, showed high levels of cyanide in their blood stream (NTSB, 1973). This accident helped to show the need for improvement in reducing the toxicity of cabin interiors when exposed to fire.

The demand for improvement led to the creation of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee in May 1978, an advisory committee which helped to define the types of research needed in fire safety and the issues of interior material toxicity and flammability for in-flight and post-crash fires (Bureau of Transportation Statistics, 2012). Over time, materials used in aeroplane interiors have improved, lowering toxicity and flammability. However, there remains a need to review new materials in an effort to continue improvement.

## 9.2 Fire Extinguishers

In addition to smoke detection and evacuation considerations, the NTSB also recommended upgrading fire extinguishers in the report of Air Canada 797. Experience of major cabin in-flight fires showed that carbon dioxide, dry chemical, and water fire extinguishers were effective in some cases, but were inadequate when combating larger, rapidly spreading fires. In FAA Technical Center tests, Halon 1211 (bromochlorodifluoromethane) showed itself to be superior to carbon dioxide, dry chemical or water fire extinguishers.

These tests encouraged the FAA, on 17 May 1984, to issue NPRM 84-5. It contained three proposed rules to address some of the NTSB's recommendations resulting from the Air Canada 797 investigation. The proposed rules required:

- The installation of automatic fire extinguishers for each toilet disposal-receptacle used for towels/paper/waste;
- The installation of smoke detector systems in the galleys and lavatories of air

transport category aircraft;

- The need for two Halon 1211 fire extinguishers to be located in passenger compartments (NTSB, 1986).

Subsequently smoke detectors have been installed universally in toilet areas, but not for galley areas. It was considered that galley areas would be monitored regularly by cabin crew, since they are routine work areas and, therefore, smoke detectors are not mandated in these areas.

## 9.3 Lithium Batteries

In February 2012, members of the ICAO's Dangerous Goods Panel developed new safety requirements for air shipment of lithium batteries and associated equipment. (ICAO, 2012)

The new requirements, effective in most ICAO member states on 1 January 2013, have been approved by the ICAO Council, and are included in the 2013-2014 Edition of the Technical Instructions for the Safe Transport of Dangerous Goods by Air and took effect in most ICAO member states on 1 January 2013. The new requirements are more stringent than regulations that have been in place in most ICAO member states since 2009.

## 9.4 Composite Structures

FAA AC 20-107B CHG 1 Composite Aircraft Structure was published in September 2009 to provide updated information on compliance with Aircraft Certification regulations. An FAA/Airbus/Boeing/EASA/Industry Working Group on essential composite technical issues reconvened in 2011 to address the following (National Institute for Aviation Research):

- Approve Composite-related Safety Awareness Course Modules;
- Initiated work on FAA policy for bonded repair size limits;
- Initiated composite damage tolerance guidance development (including high-energy, wide-area, blunt impact, e.g. vehicle collisions);
- Initiated work on crash-worthiness guidance development and possible rulemaking;
- Initiated other guidance development as determined necessary.

## 9.5 Enhanced Airworthiness Program for Airplane Systems/Fuel Tank Safety

One major area of the regulatory standards that has been updated since the 2007 SAFITA paper, is in the area of wiring safety. During the late 1990s, the FAA and industry determined they needed a better understanding of wire-related failures that could result in arcing, smoke in the cabin or flight deck, and sometimes even onboard fires. The FAA Enhanced Airworthiness Program for Airplane Systems (EAPAS), which was established in 2001, has been developing enhancements for continued safety of aeroplane wiring systems from their design, installation, and maintenance throughout their operational life.

The EAPAS program led to a final FAA rule in November 2007 that, for the first time, viewed aeroplane wiring as important systems. The rule proposed to revise current maintenance practices and specified other actions to address issues of aging and degradation in wiring. The final rule is comprehensive in addressing all aspects of electrical wiring design, installation and maintenance for transport aeroplanes; it was published on 8 November 2007. It is the result of recommendations made by industry groups working with the FAA, EASA and international authorities to increase the safety of aeroplane electrical wiring systems. See the following regulatory material for some of the relevant requirements and guidance material:

- CS 25 Subpart H/14 CFR Part 25 Subpart H Electrical Wiring Interconnection System and corresponding AMCs and ACs for showing compliance to Subpart H requirements;
- 14 CFR Section 25.981, Fuel Tank Ignition Prevention;
- 14 CFR Section 25.1529, Instructions for Continued Airworthiness;
- CS 25 Book 1 and 14 CFR Part 25, Appendix H, Instructions for Continued Airworthiness;
- Part 26, Continued Airworthiness and Safety Improvements for Transport Category Airplanes;
- AC 20-107B CHG 1 Composite Aircraft Structure;
- AC 25-8, Auxiliary Fuel System Installations;
- AC 25-9A, Smoke Detection, Penetration, and Evacuation Tests and Related Flight Manual Emergency Procedures;
- AC 25-16, Electrical Fault and Fire Prevention and Protection;
- AC 25-19, Certification Maintenance Requirements;
- AMC 25.981(a) Ignition Precautions;
- AMC 25.981(b)(1) Fuel tank flammability design precautions;
- AMC 25.981(b)(2) Fuel tank flammability definitions;
- AC 25.981-1, Fuel Tank Ignition Source Prevention Guidelines;
- AC 25.981-2, Fuel Tank Flammability Reduction Means;
- AC 120-16, Air Carrier Maintenance Programs;
- AC 120-97A, Incorporation of Fuel Tank System Instructions for Continued Airworthiness into Operator Maintenance or Inspection Programs;
- AC 120-102, Incorporation of Electrical Wiring Interconnection Systems Instructions for Continued Airworthiness into an Operators Maintenance Program.

Note that the EASA and FAA have implemented harmonised requirements in these areas, although the different regulatory structures may identify specific documents in dissimilar ways.

# 10. Recommendations

This section describes the recommended mitigations for the issues addressed in the previous sections. For each recommendation, there is a brief discussion and reference to the previous section that describes the issue. Recommendations 1-6 are new based on the new subjects included.

Recommendations 7-24 are carried over from the original 2007 document, although some supportive material has been added. In some cases, recommendations have been combined. This is due to changes in regulations, operator acceptance, or for clarity. Other recommendations found in the original 2007 document have been removed because they have already been adopted.

## 10.1 General

### Recommendation 1

Passenger, ground crew, flight crew, and cabin crew awareness of the risk posed by lithium batteries to flight operations should be enhanced. Operators should incorporate technologies to protect crewmembers while containing overheating lithium batteries in a fireproof container or a container that immediately extinguishes the fire. Adequate crewmember/firefighter protection should be provided.

### Recommendation 2

Regulators should update and improve the guidance provided to flight crews and operators on the most effective methods of fighting a lithium battery fire. This guidance should include reference to the need for adequate protection of the crewmember/firefighter and the recognition that many newer devices are water resistant or waterproof thereby reducing the current guidance of pouring water on the device.

### Recommendation 3

Provide adequate protective equipment for crewmember/firefighters to fight a lithium battery fire. Protective equipment should provide a shield or barrier between the lithium battery fire and the crewmember/firefighter.

### Recommendation 4

Alternative extinguishing agents and procedures should be identified for use in in-flight fires involving lithium batteries due to the use of water as a cooling agent becoming less effective on newer, more water resistant, devices.

### Recommendation 5

National Aviation Authorities and ICAO should require that all shipped lithium batteries to be classified as hazardous cargo requiring fireproof (fire resistant) containers. Shipment of lithium metal batteries should be prohibited on passenger aeroplanes.

### Recommendation 6

National Aviation Authorities and ICAO should require that lithium batteries to be shipped by air have adequate protection against spontaneous ignition and adjacent cell fires.

## 10.2 Composite Materials

### Recommendation 7

National Aviation Authorities should monitor in-flight or post-accident fires to ensure effectiveness of the FAA and EASA Special Conditions relating to composite materials.

Incident or accident investigations involving aeroplanes with a high percentage of composite materials should include a review of the effectiveness of the Special Conditions.

## 10.3 Technologies

### Recommendation 8

The use of predictive technology should be expanded to include monitoring, prediction and intervention for components that can cause in-flight smoke events.

## 10.4 Flight Crew Procedures

### Recommendation 9

Procedures to open flight deck windows to vent smoke should be eliminated. In addition, smoke removal procedures should be improved to ensure that smoke is removed from the flight deck as effectively as possible.

### Recommendation 10

All manufacturers and operators should apply the Flight Safety Foundation's template for design of Smoke/Fire/Fume checklists.

### Recommendation 11

National Aviation Authorities should require full-face oxygen masks and sufficient flight crew oxygen for descent and landing during a smoke/fire/fume event.

### Recommendation 12

Procedures should require pilots to don full-face oxygen masks as soon as possible when smoke or fume odours are detected in order to prevent pilot incapacitation.

## 10.5 Regulatory Improvements

### Recommendation 13

National Aviation Authorities should update guidance material to improve aeroplane crew fire-fighting techniques, including the proper use of crash axes and other fire-fighting equipment.

FAA AC 120-80A, and 20-42D should be updated to provide crews with better techniques for fighting lithium battery fires while providing adequate protection.

FAA SAFO 09013 should be updated to provide crews with better information and techniques for fighting lithium battery fires while providing adequate protection.

Other National Aviation Authorities should update similar guidance

### Recommendation 14

Aeroplanes should be evaluated for single-point failures of wiring and the potential effect on systems of the aeroplane, especially those certified prior to 2007.

### Recommendation 15

The installation of arc-fault circuit interrupter technology on new and existing transport aeroplanes should be required.

### Recommendation 16

National Aviation Authorities should update guidance for certification of transport aeroplanes during continuous flight deck smoke events.

### Recommendation 17

The FAA should revise AC25-9a to the following:
*Test Procedures. The smoke evacuation tests should be conducted with smoke generated within the compartments as follows:*
*Cockpit*

*i. The cockpit door or curtain, if installed, should be closed for the test. The crew should don protective breathing equipment as soon as the smoke is evident.*

*ii. When the cockpit instruments are obscured (standard dial indicator numbers or letters become indiscernible), smoke generation should be terminated, and the appropriate AFM fire and smoke procedures should be initiated. The smoke should be reduced within three minutes such that any residual smoke (haze) does not distract the flight crew nor interfere with operations under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR).*

*iii. To demonstrate protection from smoke generated by a continuous source in the cockpit, smoke should be generated continuously. The crew should don protective breathing equipment and initiate smoke evacuation procedures and/or activate smoke displacement devices, if needed, as soon smoke becomes evident. The ability of the crew to safely operate the airplane should not be impaired by loss of vision due to smoke from a continuous source in or contiguous with the cockpit.*

### Recommendation 18

Vision assurance technology should be implemented to improve pilot visibility during continuous smoke in the flight deck.

### Recommendation 19

Fire access ports and mark locations of minimal damage for access to inaccessible areas of the aeroplane should be installed or dedicated fire detection and suppression systems to inaccessible areas of the aeroplane should be installed.

### Recommendation 20

The number and location of sensors to alert the flight crew of smoke/fire/fumes should be increased. These sensors should minimise the false alarm rate by utilising multiple sources to detect smoke or fire.

## 10.6 Fire Extinguishers

### Recommendation 21

The capacity required for fire flight deck and cabin fire extinguishers should be increased to 2.5kg (approximately 5.5 lbs) of Halon or an equivalent effective agent.

### Recommendation 22

Maintenance procedures for the inspection of thermal acoustic insulation blankets and smoke barriers should be improved to ensure cleanliness.

### Recommendation 23

Maintenance procedures should be improved to minimise the possibility of contamination of thermal acoustic insulation blankets.

### Recommendation 24

Wiring inspection maintenance programmes should be improved by using new inspection technology instead of relying on visual inspection of wiring bundles.

# 11. Conclusion

Smoke and fire in transport aeroplanes continues to pose a risk in aviation. While the number of fatalities caused by aviation accidents has decreased, the risk of future fire related incidents or accidents has increased due to the proliferation of lithium batteries and other risks. Hundreds of lithium batteries are carried on most flights and the number is increasing. The importance of continued research, improved regulation, improved manufacturing standards, adoption of technology to mitigate in-flight smoke and fire and oversight by safety professionals is proven in this document.

The threat profile of in-flight smoke and fire is also changing due to the expansion of composite materials used in aeroplanes. Composite materials burn differently, disperse heat differently, and produce different toxic substances post-ignition. Expanding the body of knowledge surrounding composite materials related to aeroplane fires in-flight and post-impact will be necessary to ensure that an equivalent level of safety is maintained with aluminium based aeroplanes.

2017 was the safest year in aviation history by the number of accidents, and had the lowest number of fatalities (ICAO, 2018). Passenger fatalities, commercial airline accidents, and loss of aeroplanes were at their lowest rates in modern times. One result of this very low rate is the effect of a single accident, particularly a wide-body jet. A single accident like Swiss Air 111 would cause a significant spike in the accident, fatality, and aeroplane loss rate.

The aviation industry and regulators acknowledge that there will be ignition sources and fuel sources for fires within aeroplanes. Only through multiple layers of mitigation can the risk be kept to an acceptable level. To be effective these multiple layers will need to be re-evaluated regularly and to utilise available technology wisely.

The recommendations in this document provide clear directions not only to maintain today's level of safety but also to improve it. Adoption of the recommendations will decrease the likelihood of an in-flight smoke or fire event and the severity of the consequences should one occur.

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# Appendix 1

## Smoke/Fire/Fumes Checklist Template

1. 1 Diversion may be required.
2. 2 Oxygen masks (if required)............................................ On, 100%
3. 3 Smoke goggles (if required)............................................ On
4. 4 Flight crew and cabin crew communication ...................... Establish
5. 5 Manufacturer's initial steps[1] ............................................ Accomplish

If smoke or fumes become the greatest threat, accomplish *Smoke or Fumes Removal Checklist,* page.[2]

6. Source is immediately obvious and can be extinguished quickly:
   If yes, go to Step 7.
   If no, go to Step 9.

7. Extinguish the source.
   If possible, remove power from affected equipment by switch or circuit breaker on the flight deck or in the cabin.

8. Source is confirmed visually to be extinguished:
   If yes, consider reversing manufacturer's initial steps. Go to Step 17.
   If no, go to Step 9.

9. Remaining minimal essential manufacturer's action steps…. Accomplish
   [These are steps that do not meet the "initial steps" criteria but are probable sources.][3]

10. Initiate a diversion to the nearest suitable airport while continuing the checklist.
    Warning: If the smoke/fire/fumes situation becomes unmanageable, consider an immediate landing.

11. Landing is imminent:
    If yes, go to Step 16.
    If no, go to Step 12.

12. XX system actions[4] ......................................................................... Accomplish
    [Further actions to control/extinguish source.]
    If dissipating, go to Step 16.

13. YY system actions .......................................................................... Accomplish
    [Further actions to control/extinguish source.]
    If dissipating, go to Step 16.
14. ZZ system actions .......................................................................... Accomplish
    [Further actions to control/extinguish source.]
    If dissipating, go to Step 16.

15. Smoke/fire/fumes continue after all system-related steps are accomplished:
    Consider landing immediately.
    Go to Step 16.

16. Review *Operational Considerations,* page .

17. Accomplish *Smoke or Fumes Removal Checklist,* if required, page .

18. Checklist complete.

**Operational Considerations**

[These items appear after “checklist complete.” This area should be used to list operational considerations, such as an overweight landing, a tailwind landing, a ditching, a forced off-airport landing, etc.]

**Notes:**

1. These aircraft-specific steps will be developed and inserted by the aircraft manufacturer.
2. The page number for the aircraft-specific *Smoke or Fumes Removal Checklist* will be inserted in the space provided.
3. Bracketed text contains instructions/explanations for the checklist author.
4. “XX,” “YY” and “ZZ” are placeholders for the environmental control system, electrical system, in-flight entertainment system and/or any other systems identified by the aircraft manufacturer.

## Smoke/Fire/Fumes Philosophy and Definitions

This philosophy was derived by a collaborative group of industry specialists representing aircraft manufacturers, airlines/operators and professional pilot associations. The philosophy was used to construct the *Smoke/Fire/Fumes Checklist Template.*

**General**

- The entire crew must be part of the solution.
- For any smoke event, time is critical.
- The *Smoke/Fire/Fumes Checklist Template:*
  - Addresses non-alerted smoke/fire/fumes events (smoke/fire/fumes event not annunciated to the flight crew by aircraft detection systems);
  - Does not replace alerted checklists (e.g., cargo smoke) or address multiple events;
  - Includes considerations to support decisions for immediate landing (an overweight landing, a tailwind landing, a ditching, a forced off-airport landing, etc.); and,
  - Systematically identifies and eliminates an unknown smoke/fire/fumes source.
- Checklist authors should consider a large font for legibility of checklist text in smoke conditions and when goggles are worn.
- At the beginning of a smoke/fire/fumes event, the crew should consider all of the following:
  - Protecting themselves (e.g., oxygen masks, smoke goggles);
  - Communication (crew, air traffic control);
  - Diversion; and,
  - Assessing the smoke/fire/fumes situation and available resources.

**Initial Steps for Source Elimination**

- Assume pilots may not always be able to accurately identify the smoke source due to ambiguous cues, etc.
- Assume alerted-smoke-event checklists have been accomplished but the smoke's source may not have been eliminated.
- Rapid extinguishing/elimination of the source is the key to prevent escalation of the event.
- Manufacturer's initial steps that remove the most probable smoke/fumes sources and reduce risk must be immediately available to the crew. These steps should be determined by model-specific historical data or analysis.
- Initial steps:
  - Should be quick, simple and reversible;
  - Will not make the situation worse or inhibit further assessment of the situation; and,
- – Do not require analysis by crew.

**Timing for Diversion/Landing**

- Checklist authors should not design procedures that delay diversion.
- Crews should anticipate diversion as soon as a smoke/fire/fumes event occurs and should be reminded in the checklist to consider a diversion.
- After the initial steps, the checklist should direct diversion unless the smoke/fire/fumes source is positively identified, confirmed to be extinguished and smoke/fumes are dissipating.
- The crew should consider an immediate landing anytime the situation cannot be controlled.

**Smoke or Fumes Removal**

- This decision must be made based upon the threat being presented to the passengers or crew.
- Accomplish *Smoke or Fumes Removal Checklist* procedures only after the fire has been extinguished or if the smoke/fumes present the greatest threat.
- Smoke/fumes removal steps should be identified clearly as removal steps and the checklist should be easily accessible (e.g., modular, shaded, separate, standalone, etc.).
- The crew may need to be reminded to remove smoke/fumes.
- The crew should be directed to return to the *Smoke/Fire/Fumes Checklist* after smoke/fumes removal if the *Smoke/Fire/Fumes Checklist* was not completed.

**Additional Steps for Source Elimination**

- Additional steps aimed at source identification and elimination:
    - Are subsequent to the manufacturer's initial steps and the diversion decision;
    - Are accomplished as time and conditions permit, and should not delay landing; and,
    - Are based on model-specific historical data or analysis.
- The crew needs checklist guidance to systematically isolate an unknown smoke/fire/fumes source.

**Definitions:**

**Confirmed to be extinguished:** The source is confirmed visually to be extinguished.

**Continued flight:** Once a fire or a concentration of smoke/fumes is detected, continuing the flight to the planned destination is not recommended unless the source of the smoke/fumes/fire is confirmed to be extinguished and the smoke/fumes are dissipating.

**Crew:** For the purposes of this document, the term "crew" includes all cabin crewmembers and flight crewmembers.

**Diversion may be required:** Establishes the mindset that a diversion may be required.

**Land at the nearest suitable airport:** Commence diversion to the nearest suitable airport. The captain also should evaluate the risk presented by conditions that may affect safety of the passengers associated with the approach, landing and post-landing.

**Landing is imminent:** The airplane is close enough to landing that the remaining time must be used to prepare for approach and landing. Accomplishing further smoke/fire/fumes-identification steps would delay landing.

**Land immediately:** Proceed immediately to the nearest landing site. Conditions have deteriorated, and any risk associated with the approach, landing or post-landing is exceeded by the risk of the on-board situation. "Immediate landing" implies immediate diversion to a landing on a runway; however, smoke/fire/fumes scenarios may be severe enough that the captain should consider an overweight landing, a tailwind landing, a ditching, a forced off-airport landing, etc.