Reducing the Risk of Smoke and Fire in Transport Airplanes:

Past History, Current Risk and Recommended Mitigations

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Table of Contents

Executive Summary iii
Risk, Perception and Probability of Smoke, Fire and Fumes 1
A Historical Look at Smoke, Fire and Fumes: Characterizing the Problem 2
Enter the Jet 3
The Next Generation 5
Smoke/Fire/Fumes Regulations and Advisory Circulars for Transport Airplanes 6
FAA Regulatory Improvements 6
Interior Material Toxicity and Flammability 9
Fire Extinguishers 9
Single Point Failures and Relationship to Multiple System Failures 10
Smoke Barriers 11
Location, Location, Location 11
Ventilation, Open Windows and Visibility 13
Fight the Fire: Diagnosis and Training 14
Wires and Fires 15
Detection and Protection 17
Maintenance 17
Wiring Insulation and Debris 17
Wiring Health 18
Recommendations 19
Airworthiness 20
Protective Equipment 25
Maintenance 28
Pilot Procedures 29
Flight Crew Training 33
Concluding Remarks 34
Appendix 1 35
Comparison of Airworthiness Requirements between FAA & EASA/JAA 35

Executive Summary

From the beginning of aviation history uncontrolled in-flight fire has been a serious issue. Aviation's first fatal accident occurred as a result of an uncontrolled in-flight fire. In July 1785, Jean-François Pilâtre de Rozier's hydrogen balloon ignited and burned over the English Channel.[1]

The occurrence of smoke, fire or fumes aboard a commercial aircraft presents a potentially dangerous situation. Accident data show in-flight fire with the fourth highest number of on board fatalities and the seventh highest category of accidents.[2] 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, one aircraft a day is diverted due to smoke.[3]

There have been significant improvements in the safety of transport aircraft. Yet, there remain additional opportunities for improvements in equipment design and airworthiness criteria, protective equipment, maintenance, improved pilot procedures and flight crew training.

Further reducing the risk involves multiple layers of mitigation. The adoption of the recommendations may provide the needed layers while helping to reduce the risk and severity of future in-flight fires. As in the past, aviation will continue to experience in-flight fires. The recommendations are intended to help prevent the initiation of fires and reduce the likelihood that any fire that does ignite would become uncontrollable.

Recommendations to reduce the severity and effects of in-flight fires include:

Equipment Design and Airworthiness

1. Evaluate aircraft for single point failures of wiring and potential effect on systems of the aircraft.

2. Improve the engineering and installation of wires so that the routing does not endanger, by proximity, any critical system wiring. Evaluate modifications using the same approval process for Supplemental Type Certificate modification as for Type Certificates.

3. Install arc fault circuit interrupter technology on new and existing transport aircraft.

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[1] Kane, R. M. (2002). *Air transportation*. Washington, DC: Kendal Hunt Publishing Company. Doc 234.
[2] Boeing. (2005, May). Statistical summary of commercial jet airplane accidents: Worldwide operations 1959-2004. Seattle, WA: Boeing. Doc 178.
[3] Shaw, J. (2000). A review of smoke and potential in-flight fire events in 1999. Washington, DC: Society of Automotive Engineers. Doc 185.

4. Conduct continuous smoke testing for flight deck smoke evaluation tests for a type certificate.

5. Install fire access ports or dedicated fire detection and suppression systems in inaccessible areas of aircraft.

6. Mark locations of minimal damage for access to inaccessible areas of the aircraft.

7. Increase the number and location of sensors to alert the flight crew of smoke/fire/fumes. These sensors should take advantage of new technology to minimize the false alarm rate.

Protective Equipment

1. Implement vision assurance technology for improved pilot visibility during continuous smoke in the flight deck.

2. Install full-face oxygen masks and provide sufficient flight crew oxygen for descent and landing during a smoke/fire/fume event.

3. Increase size of flight deck and cabin fire extinguishers to five pounds of Halon or an equivalent effective agent.

Maintenance

1. Inspect thermal acoustic insulation blankets and smoke barriers to ensure cleanliness.

2. Modify maintenance procedures to minimize the possibility of contamination of thermal acoustic insulation blankets.

3. Improve wiring inspection maintenance programs using new technology not relying exclusively on visual inspection of wiring bundles.

Pilot Procedures

1. Improve flightcrew procedures to use autoflight systems to reduce pilot workload. Included in the procedures should be provisions for the failure or un-serviceability of the autoflight system.

2. Eliminate procedures to open flight deck window to vent smoke. Improve smoke removal procedures to ensure maximum effectiveness.

3. Redesign all transport aircraft checklists pertaining to smoke/fire/fumes to be consistent with the Flight Safety Foundation smoke/fire/fume checklist template. Consider: memory items, prevention of checklist “bottlenecks,” font size and type, where it should be found (quick reference handbook (QRH) or electronic), smoke removal, number of checklists for smoke/fire/fumes and the length of the checklists.

Flight Crew Training

1. Ensure that flight crew and cabin crew training includes the proper use of a crash ax, the necessity of proper fire extinguisher operation including vertical orientation, the proper accomplishment (or abandonment) of checklist during simulated smoke/fire/fume events, the importance of maintaining a smoke barrier during smoke/fire/fume events and the ineffectiveness of, and potential problems with, opening a flight deck window during realistic line oriented re-current flight training on a recurrent annual basis.

Cooperation of the regulators, manufacturers, air carriers and professional associations is needed to implement these safety recommendations. Only through execution of a comprehensive mitigation strategy along with developing and implementing a plan to maximize fleet coverage can the risk of in-flight smoke, fire and fumes be reduced to an acceptable level.

Risk, Perception and Probability of Smoke, Fire and Fumes

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, one aircraft a day is diverted due to smoke.[4] Fortunately, it is rare for a smoke event to become an uncontrolled in-flight fire. However, data collected by the International Air Transport Association (IATA) estimates that more than 1,000 in-flight smoke events occur annually, resulting in more than 350 unscheduled or precautionary landings.[5] 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.[6]

Over 36 months (from January 2002 to December 2004),[7] IATA conducted a study of Air Safety Reports (ASR) filed in their safety trend analysis, evaluation and data exchange system (STEADES) database from 50 commercial operators. Over the three years 2596 smoke events were recorded. The study revealed that 1701 of the 2596 events 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 aircraft are equally affected by smoke events. The origination of smoke/fume events occurred most often (in order): cabin, lavatory, flight deck, cargo hold and the galley.

Reviewing the statistics from 1987 to 2004, the four leading categories (out of 17 listed) of commercial jet airplane fatalities were loss of control (LOC), controlled flight into terrain (CFIT), specific component failure (non-powerplant) and in-flight fire. These four causes accounted for the largest number of fatalities.[8] Of the 226 accidents included in the study there were 10 in-flight fires. This was the seventh most common type of accidents tied with the accident type of undershoot/overshoots.

Advisory Circular (AC) 25-1309-1a[9] contains useful definitions for identifying the severity of potential events and relating them to the frequency of occurrence. Using these definitions, an in-flight fire can be characterized as a catastrophic event because it has the potential to be a “condition that would prevent continued safe flight and landing.”[10]

[4] Shaw, J. (2000). A review of smoke and potential in-flight fire events in 1999. Washington, DC: Society of Automotive Engineers. Doc 185.

[5] International Air Transport Association (IATA). (2005).*On-board fire analysis: From January 2002 to December 2004 inclusive*. Quebec, Canada: Author. Doc 176.

[6] Halfpenny, P. (2002). *IFSD probability analysis*. Washington, DC: Author. Doc 6.

[7] International Air Transport Association (IATA). (2005, August 8).*On-board fire analysis: From January 2002 to December 2004 inclusive*. Quebec, Canada: Author. Doc 176

[8] Boeing. (2005, May). Statistical summary of commercial jet airplane accidents: Worldwide operations 1959-2004. Seattle, WA: Boeing. Doc 178.

[9] FAA. (1988, June, 21). *AC 25.1309-1A: System design and analysis*. Washington, DC: FAA. Doc 116.

[10]FAA. (1988, June, 21). *AC 25.1309-1A: System design and analysis*. Washington, DC: FAA. Doc 116.

Most in-flight fires do not actually become catastrophic. However, the potential exists and when calculating risk it is reasonable to consider the potential outcomes.

According to the AC, a catastrophic event must be "extremely improbable" (defined as conditions having a probability on the order of 1×10^{-9} or less). Analysis of in-flight fire events by Captain Jim Shaw shows a greater likelihood of occurrence than that of "extremely improbable."[11] This is consistent with the IATA study where during the 36 months examined, there occurred an average of two and a half smoke events each day. Paul Halfpenny, in his research suggests that the probability of a diversion due to cockpit smoke could be a "reasonably probable event ($1x10^{-3}$ to $1x10^{-5}$)."[12]

Reviewing in-flight smoke/fire/fume events shows that there have been more in-flight smoke/fire/fumes events per departure than "extremely improbable". An in-flight fire can become a "catastrophic" event. Therefore, improved mitigations to reduce the occurrence rate are desirable.

A Historical Look at Smoke, Fire and Fumes: Characterizing the Problem

From the beginning of aviation history uncontrolled in-flight fire has been a serious issue. Aviation's first fatal accident occurred as a result of an uncontrolled in-flight fire. In July 1785, Jean-François Pilâtre de Rozier's hydrogen balloon ignited and burned over the English Channel.

A review of the past incidents shows that in-flight fires have continued to occur despite the efforts of manufacturers, regulators and operators. Recently the Federal Aviation Administration (FAA) acknowledged that it is unlikely to "eradicate all possible sources of ignition"[13] in fuel tanks and they also state "the examinations of large transport airplanes … revealed many anomalies in electrical wiring systems and their components, as well as contamination by dirt and debris."[14] This acknowledgement is important because it shows the need for multiple mitigations to contend with smoke/fire/fumes. Not only must internal fire sources within the aircraft be considered, but the possibility of the detonation of an explosive device and its effect on the aircraft should also be considered in the overall risk assessment.

[11] Shaw, J. (2000). A review of smoke and potential in-flight fire events in 1999. Washington, DC: Society of Automotive Engineers. Doc 185.

[12] Halfpenny, P. (2002). *IFSD probability analysis*. Washington, DC: Author. Doc 6.

[13] FAA. (2005, November 23). *NRPM:* "Reduction of fuel tank flammability in transport category airplanes;" Proposed rule, *70(225)*, Federal Register p. 70922-70962. Doc 257.

[14] FAA. (2005, October 6). *Notice of proposed rulemaking (NPRM): Enhanced airworthiness program for airplane systems/fuel tank safety (EAPAS/FTS); Proposed advisory circulars; Proposed rule and notices, 70(193),* Federal Register p. 58508-58561. Doc 233.

Some notable in-flight fires can help characterize the risk. An uncontrolled fire caused the crash of a Trans World Airline Lockheed Constellation on July 11, 1946, near Reading, Pennsylvania.[15] 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."[16] The flight crew attempted to fight the fire without success. Smoke streamed into the flight deck obscuring the instruments and filling it with dense smoke. The instructor captain opened the window in an effort to find the airport, but was unable to maintain control. The aircraft crashed killing everyone except the instructor captain. "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."[17] This was an early example of smoke causing extreme difficulties for pilots.

The National Transportation Safety Board (NTSB) 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." A contributing factor was 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."[18] Some of the same concerns raised in this accident such as electrical arcing, ignition of insulation and creation of dense smoke remain today almost 60 years later.

Enter the Jet

Commercial jet airline service began in the United States on October 26, 1958, when Pan American flew from New York to Paris. As the jets took over commercial flight operations, the accident rate declined. This was due, in part, to the improvements in design and equipment reliability. In addition, the regulatory requirements for commercial aircraft also became more stringent.

However, at least two B707s encountered serious fires that resulted in loss of the aircraft. These two accidents in 1973 caused changes in regulation, design and procedures for the 707 and future aircraft. On July 11, 1973 Varig Flight 860 departed Rio de Janeiro for Paris. After a routine flight they were approaching the Orly airport when a fire broke out in the aft cabin. Smoke filled the cabin and began filling the flight deck. Only five

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[15] Civil Aeronautics Board (CAB). (1946, November 29). *Accident investigation report: Transcontinental and Western Air, Inc. July 11, 1946* (SA-120). Washington, DC: CAB. Doc 81.

[16] Civil Aeronautics Board (CAB). (1946, November 29). *Accident investigation report: Transcontinental and Western Air, Inc. July 11, 1946* (SA-120). Washington, DC: CAB. Doc 81.

[17] Civil Aeronautics Board (CAB). (1946, November 29). *Accident investigation report: Transcontinental and Western Air, Inc. July 11, 1946* (SA-120). Washington, DC: CAB. Doc 81.

[18] Civil Aeronautics Board (CAB). (1946, November 29). *Accident investigation report: Transcontinental and Western Air, Inc. July 11, 1946* (SA-120). Washington, DC: CAB. Doc 81.

kilometers (three miles) from Runway 07, in a smoke filled flight deck where visibility of the flight instruments was diminishing rapidly, the Captain decided to land off the airport in a field. Opening windows in an effort to improve visibility did not provide enough visibility to allow the flight to continue to the runway; the aircraft landed in a field after striking trees.

Only 70 seconds remained before Varig Flight 860 would have reached the safety of the runway where Airport Rescue and Firefighting 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. Was it due to smoke or fire?

Autopsies of many of the passengers showed that the cause of death was not fire, but smoke.[19] Conditions in the flight deck may have deteriorated to such a point that there was a question about the ability to maintain control of the aircraft for another 70 seconds. An important clue to the condition of the flight deck is that the surviving crewmembers were not burned, but did suffer smoke inhalation. It is possible that the 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 is that 117 passengers survived the landing, yet all but one succumbed to asphyxiation by poisonous gas and smoke.[20]

Later in that same year, Pan Am Flight 160 (a Boeing 707-321C) departed New York for Prestwick, Scotland on November 3. About 30 minutes into the flight of this all cargo jet, the crew reported smoke on board[21] from improperly packed hazardous cargo. Unfortunately, the aircraft crashed just short of Runway 33 Left at the Logan International Airport near Boston, Massachusetts. The NTSB cited 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." The Safety Board further determined that "the dense smoke in the cockpit seriously impaired the flightcrew's vision and ability to function effectively during the emergency."[22]

Both of these examples show smoke situations so serious that crew members took drastic actions. Varig Flight 860 intentionally landed in a field and Pan American Flight 160's 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

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[19] Secrétariat d'état aux Transports, Commission d'Enquête. (1975, Décembre). *Rapport final sur l'accident survenu le 11 juillet 1973 à Saulx-les-Chartreux au Boeing 707-PP-VJZ de la compagnie Varig*. Translated from French to English, July 2005. Doc 78/79.

[20] Johnston, W. L. & Cahalane, P. T. (1985). "Examination of fire safety of commercial aircraft cabins." *Safe Journal*, 15(2), 4-9. Doc 140.

[21] NTSB. (1974, December 2). *Aircraft accident report: Pan American World Airways, Inc. November 3, 1973* (NTSB-AAR-74-16). Washington, DC: NTSB. Doc 27.

[22] NTSB. (1974, December 2). *Aircraft accident report: Pan American World Airways, Inc. November 3, 1973* (NTSB-AAR-74-16). Washington, DC: NTSB. Doc 27.

extended (which they had been for the preceding four and half minutes) the aircraft became uncontrollable. This action was probably taken without the knowledge, or agreement, of the Captain. In both aircraft there was a smoke filled flight deck; yet, there is no mention of a flight deck fire on either cockpit voice recorder (CVR). This proved that not only should fire be considered, but the effects of smoke in the flight deck also posed risk.

The loss of Varig Flight 860 and Pan American Flight 160 were instrumental in causing changes in regulation, design and flight crew procedures of transport category aircraft. Some of these changes included improved flight crew procedures for smoke removal, tightened regulation for hazardous material shipping, improved design in cabin airflows, banned smoking in lavatories and requirements that waste towel receptacles be made more fire resistant.

The Next Generation

The next generation of jets included the jumbos. There were new safety issues for the jumbos but not all were foreseen. An example was the airflow pattern of the Boeing 747. In the late 1960s there was no requirement or standard for airflow patterns in transport category aircraft. Yet it was found that smoke could be drawn into the flight deck of the B747SP during a main deck cabin fire during some airflow settings. The FAA proved this in April of 2003 during comprehensive tests.[23] The tests showed the complexity of airflow patterns in some wide body aircraft. These airflow patterns can cause smoke to accumulate in unexpected places in the aircraft.

Advancing technology provided many enhancements in this generation of jets. Some aircraft increased automation allowing the elimination of flight engineers. One consequence of increasing automation was increasing the number of wires in the aircraft. Wire bundles grew in size and number as more electrical control of systems occurred. Also adding to the number of wires in aircraft was the increase in system redundancy. Dispatch reliability was becoming a major selling point. Therefore, redundancy was increased, thus, increasing the wiring within the aircraft.

Wire adds weight to aircraft. Therefore, manufacturers attempt to lighten the wiring where it can be done safely. One of the more effective methods is by using lighter insulation materials. Some of the lighter material has experienced unexpected consequences. Some lighter insulation has been found to be susceptible to cracking which leads, in some cases, to arcing. This arcing, when combined with combustible material (which can be wire insulation), can cause a self-sustaining fire in just a few minutes. And electrical arcing is only one of the potential sources of fire and smoke in airliners.

The aviation community has recognized that multiple layers of protection are needed if advancement in fire safety is to occur. Multiple layers of protection or multiple approaches to the threat are very necessary as unexpected events occur to crews faced with an in-flight crisis because this can be a complex, once in a lifetime event. The

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[23] Blake, D. (2003, April). *Ground tests of aircraft flight deck smoke penetration resistance* (DOT/FAA/AR-TN03/36). Springfield, VA: National Technical Information Service (NTIS). Doc 5.

examples show how uncontrolled in-flight smoke/fire/fumes can cause the loss of the airplane. This historical perspective sets the stage for how aviation can improve in the future.

Smoke/Fire/Fumes Regulations and Advisory Circulars for Transport Airplanes

FAA Regulatory Improvements

The FAA responded to events, incidents and accidents with regulatory improvements. One notable accident that resulted in numerous regulatory improvements was the June 2, 1983 accident of Air Canada Flight 797 in Cincinnati, Ohio. The DC 9-30 experienced an uncontrollable in-flight fire that began in the aft lavatory. This accident resulted in several safety improvements which included, but were not limited to: detection methods for lavatory fires, full-face-mask portable oxygen bottles for cabin crewmembers, methods to identify smoke sources and requirements for airplanes certified under CAR Part 4b to comply with 14 CFR Part 25.1439.[24] These were important steps toward making in-flight fire less likely and providing the crew with better means of detecting and fighting fires.

Before this accident, the FAA did propose in 1975 to amend the regulations (specifically 14 CFR Part 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.[25] In 1981 the FAA advised the NTSB that they intended to update technical standard order (TSO) C99 that would provide a minimum standard for emergency equipment for "protection of flight crew members from toxic atmospheres."[26] The intent of the FAA was to use an AC to recommend that operators upgrade protective breathing equipment to the new TSO standards.

Much of the protective equipment in use at that time did not meet the updated TSO standard.[27] It should be noted that neither a TSO nor an AC can provide a regulatory requirement for protective breathing equipment. The NTSB did not believe the FAA's action was sufficient to "assure passenger safety."[28]

The FAA did not immediately implement the NTSB recommendations one of which was regarding lavatory fire detectors until after the Air Canada Flight 797 accident in June of 1983. In addition to action on lavatory smoke detectors and Protective Breathing

[24] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.
[25] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.
[26] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.
[27] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.
[28] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.

Equipment (PBEs), other safety enhancements resulted from NTSB recommendations from Air Canada Flight 797. New emergency lighting standards and recommendations were advised. The Board recommended tactile aisle markers and floor lighting so that people inside a smoke filled cabin could locate an emergency exit by feel alone. Improvements in fire blocking material (this required the retrofit of 650,000 seats) to slow fire propagation and emergency exit lighting requirements, became a requirement in 1986.[29]

Lavatory fires continued to occur, causing the NTSB to recommend smoke detectors and automatic discharge fire extinguishers in the waste receptacles. The FAA implemented the NTSB 1974 recommendation (A74-98) for mandating automatic discharge fire extinguishers in the lavatory waste receptacle after Air Canada Flight 797's fire in 1987.[30] Also, in 1986 the FAA required that at least two Halon fire extinguishers be in the cabin.[31]

On July 29, 1986 the FAA issued AC 25-9 to provide guidelines for certification tests of smoke detection, penetration, evacuation tests and flight manual emergency procedures.[32] The AC specifically cites continuous smoke as a condition that should be considered in the formulation of smoke and fire procedures. It cited that accidents statistics show there are conditions of continuous fire and smoke in-flight. Interestingly, the AC test procedure for flight deck smoke evacuation states that the smoke generation should be terminated after the flight instruments are obscured. However, all other tests cited in AC 25-9 require continuous smoke be used.[33] The ventilation systems are allowed three minutes to clear the smoke so that a pilot can see the instruments. This test does not represent conditions where smoke continues to be produced.

Air Canada Flight 797 experienced continuous smoke causing the Captain to land with his oxygen mask and smoke goggles on and his face pressed against the windshield.[34] Other cases of continuous smoke in the flight deck include an Air Europe Fokker 100 landing at Copenhagen on December 17, 1989, Varig Flight 860, Pan American Flight 160 and AirTran Flight 913[35]. The Air Europe flight experienced dense smoke so thick

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[29] Duquette, A. (2005, August). FAA fact sheet: Improvements to cabin safety. Retrieved October 12, 2005, from http://www.faa.gov/news/news_story.cfm?type=fact_sheet &year=2005&date-080305 Doc 229

[30] Duquette, A. (2005, August). FAA fact sheet: Improvements to cabin safety. Retrieved October 12, 2005, from http://www.faa.gov/news/news_story.cfm?type=fact_sheet &year=2005&date-080305 Doc 229

[31] Duquette, A. (2005, August). FAA fact sheet: Improvements to cabin safety. Retrieved October 12, 2005, from http://www.faa.gov/news/news_story.cfm?type=fact_sheet &year=2005&date-080305 Doc 229

[32] FAA. (1986, July 29). *AC 25-9: Smoke detection, penetration, and evacuation tests and related flight manual emergency procedures*. Washington, DC: FAA. Doc 72

[33] FAA. (1986, July 29). *AC 25-9: Smoke detection, penetration, and evacuation tests and related flight manual emergency procedures*. Washington, DC: FAA. Doc 72.

[34] Johnston, W. L. & Cahalane, P. T. (1985). Examination of fire safety of commercial aircraft cabins. *Safe Journal*, 15(2), 4-9. Doc 140.

[35] NTSB. (1970, August 24). *Brief of incident: N838AT* (DCA00MA079). Washington, DC: NTSB. Doc 180.

that the pilots could not see each other.[36] There is evidence that continuous smoke can occur in transport aircraft flight decks, yet the flight deck ventilation tests do not require that continuous smoke be present.

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; and
- Continuous smoke generation in the cockpit smoke evacuation tests.[37]

The final version of AC25-9a was published on January 6, 1994. While most of the issues and testing criteria were similar, there were changes from the draft. The revision from the original AC included recommendations for addition 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 (8): "Although the FAR[38] does not require the consideration of continuous smoke generation/evacuation, the FAA recommends that the airframe design address this situation. Accordingly, paragraphs 12a (l) and l2e (3) recommend addressing continuous smoke generation/evacuation in the cockpit."[39] 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.

The FAA testified before Congress on November 8, 1993 just before the final version of the AC was released. During that testimony they stated, "The evacuation of smoke from a cockpit is needed to enable the crew to operate the airplane. 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

[36] International Civil Aviation Organization (ICAO). (1989, May). *ICAO summary*. Montreal, Canada: ICAO. Doc 131.
[37] FAA. (1992, July 14). *Draft AC 25-9A: Smoke detection, penetration, and evacuation tests and related flight manual emergency procedures*. Washington, DC: FAA. Doc 192.
[38] FAR refers to aviation regulations under Title 14 Code of Federal Regulation.
[39] Federal Aviation Administration (FAA). (1994, January 6). *Advisory circular (AC) AC 25-9A: Smoke detection, penetration, and evacuation tests and related flight manual emergency procedures*. Washington, DC: FAA. Doc 14.

outside the aircraft, to continue safe flight and landing even when a reasonably probable continuous smoke source is present."[40]

However, this was not consistent with the experience of Federal Express Flight 1406 (a DC-10 that landed and burned on September 5, 1996), Swissair Flight 111 (A MD-11 that crashed after an major in-flight fire on September 2, 1998, described later in the paper), or AirTran Flight 913, which experienced an in-flight fire on August 8, 2000[41]. The fires aboard these aircraft burned and the crew could not extinguished or evacuate the smoke so it spread.

Interior Material Toxicity and Flammability

The flammability of material in the interior of the cabin became a concern as toxic fumes were found to be released during cabin fires. Therefore, improvements to flammability standards were 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, including (well known Watergate personality) Howard Hunt's wife, showed high levels of cyanide in their blood stream.[42] This high visibility accident helped show the need for improvement in the toxicity of cabin interiors. 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 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.[43]

Fire Extinguishers

In addition to smoke detection and evacuation considerations, the NTSB also recommended upgrading fire extinguishers in the final report of Air Canada Flight 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 insufficient in larger, rapidly spreading fires. In FAA Technical Center tests, Halon (bromochlorodi-fluoromethane) showed itself to be superior to carbon dioxide, dry chemical or water fire extinguishers. These tests encouraged the FAA on May 17, 1984, to issued Notice of Proposed Rule Making (NPRM) 84-5.[44] It contained three proposed rules to address some of the NTSB's concerns expressed during the Air Canada Flight 797 investigation. The proposed rules required the installation of automatic fire extinguishers for each

[40] Aviation competition and safety issues: *Hearing before the Subcommittee on Commerce, Science, and transportation, Senate*, 103d Cong., 60 (1993, November 8). Doc 132.
[41] NTSB. (1970, August 24). *Brief of incident: N838AT* (DCA00MA079). Washington, DC: NTSB. Doc 180.
[42] NTSB (1973, August 29). *Aircraft accident report: United Air Lines Inc. December 8, 1972 (NTSB-AAR-73-16) Washington, DC: NTSB*
[43] http://www.bts.gov/publications/the_changing_face_of_transportation/chapter_03.html
[44] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.

lavatory disposal receptacle used for towels/paper/waste, installation of smoke detector systems in the galleys and lavatories of air transport category airplanes and required two Halon 1211 fire extinguishers to be located in passenger compartments. All air carriers complied with these provisions within one year after the rules became effective.[45]

Single Point Failures and Relationship to Multiple System Failures

When considering the effect of in-flight fire on the systems of the aircraft, a single point of failure that can, and has, caused multiple systems to completely fail. Wiring failures can be catastrophic, as the loss of a Royal Air Force (RAF) Nimrod proved in May 1995.[46] The Nimrod was forced to ditch in the sea following a severe fire. The investigation found that the direct current (DC) wiring loom for the number one engine had an arcing event caused by an undetermined defect. This arcing caused the wiring loom to fail and for several wires to melt together. This joining of wires caused an uncommanded signal to the number four engine starter valve causing it to open while the engine was operating. As this valve opened the turbine starter began to spin wildly and quickly to over speed. The over-speeding starter turbine wheel flew out of its housing and punctured a wing fuel tank. The ensuing fire was catastrophic causing the need to ditch the aircraft. The belief of the investigators was 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 clearly shows the potential for a fire to cause multiple or cascading problems. The fire caused by melting wires the uncommanded 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 and the fire defeated all the redundancies that were designed to protect the aircraft.

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. 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 and the effects on multiple aircraft systems. The STC requirements as shown by the in-flight entertainment (IFE) system installation on Swissair Flight 111 may be inadequate. 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.[47] Therefore, there could be no consideration of the location of

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[45] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.

[46] Air Accidents Investigation Branch (AAIB). (1998, January 9). Report of N653UA at LHR. Doc 2.

[47] TSBC. (2003, March 27). Aviation investigation report: In-flight fire leading to collision with water Swissair Flight 111 September 2, 1998. Quebec, Canada: TSBC. Doc 188.

the IFE power wires contained in the STC. This lack of specific wire routing within the STC could allow for wire chafing and allow the bypassing of the CABIN BUS switch. The overall health of the wires within the bundle of the MD-11 was not evaluated during the installation of the IFE.[48]

Smoke Barriers

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

In most modern transports 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. One example occurred when a cabin crew member 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!"[49] However, the entry of smoke and fumes continued (the report is unclear if the door was closed at the Captain's command). The barrier did not prevent the flight deck from becoming full of smoke and fumes.

Once the flight deck door is opened it is no longer a barrier. Another example was Air Tran Flight 913, which had the flight attendants open the flight deck door while smoke was pouring into the 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 in a smoke event is not a rare exception. This tendency to open a flight deck door shows that crew training does not effectively address the importance of maintaining the smoke barrier.

Other flights have lost an effective smoke barrier even before takeoff. 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."[50] 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.

Location, Location, Location

Experience shows that fires can start in inaccessible locations, making it difficult or impossible to extinguish the fire. The fire in the "attic" of Swissair Flight 111 spread rapidly without the ability of the crew to extinguish it due to its location. There was no

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[48] TSBC. (2003, March 27). Aviation investigation report: In-flight fire leading to collision with water Swissair Flight 111 September 2, 1998. Quebec, Canada: TSBC. Doc 188.

[49] Commission of Enquiry. (1977, March). *Aircraft accident: Cubana de Aviacion, DC8-43October 6, 1976*. Bridgetown, Barbados: Commission of Enquiry. Doc 136.

[50] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71

means to direct a fire extinguisher agent at the source of the fire in the area above the interior ceiling.

The inability to have access to the source of the fire is a serious limitation. All fire extinguishers work best when they are discharged at the source or the base of the fire. In Air Canada Flight 797, as the fire grew behind the aft lavatory wall, flight attendants knew that there was growing smoke, but that the fire was inaccessible.

A growing fire needs combustible fuel. Insulation blankets, often located in inaccessible areas, can provide the needed fuel for a fire. The FAA specifies the flammability of insulation blankets during initial certification of the aircraft.[51] However, as the aircraft ages, contaminates such as lubricants, corrosion inhibitors, hydraulic fluid and dust can coat the insulation blankets. As shown in NTSB investigations[52] and FAA tests,[53] 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.[54] This upgrade was the result of major work done by the FAA Technical Center in flammability testing and material flammability resistance.

Not all fires have insulation blankets providing the fuel. In some electrical fires the panel material or insulation can provide the fuel.[55] The requirements of the flammability of the insulation material of wires are specified in 14 CFR Part 25.869. These requirements have been improved over the years, but there are some aircraft, such as Air Tran Flight 903, which involve wiring that met the standards of the initial type certificate issuance date but did not meet the current standard.

In some fires the surrounding material and location combine to create a serious hazard. Air Tran Flight 903 experienced an electrical fire in the electrical power center located just ahead of the flight attendant jumpseat. The flight attendant did not attempt to find the source of the smoke nor did either flight attendant attempt to discharge a fire extinguisher. The source of the smoke was uncertain and the flight attendants were not trained to remove interior panels when searching for smoke sources. Again, the location of the electrical fault and the lack of proper training prevented fire fighting from occurring.

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[51] FAA. (2005, September 1). *FSAW: Implementation of thermal and acoustic insulation blankets flammability requirements* (FSAW 05-09). Washington, DC: FAA. Doc 243.

[52] Keegan, C. (2001, October). NTSB: Investigations involving in-flight fire [Power Point presentation]. *Proceedings of the Third Triennial International Fire & Cabin Safety Research Conference*. Atlantic City, NJ. Doc 104.

[53] Blake, D. (1991, February). *Development and growth of inaccessible aircraft fires under inflight airflow conditions* (DOT/FAA/CT-91/2). Springfield, VA: NTIS. Doc 43.

[54] FAA. (2005, September 1). *FSAW: Implementation of thermal and acoustic insulation blankets flammability requirements* (FSAW 05-09). Washington, DC: FAA. Doc 243.

[55] Keegan, C. (2001, October). NTSB: Investigations involving in-flight fire [Power Point presentation]. *Proceedings of the Third Triennial International Fire & Cabin Safety Research Conference*. Atlantic City, NJ. Doc 104.

Ventilation, Open Windows and Visibility

Adequate ventilation of aircraft cabins is essential. The exchange rate of air within the cabin is carefully regulated. During times of smoke contamination, this exchange rate can be even more important. Greater amounts of fresh air introduced into the cabin dilute the smoke at a faster rate. If the smoke production overwhelms the ability of the ventilation system to send it overboard, smoke will begin to accumulate in the cabin, usually near the outflow valve or main outflow valve for aircraft with more than one outflow valve. This accumulation will then begin to spread through the cabin. One solution to a ventilation system being overcome is to use ram air from outside the aircraft. While the aircraft must be at an altitude where it can be depressurized, some manufacturers installed ram air valves to allow uncontaminated air into the cabin at a higher rate.

Most aircraft 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. In some aircraft this positive pressure does not work as well as initially intended. The FAA Technical Center found that during tests in a Boeing B747SP that smoke could migrate into the flight deck because there was not positive pressure to prevent it.[56]

Another consideration in smoke migration patterns is the buoyancy of the smoke. Very buoyant smoke will tend to remain on the ceiling where it will disperse and follow the contours of the ceiling. Cooler, less buoyant smoke will interact differently with the air flow pattern, making its distribution more homogeneous throughout the cabin.

During the investigation of Air Canada Flight 797's fire the procedure to open a window or 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 into the 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 airplane.[57]

Boeing's 737 Smoke Removal Checklist notes that opening a window may not be possible at speeds greater than holding speeds[58] and Airbus's Smoke/Fumes Removal checklist for A319/A320/A321 requires that the aircraft be decelerated to 200 knots before opening the window.[59] This requires slowing the aircraft 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 minimize the time to the airport and slowing to holding speed to open a window.

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[56] Blake, D. (2003, April). *Ground tests of aircraft flight deck smoke penetration resistance* (DOT/FAA/AR-TN03/36). Springfield, VA: National Technical Information Service (NTIS). Doc 5.

[57] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.

[58] Boeing. (1998, February 13). 733 Operations manual: Smoke removal checklist. Doc 35

[59] Airbus. Smoke/fumes removal checklist. Doc 245

The remaining important issues of opening a flight deck window are effectiveness and consequences. A review of some incidents shows that the effectiveness is variable. Air Canada Flight 797 opened and closed the First Officer's window several times. The noise level was so high that no communication could take place between the flight crewmembers. The venting was unsuccessful as the cabin and flight deck remained full of smoke.

In cases of continuous smoke, no manufacture suggests opening a window, because it can cause the fire to spread. Several serious in-flight fires show that the flight crews opened the window without improving the visibility significantly and, in some cases it was made worse. An open window creates high wind noise, which prevents effective communication between crewmembers. 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).

Fight the Fire: Diagnosis and Training

Air Canada Flight 797 departed Dallas, Texas for Toronto, Canada on June 2, 1983.[60] The flight attendants discovered a fire in the aft lavatory. In the next seventeen minutes the flight crew faced a growing in-flight fire. One flight attendant discharged a cabin fire extinguisher into the lavatory, but the fire continued to burn behind the wall. The First Officer planned to discharge another extinguisher into the lavatory, but after feeling the heat of the door wisely decided not to open it. The fire was out of control, and spread rapidly in inaccessible locations of the airplane.

The flight attendants did not know either the location of the fire or the most effective placement of the fire extinguisher. A general discharge into the lavatory did not arrest the fire's progress because the fire was behind the lavatory wall. Had there been access ports in the wall, it is possible that this fire might have been extinguished, provided the flight attendants had been trained to access and fight hidden fires through such access ports.

As with the Varig B707 accident, the FAA modified the regulations after evaluating NTSB recommendations and industry input. The installation of Halon fire extinguishers, automatic fire extinguishers in lavatory trash receptacles, and more stringent flammability standards for interior components were a few changes to the transport aircraft fleet.

As recently as August 8, 2000, another in-flight fire showed that the lessons from Air Canada Flight 797 were incomplete. An Air Tran DC9-32 (the same type as Air Canada Flight 797), Flight 913, departed Greensboro, North Carolina for Atlanta. Shortly after takeoff two flight attendants began to smell smoke. One of them opened the flight deck

[60] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.

door only to find it full of smoke and the pilots wearing oxygen masks and smoke goggles. The Captain advised the flight attendant that they were returning to Greensboro. The flight attendants heard “popping noises”[61] and saw “arcing and sparking” at the front of the cabin. While the flight attendants considered using a Halon fire extinguisher, they took no action as they were unsure where to aim it. There was no open flame and their training did not address hidden fires.

The fires of Air Tran Flight 913 and Air Canada Flight 797 have some similarities. In both cases the fires escalated quickly and became self-sustaining so that the opening of the circuit breakers did not stop the fire. Flight crew training did not prepare the crew to successfully extinguish the fire, communicate effectively, or maintain the smoke barrier in place (by keeping the flight deck door closed).

Wires and Fires

The FAA has recognized that electrical systems are, and are going to be, potential sources of ignition. In the November 23, 2005 NPRM for fuel tanks, the FAA acknowledged, “We have concluded we are unlikely ever to identify and eradicate all possible sources of ignition.”[62]

The most frequent source of fire in transport aircraft is electrical. A Boeing study showed that between November 1992 and June 2000 that almost two thirds of the in-flight fires on Boeing aircraft were electrical[63].

A major ignition source for electrical fires is aircraft wiring. In a modern large transport there is over 500,000 feet of wire.[64] As the complexity and diversity of systems has grown in transport jets, so has the amount of wire. The addition of more wire has increased the probability of wiring-caused problems and fires. The industry is recognizing that the wiring does not last the life of the aircraft.[65]

The US Navy found that between 1995 and 1997 their transport aircraft experienced just over an average of two fires per month and that most would have been prevented by arc fault circuit interruption protection.[66]

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[61] National Transportation Safety Board (NTSB). (2002, January 4). *Safety recommendation: Recent in-flight fires*. Washington, DC: NTSB. Doc 8.

[62] FAA. (2005, November 23). *NRPM: Reduction of fuel tank flammability in transport category airplanes; Proposed rule, 70(225)*, Federal Register p. 70922-70962. Doc 257.

[63] Boeing Aero No. 14. (2000). In-flight smoke. Retrieved May 18, 2005, from http://www.boeing.com/commercial/aeromagazine/aero_14/inflight_story.html Doc 28.

[64] Potter, T., Lavado, M., & Pellon, C. (2003, July). “Methods for characterizing arc fault signatures in aerospace applications” [Power Point presentation]. Attleboro, MA: Texas Instruments. Doc 149.

[65] Teal, C., & Sorensen, D. (2001, October). Health management for avionics performance. *Proceedings of the 20th Digital Avionics Systems Conference*. Daytona Beach, FL. Doc 121.

[66] Potter, T., Lavado, M., & Pellon, C. (2003, July). *Methods for characterizing arc fault signatures in aerospace applications* [Power Point presentation]. Attleboro, MA: Texas Instruments. Doc 149.

Another issue is the Supplemental Type Certificate (STC) additions to aircraft using existing circuit breakers to power equipment that is being added to the aircraft. FAA Technical Center experts 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."[67] This is in violation of 14 CFR Part 25.1357. It can cause overloading of the circuit and the circuit breaker will not provide proper protection. In the past of STC engineering requirements were not a stringent as the requirements for original type certificates.

Electrically caused fires can grow rapidly, as the Air Canada Flight 797 illustrated. 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."[68]

A well-known example of the rapidity of a fire is an MD-11 that was lost on September 2, 1998, Swissair Flight 111. Of significant importance was the cascade of multiple failures as the fire affected electrical wiring throughout the overhead of the MD-11. This caused multiple simultaneous system failures, causing the flightcrew's workload to increase dramatically.

Rapid growth and severity of the fire are reasons why minimizing ignition sources is necessary. Yet examination of transport aircraft has shown that many had ignition risks on board.[69] It should be assumed that every transport aircraft in service also has a risk of electrical fire.

Another example of an accident caused by a wiring fault is Trans World Airlines (TWA) Flight 800. The B747 took off from JFK and exploded climbing through 13, 000 feet. The NTSB found the cause to be an explosion of the center fuel tank. In the recovered wreckage was evidence of arcing in the wiring, which could have allowed high voltage electricity into the fuel quantity wiring causing an explosion of the center fuel tank.[70] During the investigation the NTSB examined the wiring in 25 transport aircraft. Only one of the aircraft (a new B737) did not have metal shavings on or near wiring bundles. Many of the airplanes had foreign material (lint, metal shavings, washers, screws, rivets, corrosion prevention compound, paint and pieces of paper) between wires or wiring bundles. Wire insulation was damaged or cut by the metal debris. There were cases of

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[67] (2003, February 10). More attention needed for safe functioning of circuit breakers. *Air Safety Week*. Doc 151.

[68] Boeing Aero No. 14. (2000). In-flight smoke. Retrieved May 18, 2005, from http://www.boeing.com/commercial/aeromagazine/aero_14/inflight_story.html Doc 28.

[69] Sadeghi, M. (2003, October 6). Enhanced airworthiness program for airplane systems (EAPAS) [Power Point presentation]. *Proceedings of the National Business Aviation Association*. Orlando, FL. Doc 152.

[70] NTSB (2000, August 23). Aircraft Accident Report: Inflight Breakup over the Atlantic Ocean TWA Flight 800, July 19, 1996 (NTSB/AAR-00/03) Washington, DC: NTSB

the core conductor being exposed. Five of the aircraft showed signs of fire or heat damage in wiring.[71]

Detection and Protection

There is fire detection and protection in the engines, auxiliary power unit (if installed) and cargo compartments of modern transports aircraft. Smoke detectors are installed in lavatories with automatic fire extinguishers in the waste bins. But other parts of the aircraft are unprotected. In the unprotected areas detection of a fire depends upon the flightcrew.

Smell is usually the first indication of a fire or potential fire. Once the odor is detected, it can be difficult to locate the source. Locating the source is made more difficult by the high air exchange rate in the cabin of a jetliner. The air is exchanged once every two or three minutes, on average with all air conditioning packs operating. This causes rapid dilution of the smoke and dispersal throughout the cabin. This exchange rate can be reduced significantly as a flight crew shuts off re-circulating fans and/or air conditioning packs during the Smoke/Fire/Fume checklists. Increasing the number of detectors would help in the early detection of smoke/fire/fumes and help pinpoint the source location.

Maintenance

Wiring Insulation and Debris

An example of wire insulation break down and how it can result in multiple simultaneous failures that may be confusing to the flight crew was United Airlines Flight 95, a Boeing 767 on January 9, 1998.[72]

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 electronic flight information system (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 Electronics and Equipment (E&E) bay. Investigators saw arcing and hot spots when power was applied to the aircraft in these wiring looms. Further investigation found that there 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.

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[71] NTSB (2000, August 23). Aircraft Accident Report: Inflight Breakup over the Atlantic Ocean TWA Flight 800, July 19, 1996 (NTSB/AAR-00/03) Washington, DC: NTSB

[72] Air Accidents Investigation Branch (AAIB). (1998, January 9). Report of N653UA at LHR. Doc 2

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 neither mechanic had replaced a Boeing 767 chiller previously. 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 uncovered by the investigation was the presence of conductive debris in the E&E bay. Items such as coins, locking wire (stainless steel) 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.

This finding raised the question of the amount of debris found in other in-service aircraft 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 aircraft were examined and in almost all there was conductive and non-conductive debris. One aircraft had its wiring looms covered in grime, dirt and dust. Metal shavings were found on many aircrafts' wiring, and 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 aircraft.[73]

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 October 6, 2005.[74]

Wiring Health

Good wiring health requires a comprehensive wiring inspection program. 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 need for improvements in maintenance practices and inspections.

From 1995 to 2002 the FAA found 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 these wiring failures cause over 22 flight delays per year and over 27 unscheduled landings per year

[73] Air Accidents Investigation Branch (AAIB). (1998, January 9). Report of N653UA at LHR. Doc 2.
[74] FAA. (2005, October 6). *Notice of proposed rulemaking (NPRM):* Enhanced airworthiness program for airplane systems/fuel tank safety (EAPAS/FTS); Proposed advisory circulars; Proposed rule and notices, 70(193), Federal Register p. 58508-58561. Doc 233

on average.[75] The number of reports should be considered as a minimum number as it is widely believed that this type of finding is underreported by the industry.

Additionally, investigation of the in-flight explosion of TWA Flight 800 and the in-flight fire aboard Swissair Flight 111, led to examination of other aircraft where examples of wire deterioration, improperly installed wires and contamination of wire bundles with dust, fluids and metal shavings were commonly found. The FAA realized that today's maintenance practices do not address the condition of wires to a satisfactory level and that improvements need to be made.[76]

In 2003 MITRE reported on inspection efforts to evaluate the state of wiring in transport aircraft.[77] The non-intrusive inspections of electrical wiring on large transport airplanes found that of the 81 airplanes inspected, there were 40 wiring anomalies per airplane on average. These finding resulted in the issuance of 23 Airworthiness Directives (ADs). On small transport aircraft, 39 airplanes were inspected with 58 anomalies found per airplane on average.[78]

This led to the FAA issuing a NPRM on October 6, 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."[79] The FAA NPRM addresses type certificate holders, applicants and supplemental type certificates. In this NPRM, focus on the health of the wiring in the aircraft is specifically required (if the NPRM is adopted as proposed) for the first time.

Recommendations

Previous sections of the paper have shown the risks of in-flight fire and provided historical accounts of aircraft accidents in which fire occurred. The history of in-flight fire is important because it illustrates the successes and where further improvements are needed. The following recommendations are intended to address realistic solution to many of the issues presented.

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[75] FAA. (2005, October 6). *Notice of proposed rulemaking (NPRM): Enhanced airworthiness program for airplane systems/fuel tank safety (EAPAS/FTS); Proposed advisory circulars; Proposed rule and notices, 70(193)*, Federal Register p. 58508-58561. Doc 233.

[76] FAA. (2005, October 6). *Notice of proposed rulemaking (NPRM): Enhanced airworthiness program for airplane systems/fuel tank safety (EAPAS/FTS); Proposed advisory circulars; Proposed rule and notices, 70(193)*, Federal Register p. 58508-58561. Doc 233.

[77] Sadeghi, M. (2003, October 6). Enhanced airworthiness program for airplane systems (EAPAS) [Power Point presentation]. *Proceedings of the National Business Aviation Association*. Orlando, FL. Doc 152

[78] Sadeghi, M. (2003, October 6). Enhanced airworthiness program for airplane systems (EAPAS) [Power Point presentation]. *Proceedings of the National Business Aviation Association*. Orlando, FL. Doc 152.

[79] NTSB. (1999, September 17). *Brief of incident: N947DL* (NYC99IA231). Washington, DC: NTSB. Doc 223.

Airworthiness

Evaluate aircraft for single point failures of wiring and potential effect on systems of the aircraft. Evaluate modifications using the same approval process for supplemental type certificate modifications as for type certificates.

Fires are capable of inflicting damage on multiple aircraft systems as they spread. Wires within a wiring bundle where the fire starts are particularly susceptible. This can cause multiple circuit breakers to trip in a short time. This is noted in AC120-80[80] as one warning symptom of a fire in a hidden area.

A common feature of modern transport aircraft is not to co-locate critical wires so that arcing in one wire can cause failure of another critical system. However, the installations of supplemental equipment, such as in-flight entertainment systems, have not always been evaluated for their wiring proximity to critical system wiring. This was noted as a problem in the report of Swissair Flight 111.[81] The STC engineering did not specify the routing of the some wires of the in-flight entertainment system. As a result, entertainment system wiring was placed in close proximity to critical system wires. It is believed by TSBC this was the location of the original arcing or short in the fire sequence.[82]

Cascading Failures

While similar to multiple failures, cascading failures are a specific type of multiple failures. The failure of a system due to the failure of another is known as cascading because the effect to the pilots is failures that occur in a sequence. An example would be the failure of an autopilot because the electrical system failed.

In today's complex aircraft (fly by wire and conventional) the interrelationship of systems is extensive. Similar to multiple failures, evaluation of the effects of fires in various locations in the aircraft causing predictable cascading failures should be considered and include sub or interrelated systems.

Improve the engineering and installation of wires so that the routing does not endanger by proximity any critical system wiring.

Swissair Flight 111's in-flight entertainment system was installed under an STC. The FAA required that the IFE be tested in accordance with 14 CFR 25.1309 and AC

[80] FAA. (2004, January 8). *AC 120-80: In-flight fires*. Washington, DC: FAA. Doc 110.

[81] TSBC. (2003, March 27). Aviation investigation report: In-flight fire leading to collision with water Swissair Flight 111 September 2, 1998. Quebec, Canada: TSBC. Doc 188.

[82] TSBC. (2003, March 27). Aviation investigation report: In-flight fire leading to collision with water Swissair Flight 111 September 2, 1998. Quebec, Canada: TSBC. Doc 188.

25.1309-1a.[83] It was considered a non-essential item with any failure considered to have a minor effect on the aircraft systems. This process did not require detailed engineering drawing for wiring routing which allow for the installation to wire the IFE into the system in such a way that it was not unpowered by the CABIN BUS switch.[84] While the FAA group that approved the STC included several specialists, it was not as comprehensive as the original type certificate. The testing for this STC proved inadequate and demonstrated a need to bring the STC process more closely to the original type certificate requirements.

Install arc fault circuit interrupter technology on new and existing transport aircraft.

The FAA in AC120-80 states, "[a] majority of hidden in-flight fires are the result of electrical arcs along wire bundles." One means to dramatically reduce the ability for a wire to arc is to provide arc fault circuit breakers or interrupters for the circuit. Conventional circuit breakers do not provide acceptable protection from arcing. Therefore, replacing existing circuit breakers with arc fault circuit interrupters would mitigate the arc hazard.

Tests have shown these circuit interrupters are effective and are not prone to nuisance activation.[85] There is the availability of most needed types of arc fault interrupter circuit (AFIC) breakers to replace existing circuit breakers and a new released NPRM for a TSO for AFIC.[86] Arc fault circuit interrupters would probably have prevented many of the fires cited in this paper.

Conduct continuous smoke testing for flight deck smoke evaluation tests.

Unlike other smoke tests, the flight deck smoke evacuation test is unusual because the smoke is not required to be continuously generated (although it is recommended) throughout the test. All other smoke tests contained within AC 25-9a require the applicant to continuously generated smoke. Although the FAA knew of incidents and accidents of continuous smoke, and they recommended that applicants use continuously generated smoke, it was not required for compliance. The manufacturers have obtained the type certificate for new aircraft partially based on the testing standards of AC25-9a. None to date have followed the recommendation for flight deck smoke evacuation test using continuous smoke.

As there have been a considerable number of in-flight fires with continuous smoke, the test standards for flight deck evacuation does not always represent conditions that can be

[83] TSBC. (2003, March 27). Aviation investigation report: In-flight fire leading to collision with water Swissair Flight 111 September 2, 1998. Quebec, Canada: TSBC. Doc 188.
[84] TSBC. (2003, March 27). Aviation investigation report: In-flight fire leading to collision with water Swissair Flight 111 September 2, 1998. Quebec, Canada: TSBC. Doc 188.
[85] Pappas, R., & Singer, C. (2001, October). *Arc fault circuit breaker development and implementation* [Power Point presentation]. Atlantic City, NJ: William J. Hughes Technical Center. Doc 108.
[86] FAA Proposed Technical Standard Order TSO-C178, Washington, DC: FAA

found in actual fires. As noted earlier, the smoke evacuation procedures may not be effective against a growing, self-sustaining fire that produces continuous smoke.

Install fire access ports or dedicated fire detection and suppression systems to inaccessible areas of aircraft.

Fires in inaccessible areas of the aircraft continue to pose a threat to transport aircraft. The area of the aircraft without fire detection is large. Should there be a fire in an unprotected area, the ability to fight the fire will be limited by lack of access. As in the example of Swissair 111, once the fire was detected there was no way to access the area where the fire was burning and to allow the application of extinguishant. This deficiency can be corrected with strategically located ports throughout much of the currently inaccessible areas of the aircraft.

An example of the criticality of access to inaccessible areas and the effectiveness of an access port occurred on November 29, 2000 as American Airlines Flight 1683 (a DC-9-82) experienced an in-flight fire in a fluorescent light ballast unit soon after departure. A flight attendant observed dark, dense black smoke coming from the ceiling panels. Borrowing a passenger's knife the flight attendant cut a circular hole allowing access for a Halon fire extinguisher. The fire was successfully extinguished.[87]

Some wide body aircraft may have attics so large that a fire access port will not provide adequate coverage of extinguishant. In those aircraft alternative means of extinguishing a fire should be installed such as a dedicated fixed fire extinguishing system.

Mark locations of minimal damage for access to inaccessible areas of the aircraft.

AC 120-80 provides guidance to flightcrew for a fire in hidden or inaccessible areas of the aircraft. "If this is the only way to gain access to the fire … the risk of damaging equipment behind the paneling and the possibility of creating a bigger problem must be weighed against the catastrophic potential of in-flight fires left unattended."[88] The NTSB noted in the investigation of AirTran 913 "although the emergency training requirements specified in 14 CFR 121.417 require instruction in fighting in-flight fires, they do not explicitly require that crewmembers be trained to identify the location of a hidden fire or to know how to gain access to the area behind interior panels." Gaining access would improve by marking locations of access where minimal damage would occur.

Increase the number and location of sensors to alert the flight crew of smoke/fire/fumes. These sensors should take advantage of new technology to minimize the false alarm rate.

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[87] Blakey, M.C. (2002, January 4) Letter from NTSB Chairman to Honorable Jane F. Garvey, FAA Administrator. Washington, DC: NTSB

[88] FAA. (2004, January 8). *AC 120-80: In-flight fires*. Washington, DC: FAA. Doc 110.

Detection of a fire or a potential fire is one of the most important steps towards a successful outcome. A small fire is much easier to extinguish than a well-established, self-sustaining one. The adage of "the earlier the detection the better" is very true and should be a prime consideration in the design and operation of aircraft.

Protected areas within the aircraft contain a means of detection. Unfortunately, detection of a fire within most of the cabin and flight deck is up to the ability of a flight crew member to see or smell smoke. There are technologies available that could help flight crewmembers detect smoke and/or fire earlier.

In some cases, smoke can be a good indicator of a fire or potential fire. However, there can be cases where there is minimal smoke as the temperature rises. The types of infrared detectors used by fire departments throughout the world could help a flight crewmember locate "hot spots" within the cabin. Once the flightcrew determines an accurate location they can gain access and fire fighting can begin at the source. There have been tests conducted with this technology.[89] While this technology depends on surface heating and smoke may be evident, there is overall benefit to the ability to locate area of high heat.

Another means of detection is thermal sensors in the areas where wiring bundles are located. This newer and evolving technology has the potential to provide the flight crew information of rising temperatures in a wire bundle which could be located in an inaccessible area long before the smoldering grows the point where a crewmember could detect it. Research should continue to advance this technology.

AC 120-80 provides guidance to the flight crews in locating a hidden fire. The indication of a fire can include:

- Failure or uncommanded operation of an aircraft component
- Circuit Breakers tripping especially multiple circuit breakers tripping
- Hot Spots
- Odor
- Visual Sighting – Smoke

However, these indications usually represent a well-established fire. A fixed detection system throughout the aircraft would allow fire fighting to begin earlier and improve the ability of the flight crew to locate the actual source of the fire.

The United Kingdom's Civil Aviation Authority published the need for enhanced protection from fires in hidden areas.[90] Their conclusion using a mathematical model was that enhancing the detection of and the protection from fires in hidden areas could save a significant number of lives.

[89] FAA. (2005). *Testing of thermal imaging device* [Power Point presentation]. Atlantic City, NJ: FAA Technical Center. Doc 171.

[90] CAA. (2002, September 6). *A benefit analysis for enhanced protection from fires in hidden areas on transport aircraft* (DOT/FAA/AR-02/50). West Sussex, United Kingdom: CAA. Doc 128.

Detection devices or systems are now available and it should be an industry priority to study the effectiveness of these devices and systems to find the most effective solutions (both in cost and sensitivity).

False detection rates

During a 36 month study from January 2002 to December 2004, The International Air Transport Association (IATA) found 2,596 reports (including jets, turbo props and helicopters) of fire/sparks/smoke/fume occurrences. [91] Of the 2,596 reports, 525 (20%) were false warnings with 11% of in-flight diversions due to false warnings. Approximately 50% of cargo compartment fire warnings were false.[92]

Following the May 1996 accident of ValuJet Flight 592, the FAA required the installation of fire detection and suppression systems of class D cargo compartments in air carrier aircraft by March 19, 2001. Approximately 3,000 aircraft required retrofitting.[93] This requirement, as expected, caused a significant increase in cargo compartment fire warnings.[94] The 14 CFR Part 25.858 (a) (and EASA/JAA) requires that detection system must provide a visual indication to the flight crew within one minute after the start of the fire. There is a compromise of speed of the warning and the susceptibility to 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, and at that time was 200 - to - one based on data from the previous five years.[95] The rate of false warning is too high and improvements in the reliability of smoke and/or detectors should be improved.

Multi-source sensors

False engine fire warnings plagued pilots in the past. Modern jets 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 and other fixed detection systems.

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[91] International Air Transport Association (IATA). (2005).*On-board fire analysis: From January 2002 to December 2004 inclusive*. Quebec, Canada: Author. Doc 176.

[92] International Air Transport Association (IATA). (2005).*On-board fire analysis: From January 2002 to December 2004 inclusive*. Quebec, Canada: Author. Doc 176.

[93] Blake, D. (2000, June). *Aircraft cargo compartment smoke detector alarm incidents on U.S.-registered aircraft, 1974-1999* (DOT/FAA/AR-TN00/29). Springfield, VA: NTIS. Doc 44.

[94] Schmoetzer, K. (2003, March 19). Multi criteria fire/smoke detector for cargo holds. *International Aircraft Systems Fire Protection Working Group Meeting*. Phoenix, AZ. Doc 56.

[95] Blake, D. (2000, June). *Aircraft cargo compartment smoke detector alarm incidents on U.S.-registered aircraft, 1974-1999* (DOT/FAA/AR-TN00/29). Springfield, VA: NTIS. Doc 44.

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

Cargo compartments on aircraft manufactured up to 2005 have only single source fire detectors. Some manufacturers have proposed using multi-source sensors in new aircraft.[96] This technology dramatically reduces the possibility of false fire warnings. Using similar technology, now that it is proven, should be considered for application is other areas of the aircraft. Detection of a fire in the vast inaccessible areas of the aircraft should use multi-source sensors.

Protective Equipment

Implement vision assurance technology for improved pilot visibility during continuous smoke in the flight deck.

Pilot vision during a smoke event is essential. The FAA's Aviation Safety Reporting System (ASRS) has numerous pilot reports of restricted visibility during smoke events. Some pilots report smoke so thick that they could not see each other.[97]

Following Air Canada Flight 797, the FAA required the installation of Protective Breathing Equipment (PBE) on all 14 CFR Part 121 aircraft. As 14 CFR Part 25.1439(b)(1)[98] states, in pertinent part, that PBE must be designed to protect the flightcrew from smoke, carbon dioxide and other harmful gases, while on the flight deck and while combating fires in cargo compartments. The need for visibility to combat the fire was included in the justification for the need for PBEs. There is a similar need for pilot visibility to fly the aircraft during continuous smoke events.

The visibility must be enough to see the attitude indicator or primary flight display and to see outside the aircraft for landing. In addition, the pilots must see instruments to navigate and they must see to program the flight management computer, if installed. The checklist must be visible so that procedures can be followed to prepare for landing and fight the smoke/fire/fumes. Adequate visibility on the flight deck should be maintained during a smoke/fire/fume event.

Head Up Display

Head Up Display (HUD) technology is a growing addition to the civil transport fleet. Many new aircraft have HUDs available and some older aircraft are being retrofitted.

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[96] Schmoetzer, K. (2003, March 19). Multi criteria fire/smoke detector for cargo holds. *International Aircraft Systems Fire Protection Working Group Meeting*. Phoenix, AZ. Doc 56.

[97] International Civil Aviation Organization (ICAO). (1989, May). *ICAO summary*. Montreal, Canada: ICAO. Doc 131.

[98] FAA. (1998, August 31). *Flight standards handbook bulletin for air transportation: Smoke goggles and oxygen masks (PBE)* (HBAT 98-29). Washington, DC: FAA. Doc 247.

BAE Systems has done research to take that technology and adapt it to the environment of smoke on the flight deck. A 1998 study by Embry-Riddle for BAE Systems showed that the visibility of the HUD was viewable for much longer that the Electronic Flight Instrument Systems (EFIS) display. This visibility difference could make a major difference in the outcome of a smoke event.

The use of the HUD eliminates the need to open the window to improve visibility, thereby maintaining the ability of the flight crewmembers to communicate with each other. If two HUDs are installed, there is the ability to monitor the flying pilot's performance, which is an important element of transport aircraft operations. A single HUD installation does not allow the First Officer to monitor the Captain unless the normal flight instruments are visible.

While this technology provides improvement in visibility over the standard flight instruments or EFIS, it does not provide improvement in the ability to see outside the aircraft. This limitation is important, as there are examples of fire causing the flight instruments to fail. This dependence of aircraft electrical power could allow this type of failure to affect the HUD and require the pilot to look at the natural horizon for attitude reference.

HUD is an improvement in the vision available to pilots, but its cost is high and it has operational limitations.

Emergency Vision Assurance System

The need for clear vision in a smoke filled flight deck can be met in many cases by a clear plastic bubble filled with clear air. This device is known as Emergency Vision Assurance System (EVAS). Like the HUD, it provides the pilot with the ability to see critical flight instruments regardless of the density of smoke. It has the additional advantage of providing clear vision to the windshield.

EVAS is a clear plastic device that allows a pilot place his/her goggles and mask against the unit and see the flight instruments and outside the windshield. The unit inflates in less than 30 seconds, using a self contained battery and blower, thereby not being dependent on the aircraft's electrical system. The flight deck air is filtered and cleaned of smoke then used to inflate the device. Like the HUD, this device eliminates the need of opening a window and therefore avoids interfering with flight crew communications.

It is possible that improved vision of the flight instruments and the windshield would have allowed Varig Flight 860 to land on the runway instead of in a field. This is the most dramatic example of potential improvements with vision assurance technology, but others, such as Air Canada Flight 797, Pan American Flight 160 and the Air Europe Fokker landing in Copenhagen may also be have been positively affected.

In a smoke filled flight deck, the ability of the non-flying pilot to monitor the other pilot is dependent on his/her ability to see the flight instruments and if they are functioning.

This monitoring activity is a fundamental part of transport aircraft training and operations. EVAS allows pilot monitoring to continue during smoke/fire/fume events thereby maintaining normal pilot redundancy.

Provide full-face oxygen masks and sufficient flight crew oxygen for descent and landing during a smoke/fire/fume event.

Flight crews must be protected from toxic fumes to safely fly and land their aircraft. Protecting the crew primarily consists of oxygen masks and smoke goggles. Providing an independent oxygen source and clean air for protection for the eyes of the crew is essential. In the past smoke goggles have been found to be ill fitting and not providing 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."[99] 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.[100] Masks that cover the entire face, known as full-face oxygen masks, alleviate this concern, as it is a single unit. These single unit masks and goggles allow a better, tighter fit and more effective purging in the mask.

Increase Flight Crew Oxygen Quantity

The quantity of oxygen available to a flight crew determines how long their uncontaminated supply of air will last. The demand of oxygen will depend on several factors, such as the number of crewmembers using oxygen and the rate at which each crewmember breathes. As in-flight fire is one of the highest stress events a pilot can face,[101] it is reasonable to expect higher than normal oxygen consumption during a smoke/fire/fume event. The capacity of the oxygen bottle and the level of fullness then determine how much time is available to the crew before depletion. In some cases, the time required to descend and land may be greater than the time of available oxygen. Depletion of the oxygen would eliminate the source of uncontaminated breathing gas and force the flight crew to breathe the smoke filled flight deck air. The performance of the flight crew could be adversely affected.

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[99] NTSB. (1974, December 2). *Aircraft accident report: Pan American World Airways, Inc. November 3, 1973* (NTSB-AAR-74-16). Washington, DC: NTSB. Doc 27.

[100] NTSB. (1998, July 22). Aircraft accident report: In-flight fire/emergency landing, Federal Express Flight 1406 September 5, 1996 (NTSB/AAR-98/03). Washington, DC: NTSB. Doc 68.

[101] Krahenbuhl, G. S., Harris, J., Malchow, R. D., & Stern, J. R. (1985, June). Biogenic amine/metabolite response during in-flight emergencies. *Aviation Space & Environmental Medicine*, (56)6, 576-580. Doc 126.

Aircraft can be dispatched with crew oxygen at minimum levels in accordance with the Minimum Equipment List (MEL). The consideration is only the demand for an emergency descent and not the demand of a smoke/fire/fume event. There should be sufficient supply of oxygen for the flight deck crew to descend and land the aircraft.

Increase size of fire flight deck and cabin fire extinguishers to five pounds of Halon or an equivalent effective agent.

By regulation (14 CFR Part 25.851 (6)), air carrier transport aircraft are required to have two Halon fire extinguishers. Halon is a liquefied gas that extinguishes fires by chemically interrupting a fire's combustion chain reaction, rather than physically smothering it. This characteristic, along with the property of changing into a gas when discharged and spreading throughout the area, are two of the main reasons that Halon extinguishers are effective, especially when the exact source or type of the fire cannot be positively determined.[102]

Halon is now carried in two-and-one-half-pound fire extinguishers on board air carrier transports. However, tests at the FAA Technical Center found that in some test conditions the amount of extinguishing agent was insufficient to extinguish a test fire in a Class B cargo compartment fire.[103] During the tests flight attendants attempted put out a fire. All failed with two-and-one-half-pound extinguishers.

Maintenance

Inspect thermal acoustic insulation blankets and smoke barriers to ensure cleanliness.

The regular inspection and cleaning of thermal acoustic blankets and smoke barriers during scheduled maintenance could allow the removal contaminates. This improved cleanliness could reduce the flammability of the blankets.

Modify maintenance procedures to minimize the possibility of contamination of thermal acoustic insulation blankets.

When a maintenance procedure is designed, consider the possibility of thermal acoustic blanket contamination. As an example, the application of corrosion blocking material to the aircraft should not contaminate a thermal acoustic blanket.

Improve wiring inspection maintenance programs by using new inspection technology and not rely exclusively on visual inspection of wiring bundles.

[102] FAA. (2004, January 8). *AC 120-80: In-flight fires*. Washington, DC: FAA. Doc 110.
[103] Blake, D. (1999, April). *Effectiveness of flight attendants attempting to extinguish fires in an accessible cargo compartment* (DOT/FAA/AR-TN99/29). Springfield, VA: NTIS. Doc 90.

"It is clear … that the vast majority of aircraft electrical wiring problems are related to improper installation and inadequate inspection and maintenance."[104] Therefore, many electrical hazards in aircraft can be mitigated through an improved maintenance program.

The finding that circuit breakers and wires were exposed to significant amounts of dust and grease[105] shows the need for improved maintenance programs for wiring. The recognition of the effect of contaminants (conductive and non conductive) on the potential of contribution of in-flight fire is essential. The philosophy and practice of careful cleaning and debris containment during all maintenance activity must not only be adopted, and but must be meticulously adhered to.

The inclusion of wiring considerations in an overall maintenance plan must also include the careful inspection of insulation blankets for contaminates. An example of this "holistic" approach would be to modify the application procedure of corrosion blocking sprays so that there would be no contamination of insulation blankets in or near the sprayed area.

Maintenance training which emphasizes the susceptibility of wiring to contamination and the need to "clean as you go" has the potential to improve some of the maintenance-induced incidents. The need for ongoing or recurrent maintenance training specific to fire reduction techniques is clear.

Wiring Inspection Program

Regular inspection of wiring is an essential check of the overall health of the aircraft. 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 aircraft should be scheduled regularly for wiring that can be covered in dust, grease and other contaminates and carefully inspect nearby thermal acoustic insulation blankets. Cleaning or removal of contaminates should be a priority so that the source of fuel for a fire can be reduced.

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 airplane. Higher technology inspection found over 60 breaks. This finding was later verified in a laboratory.[106]

Pilot Procedures

[104] Sarkos, C. P. (2000). An overview of twenty years of R&D to improve aircraft fire safety. *Fire Protection Engineering*, 5. Doc 93.
[105] (2003, February 10). More attention needed for safe functioning of circuit breakers. *Air Safety Week*. Doc 151.
[106] Lectromec Design Company. (2005). *Aircraft wire maintenance solutions* [Brochure]. Dulles, VA: Author. Doc 184.

Improve flightcrew procedures to use autoflight systems to reduce pilot workload. Included in the procedures should be provisions for the failure or un-serviceability of the autoflight system.

The use of the autoflight system can provide a dramatic reduction in pilot workload during smoke/fire/fume events. Engaging the autoflight system while accomplishing the complex checklists, required by some manufacturers, during smoke/fire/fumes conditions 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. During a time of high stress situational awareness is essential to avoid controlled flight into terrain.

Additionally, the necessary reprogramming of Flight Management System (FMS) computers can be done more effectively. Reconfiguration of the air conditioning/pressurization system, electrical system and/or other necessary system adjustments can be made with the redundancy of two pilots using the proven method of challenge response checklist.

However, as previously shown, there is the possibility of multiple system failure or cascading failures, which could eliminate the autoflight system and should be considered in procedure design.

Eliminate procedures to open flight deck window to vent of smoke and improve smoke removal procedures to ensure maximum effectiveness.

Once smoke enters the flight deck its effects can be significant. Aircraft manufacturers include procedures for a flight crew to evacuate or remove flight deck smoke. Notably, there is difference in methods chosen by manufacturers to remove smoke from the aircraft.

The procedure for opening windows continues to be part of some manufacturers smoke removal checklist despite the examples of ineffectiveness. Unfortunately, there are flight deck crewmembers who continue to believe that opening a window will help vent the flight deck of smoke. One negative result of attempting to open a flight deck window is the requirement to slow the aircraft before it can be opened, which delays the aircraft from landing.

With the window open the noise level may have a severe impact on intra flight deck communication. The inability of a flight crew to communicate during an emergency is serious hazard that should be avoided. Orderly communication is necessary to complete complex procedures contained in abnormal and emergency checklists; this requires a flight deck noise level far below that when a window is open.

Redesign all transport aircraft checklists pertaining to smoke/fire/fumes to be consistent with the Flight Safety Foundation smoke/fire/fume checklist template. Consider: memory items, prevention of checklist “bottlenecks,”

font size and type, where it should be found (quick reference handbook [QRH] or electronic), smoke removal, number of checklists for smoke/fire/fumes and the length of the checklists.

The foundation of modern transport aircraft operations is compliance with Standard Operating Procedures (SOP). Within SOPs are carefully designed checklists. These checklists provide a flight crew procedural guidance through most normal, non-normal (abnormal) and emergency conditions. The use of checklists is an integral part of a pilot training and usage of checklist is essential to modern safe flight operations.

In cases of in-flight fire, there are numerous checklists that should be completed before the aircraft lands. Furthermore, the priority of completion of these checklists can change, depending on the situation, adding confusion and increasing the likelihood of errors.

Many checklists in current use still adhere to an old philosophy of attempting to locate the source of the smoke/fire/fume before directing the crew to land the aircraft. Landing is suggested to crews only after all troubleshooting items have been exhausted and found to be ineffectual. However, recently the industry has acknowledged the need to get flight crews considering and/or conducting a diversion early in the checklist, and to stress the need to land as soon as possible or even consider landing immediately, if necessary. This shift in priority is important and should improve response to smoke/fire/fume events in the future.

Careful procedural development, checklist design and training are necessary to have the best outcome. Integrated checklists can be designed so that a flight crew member can remain within a single checklist to the maximum extent possible. These reports clearly show that pilots can become task saturated and distracted during smoke/fire/fume events.

Font size and type style should be easily read by a pilot wearing an oxygen mask and smoke goggles in low visibility conditions. The verbiage of the checklist should be as unambiguous as possible, including specific tasks of the crewmembers.

Pilots involved in smoke events comment that they "feel rushed" which can easily lead to committing errors. 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."[107] In the NTSB report the failure of the flight engineer to complete the "Fire and Smoke" checklist caused the aircraft be pressurized on the ground after landing, thereby delaying the evacuation.[108]

A noteworthy example is a regional jet landing without accomplishing the pre-landing checklist. As described by the pilot during a smoke event "I feel that I became too focused on finding the circuit breakers and that communications between me and the

[107] NTSB. (1998, July 22). *Aircraft accident report: In-flight fire/emergency landing, Federal Express Flight 1406 September 5, 1996* (NTSB/AAR-98/03). Washington, DC: NTSB. Doc 68.
[108] NTSB. (1998, July 22). *Aircraft accident report: In-flight fire/emergency landing, Federal Express Flight 1406 September 5, 1996* (NTSB/AAR-98/03). Washington, DC: NTSB. Doc 68.

captain broke down. I found myself unaware of our location and when I realized where we were, we were already on short final."[109] 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 loss of situation awareness.

Effective fire fighting is best accomplished by using all available crewmembers. Cabin and flight deck smoke/fire/fume checklists should be integrated to maximize their effectiveness and compatibility with specific tasks assigned to specific crewmembers. By clearly assigning tasks, crew coordination can occur.

Flight Safety Foundation Template

The Flight Safety Foundation recognized the need for improvements in checklist design and in 2005 led an industry group that published a checklist template and an accompanying philosophy for in-flight smoke/fire/fume events that are not annunciated through aircraft alert and warning systems (e.g. air conditioning smoke or electrical fire). This template was developed through consensus by several industry participants representing major manufacturers, air carriers and professional organizations. The Air Line Pilot Association (ALPA), one of its participants, presented the need for, and the applicability of, this template at the International Flight Safety Seminar in 2005.[110]

This template streamlines the checklists used by a flight crew to address smoke of unknown origin. It does so by integrating all or most of the smoke, fire and fumes checklist used to respond to un-alerted events into a single checklist. A single integrated checklist eliminates the need for flight crews to first make a determination of what type of smoke/fire/fumes they are encountering in order to know which checklist to access. Checklists developed using the template will also stress the need to consider diversion at early stages of the event and the need for an immediate landing if the fire is uncontainable.

The FAA has indicated plans to integrate the template, philosophy and development rationale[111] into AC 120-80, which addresses issues related to in-flight fires. This, in turn, will hopefully lead to manufacturers and operators revising their smoke/fire/fume checklists accordingly.

Checklist Priority

[109] (2003, September 22). In-flight fires wreak havoc with systems reliability. *Air Safety Week*. Doc 29.

[110] Bombardi, H. G. (2005, November). Center, we have a fire on board and need to land immediately: A pilot's perspective on dealing with fire in flight [Power Point presentation]. *Proceedings of the 17th Annual European Aviation Safety Seminar*. Moscow. Doc 254

Bombardi, H. G. (2005, November). Center, we have a fire on board and need to land immediately: A pilot's perspective on dealing with fire in flight. *Proceedings of the 17th Annual European Aviation Safety Seminar*. Moscow. Doc 255.

[111] Bombardi, H. G. (2005, November). Center, we have a fire on board and need to land immediately: A pilot's perspective on dealing with fire in flight. *Proceedings of the 17th Annual European Aviation Safety Seminar*. Moscow. Doc 255.

Setting the proper priority of checklists can be essential. During a rapid descent to an airport for landing following the discovery of smoke/fire/fumes within an airplane is, as shown, very workload intensive. Yet, there is a necessity that the aircraft be prepared to land safely and configured so that an evacuation can be initiated if necessary.

There is a conflict that arises when the need to complete the Smoke/Fire/Fume checklist takes more time than is available to land. When is the FMS going to be reprogrammed? When is the pressurization going to reset to the new landing airport? When are the navigation radios going to be re-tuned? When is the descent checklist going to be accomplished? When is the before landing checklist going to be accomplished? Who is going to talk to air traffic control? These are just a few of the questions that a flight crew must answer in the brief time as they prepare to land a smoke filled aircraft. Within the template is recognition that there may be occasions, such as when landing is imminent, that smoke, fire and fumes checklist completion should be suspended so the crew can turn their attentions to the more pressing task at hand (i.e. landing). Adoption of the new template will help flightcrew prioritize the necessary tasks.

Flight Crew Training

Assure improved flight crew and cabin crew training on the importance of maintaining a smoke barrier during smoke/fire/fume events and the ineffectiveness of, and potential problems with, opening a flight deck window, the necessity of proper fire extinguisher operation, the proper use of a crash ax, the proper accomplishment (or abandonment) of checklist during simulated smoke/fire/fume events, during realistic line oriented flight training.

Smoke Barrier

The success of maintaining the smoke barrier can depend on the training of the flight crew in communications. The examples of Air Canada Flight 797 and Air Tran Flight 913 show that the flight deck door may be opened by well-intentioned flight crewmembers who unwittingly compromise the smoke barrier. One success of the Federal Express Flight 1406 flight crew was their ability to keep a smoke barrier in place and their flight deck relatively free from smoke. This important training should be included in much more realistic training than is currently required.

Fire Extinguisher and Crash Ax Training

Specialized training for the proper use of access ports when they are installed will be needed. The fire extinguisher operation in the access port should be demonstrated to the flight crew. They should demonstrate the proper use of the fire extinguisher.

Should an air carrier use the ax as a means of access, more detailed training should be accomplished. The location and routing of wiring bundles and other important components should be shown and provided in a manual available to flight crewmembers in-flight. The NTSB in the report of Air Canada Flight 797 recommended this.[112] Interior panel removal methods should be demonstrated and marked, as should the location of good access points for extinguisher discharge.

The NTSB recommended changes to 14 CFR 121.417 in their January 4, 2002 letter to the FAA.[113] Those recommended changes will improve the initial and recurrent training of flight crews, however the recommendations included in this paper exceed the NTSB's and would help improve flight crew performance to in-flight fire even more.

Concluding Remarks

There will continue to be in-flight fires because it is not possible to eliminate all the ignition sources that could start a fire or the fuel necessary to sustain a fire in remote locations for fires in aircraft. Effective mitigation is required to reduce the risk and effect of fire aboard aircraft.

Improving the aircraft equipment design, the procedures and the regulations will give flight crewmembers the best chance. In recent times the best chance for success has been industry consensus initiatives such as the Flight Safety Foundation checklist template. Cooperation of the regulators, manufacturers, air carriers and professional associations is needed to implement these safety recommendations. Only through execution of a comprehensive mitigation strategy along with developing and implementing a plan to maximize fleet coverage can we reduce the risk of in-flight smoke, fire and fumes.

[112] NTSB. (1986, January 31). *Aircraft accident report: Air Canada Flight 797 June 2, 1983* (NTSB/AAR-86/02 Supersedes NTSB/AAR-84/09). Washington, DC: NTSB. Doc 71.

[113] Blakey, M.C. (2002, January 4) Letter from NTSB Chairman to Honorable Jane F. Garvey, FAA Administrator. Washington, DC: NTSB

Appendix 1

Comparison of Airworthiness Requirements between FAA & EASA/JAA

The European Aviation Safety Agency (EASA), the Joint Aviation Authorities (JAA) and FAA have adopted, or harmonized, many of their aviation regulations. However, some key regulations remain different. The harmonization efforts continue to work with the conditions of aging aircraft, aircraft wiring and arc fault. Four regulations, 14 CFR Part 25.831, 25.1309, 25.1353 and 25.1357 are significant when considering in-flight fire issues.

FAA 14 CFR Part 25.831 and EASA Certification Specification (CS) 25.831 titled "ventilation" are mostly harmonized, but still have a few inconsistencies within subpart a. The European regulations state that:

(a) Each passenger and crew compartment must be ventilated and each crew compartment must have enough fresh air (but not less than 0.28 m^3/min. [10 cubic ft per minute] per crewmember) to enable crewmembers to perform their duties without undue discomfort or fatigue).

14 CFR Part 25.831 does give a standard for air flow, but it differs from EASA CS 25.831, stating:

(a) Under normal operating conditions and in the event of any probable failure conditions of any system that would adversely affect the ventilating air, the ventilation system must be designed to provide a sufficient amount of uncontaminated air to enable the crewmembers to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort. For normal operating conditions, the ventilation system must be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute.

Do these air flow amounts compare?

The most inconsistent of the regulations is 25.1309 titled "Equipment, systems and installations." Although the Europeans have separated some of 14 CFR Part 25.1309 into JAA CS 25.1310 titling it "Power source capacity and distribution," CS 25.1310 equates to 14 CFR Part 25.1309 (e), (f) and (g) respectively. 14 CFR Part 25.1309 states that equipment, systems and installations "must be designed to ensure that they perform their intended functions under any foreseeable operating condition." The European regulations do not have an equivalent for this paragraph. Subparagraph (b) in the Federal Aviation Regulations and (a) in the Joint Aviation Regulations relate to system design.

(b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that –

   (1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and
   (2) The occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable.

Whereas JAA CS 25.1309 states that the “equipment and systems must be designed and installed so that:

   (1) Those required for type certification or by operating rules, or whose improper functioning would reduce safety, perform as intended under the aeroplane operating environmental conditions.
   (2) Other equipment and systems are not a source of danger in themselves and do not adversely affect the proper functioning of those covered by sub-paragraph (a)(1) of this paragraph” (above).

In relation to the failure modes within the regulations, the European regulations do, in subparagraph (b) list design criteria for systems and associated components, to be designed so that:

   (1) Any catastrophic failure condition
      (i) is extremely improbable; and
      (ii) does not result from a single failure; and
   (2) Any hazardous failure condition is extremely remote; and
   (3) Any major failure condition is remote.

Several key regulations have finished the harmonizing process. 14 CFR Part 25.1353 and EASA CS 25.1353 titled “Electrical equipment and installations” have recently been harmonized. The Federal Aviation Regulations now read as the European regulations read. Noteworthy are the changes below:

(d)(1) The electrical cables used must be compatible with the circuit protection devices required by §25.1357 of this part, such that a fire or smoke hazard cannot be created under temporary or continuous fault conditions.

(3) Electrical cables must be installed such that the risk of mechanical damage and/or damage caused by fluids, vapors, or sources or heat, is minimized.

14 CFR Part 25.1357 and JAA CS 25.1357 titled “Circuit protective devices” are now harmonized as of the 2006 Federal Aviation Regulations. Some of the important changes highlight:

(a) Automatic protective devices must be used to minimize distress to the electrical system and hazard to the airplane in the event of wiring faults or serious malfunction of the system or connected equipment.
(b) The protective and control devices in the generating system must be designated to de-energize and disconnect faulty power sources and power transmission equipment from their associated busses with sufficient rapidity to provide protection from hazardous over-voltage and other malfunctioning.

While the harmonizing process is not complete, there has been and continues to be an effort by the FAA and EASA/JAA to integrate the best of the previous regulations into the harmonized ones. This process can help incorporate some of the multiple layers of mitigation recommended within this paper.

The current differences in relevant regulations are shown in the table.

Table 1

	FAA	EASA/JAA	Differences
Ventilation	FAR 25.831	CS 25.831	(a)
Equipment, systems, and installations	FAR 25.1309	CS 25.1309	(a), (b), (c), (d), (e), (f), (g)
Electrical equipment and installations	FAR 25.1353	CS 25.1353	(e)
Circuit protective devices	FAR 25.1357	CS 25.1357	None