Reducing the Risk of Smoke and Fire in Transport Airplanes: Past History, Current Risk, and Recommended Mitigations

Regulating, Training and Equipping for the Unthinkable

By:

John M. Cox, FRAeS
President
Safety Operating Systems

Smoke, Fire and Fumes in Transport Aircraft

Past History, Current Risk and Recommended Mitigations

A specialist paper by the Royal Aeronautical Society and the Guild of Air Pilots and Air Navigators London

February 2007

Smoke, Fire and Fumes in Transport Aircraft

Past History, Current Risk and Recommended Mitigations

A Specialist Paper prepared by
Captain John M. Cox, FRAeS
President, Safety Operating Systems (USA)

With original Appendices material by the Reviewing team of the
RAeS Flight Operations Group (FOG) Committee

The Appendices must be read in conjunction with the Main Paper.
They are complementary corollaries and an important part of this Specialist Paper

THE AUTHOR
A veteran major airline, corporate and general aviation pilot, Captain Cox has flown over 14,000 hours with over 10,000 in command of jet airliners. Additionally, he has flown as an instructor, check pilot, and test pilot in addition to extensive involvement in global air safety. He holds an Air Line Transport Pilot Certificate with type ratings in the Airbus A320 family, the Boeing 737 family, the Fokker F28 and the Cessna Citation. He is an experienced accident investigator having been involved in six major NTSB investigations (the best known being the US Air 427 accident in Pittsburgh in 1994) and numerous smaller investigations. He holds an Air Safety Certificate from the University of Southern California. The International Federation of Airline Pilots Association (IFALPA) certified him as an international accident investigator. For over twenty years he served as an Air Safety Representative for the Air Line Pilots Association rising to the position of Executive Air Safety Chairman, ALPA's top safety job. ALPA awarded him their highest safety award in 1997. A Fellow of the Royal Aeronautical Society, he was awarded a Master Air Pilot Certificate by the Guild of Air Pilots and Air Navigators in October 2004. In December 2004 he retired from airline flying after 25 years to found Safety Operating Systems a Washington, DC, based aviation safety consulting firm.

THE ROYAL AERONAUTICAL SOCIETY FLIGHT OPERATIONS GROUP
The Flight Operations Group committee consists of 30 members from both the civilian airline and military transport & flying training sectors, with Flight Safety and the Quality of Training throughout the Public Transport Industry being its primary objectives. The FOG is a discussion group that focuses on issues which primarily concern civil aviation, although it touches upon aviation safety in the armed forces, specifically where the safety issues could also be applicable to civilian operations. Its membership is highly respected within the civil aviation operations area and brings together a team with many years of experience in the field of aviation.

FLIGHT OPERATIONS GROUP COMMITTEE MEMBERS (2006-07)
P. Moxham (Chairman), Capt P.H.S. Smith, (Vice-chairman), Sqn Ldr N.R. Scopes RAF (Secretary), Dr Kathy H. Abbott (FAA), Dr S.B. Bennett (Leicester University), B.M. Collings, Capt J.M. Cox (SOS Inc), Capt H.P.C. Dibley (Airbus-Toulouse), F/O L. Foat (YMB), L.J. Ghibaut, M.P. Green (NATS), Capt P. Griffiths (CAA), Capt R.K.J. Hadlow, M.E.J. Hickmott, Capt J.C. Hutchinson, Capt R. Kohn, I. Newman (BA CSD), Capt S.J. Lawrence (Emirates Airlines), Capt S.P.J. Lyttle, Capt R. Macdonald, Capt D.A.J. Martin, Capt A.C. McLaughlan, K. O'Neil, SFE P.G. Richards, Capt M.C. Russell, Capt T.H. Sindall, Capt D.R. Smith (Alaska Airlines), Capt D.H. Thomas (EFT Jerez), P. Wills (AOA/BAA) and Capt C.N. White.

PARTICIPATING CONSULTANTS
P.P. Baker (Test Pilot), Capt G.L. Fretz, A.J.L. Lamb, R.C. Metcalfe, D.A. Nakamura (Boeing), Capt R. Scott, Dr J.D. Stevenson (USAF Ret) and Capt P. Wilson.

Risk, Perception, and Probability of Smoke, Fire and Fumes

What are the odds?

Probability

In-flight fire is the 4th leading cause of fatalities in commercial jet aircraft accidents 1987 – 2004 (Boeing Study)

- Loss of Control (LOC)
- Controlled Flight into Terrain (CFIT)
- Specific Component failure (non-powerplant)

Probability is > 1 in 10,000

Probability

IATA STEADES DATA

36 months: Jan. 2002 to Dec. 2004

Total Air Safety Reports (ASRs) = 2,596

1701 of the 2596 events were in-flight occurrences of smoke

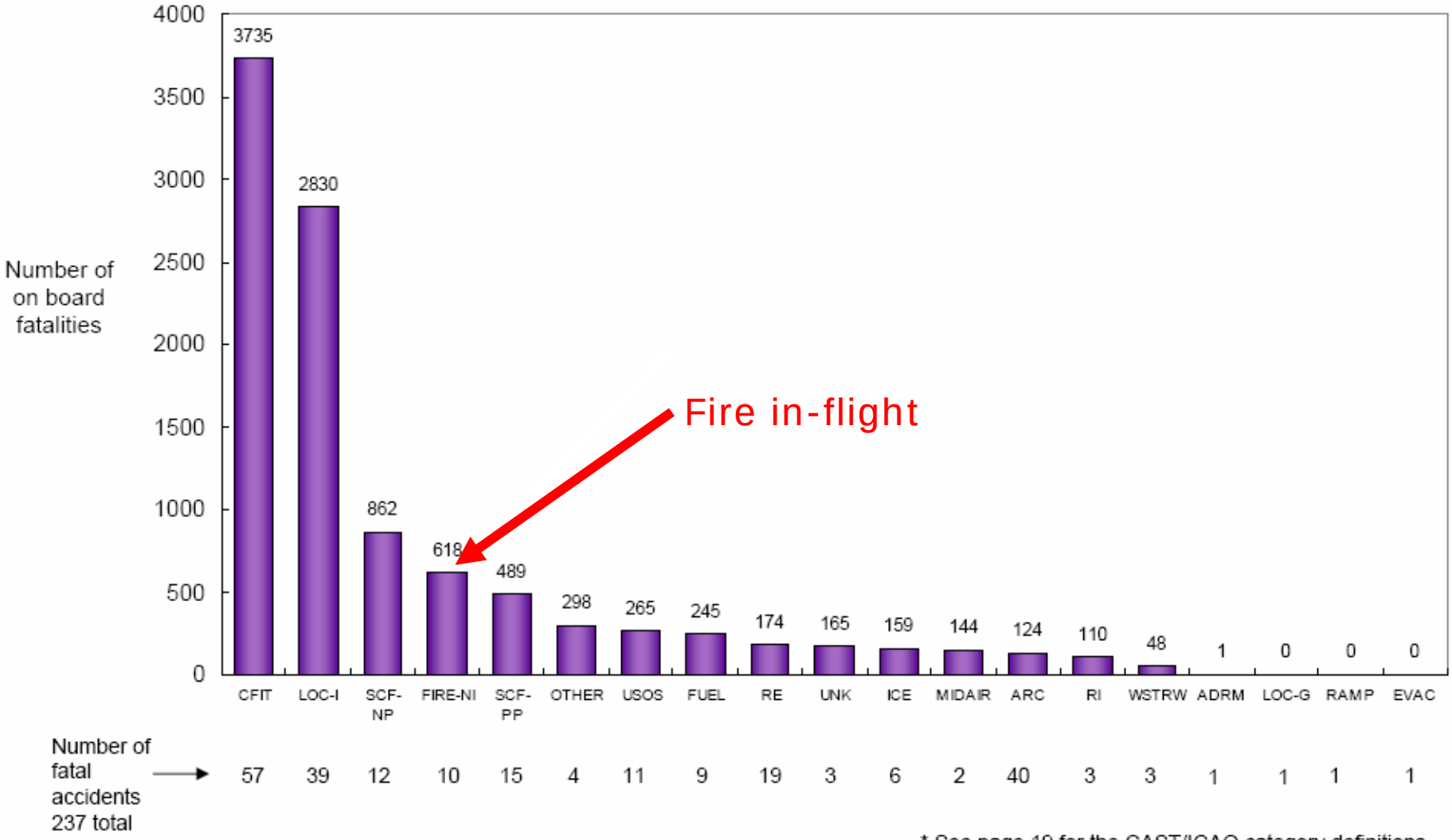
Probability

- > 1000 in-flight smoke events occur annually
- Resulting in >350 unscheduled or precautionary landings
- In-flight smoke rate is 1 in 5000 flights
- In-flight smoke diversion rate is 1 in 15,000 flights

IATA Data

Fatalities by CAST/ICAO Taxonomy Accident Category*

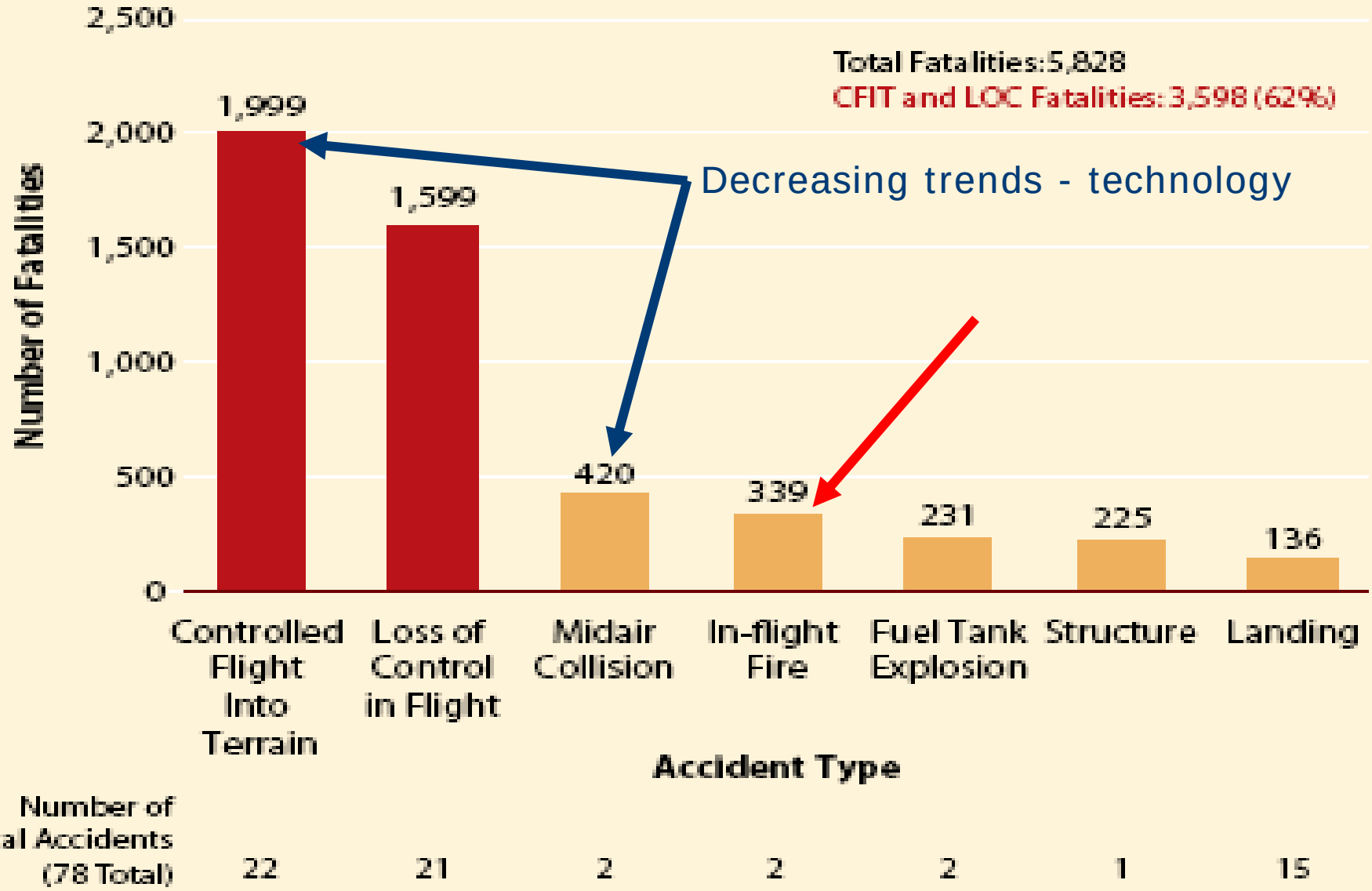
Fatal Accidents – Worldwide Commercial Jet Fleet – 1987 Through 2005



* See page 19 for the CAST/ICAO category definitions

BOEING

Worldwide Airline Fatalities, By Accident Type, 1995–2004



Number of Fatal Accidents (78 Total)	22	21	2	2	2	1	15

Source: Boeing

Flight Safety Foundation Aviation Safety World July 2006

Terms

- AC 25-1309 1A
  - Catastrophic (not all fires are, but potential)
  - Extremely improbable
    - 1×10^{-9} or less
- Probability of diversion due to cockpit smoke could be a reasonably probable event and within the range of remote (Halfpenny)

History

- July 1785, Jean-François Pilâtre de Rozier's hydrogen balloon ignited and burned over the English Channel.
- Aviation's first fatal accident was an in-flight fire

Credits - 2001 National Air and Space Museum, Smithsonian Institution (SI Neg. No. A-4691)

1973 and B707 fires

Varig Flight 860, July 11, 1973

- Cabin fire with heavy smoke
- Landed in a field 70 second from Paris Orly
- Crew and Passenger smoke inhalation
- Open Flight Deck Windows did not provide sufficient visibility

Varig Flight 860

Pan Am Flight 160

- November 3, 1973
- Cargo Flight - Hazardous Material Fire
- Smoke overwhelmed Flight Deck
  - Continuous Smoke Generation
- Flight Deck Window Opened - Not Successful Landing

Air Canada Flight 797

- June 2, 1983 – DC-9-30
- Fire began in Aft Lavatory – Spread
  - Cause believed to be electrical near flush motor
- Smoke filled Cabin and Flight Deck
- Flight Deck Door Broken

Air Canada Flight 797

- F/A and Passengers Smell Smoke
- Pilots Hear Circuit Breaker Trip
  - Reset once
- Smoke Increases
- CO_2 Fire Extinguisher Discharged into Lavatory
  - Not effective
  - Not applied directly at base of fire

Air Canada Flight 797

- Fire and Smoke Spread
- First Officer Went Aft to Investigate
- Flight Deck Door Left Open
- First Officer Switched Off Air-conditioning Packs
  - Ventilation flow aft stopped
- Flight Deck Windows Opened and Closed
  - Reversed
  - High Noise

Air Canada 797

Changes

- Lavatory Fire Detection
- Full Face Masks Portable Crew Oxygen
- Protective Breathing Equipment
- Fire Blocking Seats (650,000)
- Halon Fire Extinguisher (2 – 2.5 lb)
- AC 25-9
  - Smoke Testing

Single Failure – Multiple Results

Single Failure – Multiple Results

- RAF Nimrod Example
  - #1 Engine DC Wire Loom Failure
  - Uncommanded Opening of #4 Engine Starter
  - Starter Turbine Valve Over Speeds
    - Air from operating engine
  - Starter Turbine Disintegrates
  - Turbine Escapes Housing
  - Turbine Punctures Fuel Tank
  - Severe Fuel Tank Fire
  - Ditching in the North Sea – All Survived

Single Failure – Multiple Results

- Swiss Air 111
  - In-Flight Entertainment Systems Wiring
    - Likely initial location of arcing and/or fire
  - Spread to Nearby Wiring
    - Multiple system failure
    - Flight instruments failed
  - Unrelated Systems Affected by Initial Event

Location, Location, Location

- Inaccessible Areas Contain
  - Wiring
  - Thermal Acoustic Blankets
  - Contaminates
    - Conductive
    - Non-Conductive
    - Liquids
    - Corrosion Block
    - Lubricants


A
B
C
28 VAC
28 VAC
RIGHT ENGINE OIL PRESS
RIGHT FLAP POSITION
1A
1A
RIGHT HYDRAULIC
SYSTEM PRESS
BRAKE PRESS
OIL QUANTITY
1A
1A
1A
RIGHT TEMP CONTROL VALVE POSITION
RIGHT SUPPLY AIR TEMPERATURE
1A
1A
RIGHT INSTRUMENT BUS
FIRST OFFICER'S HEADING OUTPUT
A
B
C
1A
1A
1A
VHF NAV-2
ADF-2
ALTITUDE ALRTS-2
1A
2A
1A
RIGHT RADIO BUS
LEFT RADIO BUS
RADIO ALTIMETER -2
COCKPIT VOICE RECORDER
AUTOPILOT & ALTERNATE LONGITUDINAL TRIM

Unprotected Area of Aircraft

- Examples were all unprotected areas
  - No Detection
  - No Suppression
- Most in-flight fires are in unprotected areas

Wiring

Wiring

- 2/3 In-Flight Fires are Electrical
- 2003 MITRE Report
  - 81 Large Transports Inspected
    - 40 wiring anomalies PER airplane average
  - 39 Small Transports Inspected
    - 58 wiring anomalies PER airplane average

Wiring

- FAA Report 1995 to 2002
  - 397 Wiring Failures
    - 84% burned, loose, damaged, shorted, failed, chafed or broken wires
- TWA 800 NTSB Report
  - Examined 25 Transport Aircraft
    - 24 had metal shavings in wiring bundles
    - 5 showed evidence of heat or fire damage

Wiring

- Supplemental Type Certificate
  - FAA Study of 316 Circuit Breakers
    - Many lugs contained two different size wires
    - Violation of 14 CFR Part 25.1357
  - Swiss Air 111 IFE
    - No wiring routing drawings
    - By-Passed Cabin Bus Switch

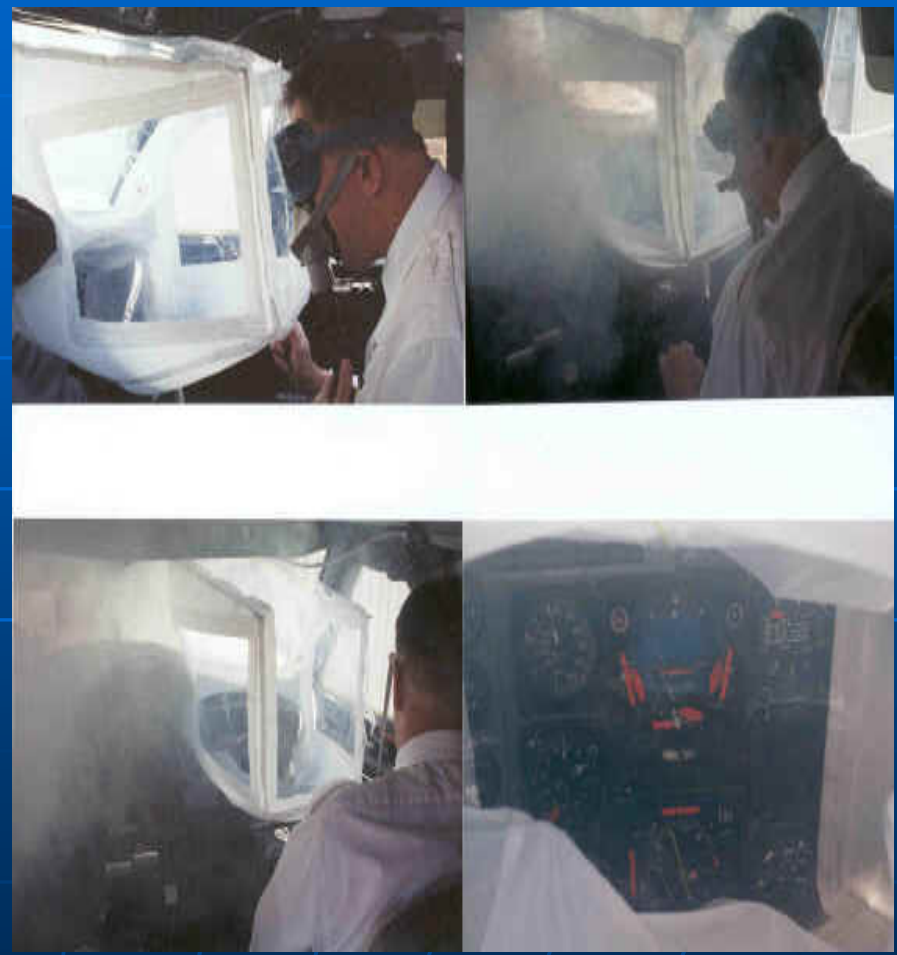
Wiring

Video Deleted

Arc Fault Circuit Breaker

Vision Assurance

- Vision to Maintain Control
- Navigate
- Accomplish Checklist
- Land



Full Face Masks

- Full Face Masks
  - Better protection
  - Better ability to purge
  - Eliminates ability to only use mask
    - FedEx 1406
- Sufficient Oxygen Supply for Landing
  - MEL does not consider Smoke/Fire/Fumes

Halon Fire Extinguishers

- FAA Tests
  - 2 ½ lb did not extinguish fire
  - 5 lb could have extinguish fire

Training

Video Deleted

FAA Tech Center

Training

- FAA Tests
  - Line Flight Attendants
    - With 2 ½ lb Halon – Fire was not extinguished
    - PBE problems
    - Smoke Migration
  - Training was not adequate

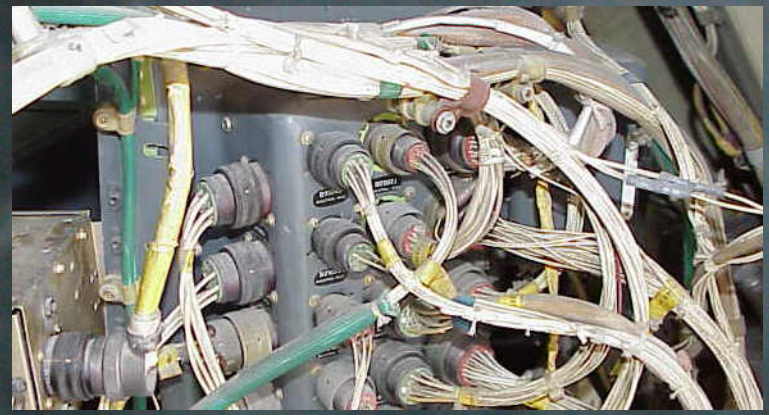
Training

- Smoke
  - Toxicity
    - Improved but still a serious consideration
  - Location
    - Access
      - Remove panel or “ax it”
      - Collateral Damage
  - Amount
    - Continuous
      - Combustion ongoing

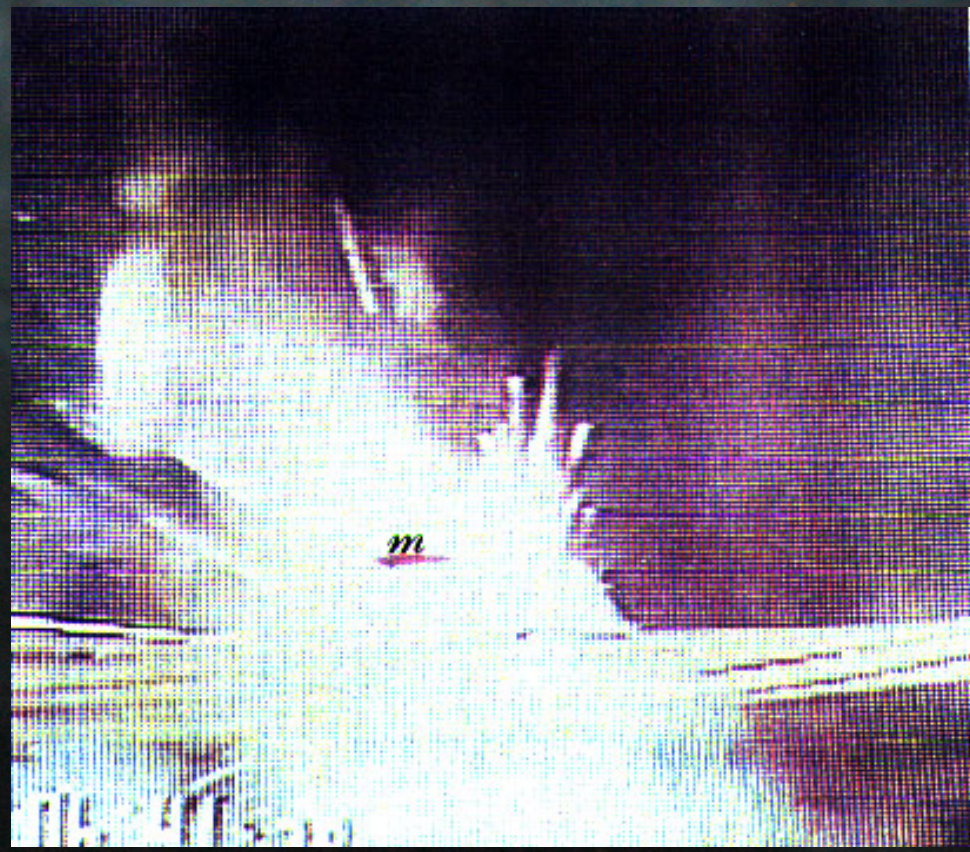
Training

- Use of the Ax
- When?
- Where?
- How?

+



CAN =



Checklists

- Various manufacturers – various checklists
  - e.g. Testing with a smoke filled simulator required 25 minutes to complete electrical smoke checklist
- Confusion
  - Most complex checklist for use in the highest stress time.

Flight Safety Foundation Template

INDUSTRY TEMPLATE
Smoke/Fire/Fumes Checklist Step Sequence and Rationale

The numbered items below comprise the industry template for an integrated, non-alerted SFF checklist. The accompanying rationales include the purpose of each step and the reason for each step's sequential placement within the checklist.

Protect the flight crew then assess the situation

1	Diversion may be required
Rationale	This step establishes the mindset that a diversion may be required. We use the word 'may' because the crew should not initiate a diversion before a preliminary assessment of the immediate fire/source. This step is placed at the beginning of the checklist to establish immediately in the minds of the flight crew a diversion may be required.

2	Oxygen Masks (If required) .....ON, 100%
3	Smoke Goggles. (If required) .....ON
Rationale	These steps protect the flight crew from smoke inhalation and fume absorption. Oxygen masks are on at 100% so O_2 supply does not mix with smoke or fumes. Steps are early in the checklist to ensure the cockpit crew is protected immediately after smoke/fumes detection. Steps are separate because they may be separate devices. The flight crew should don oxygen masks any time smoke/fumes are detected on the flight deck. The trigger to don masks is the smoke not the checklist. The steps are not recall nor are they required because oxygen masks and smoke goggles may not be required for all smoke events. We rely on cockpit crew judgment to decide when to don the devices. The "if required" statement also permits airlines to be flexible in training when to don the masks or to leave the timing decisions to the cockpit crew's discretion.

4	Crew & Cabin Communications .....Establish
Rationale	This step initiates timely co-ordination and communication between the cabin and cockpit crew. The step is placed after 2 and 3 to not delay donning of oxygen masks and goggles if required. The communication with cabin crew is made explicit in the step because the cabin crew is an important resource for assisting the cockpit crew with source identification and confirmation of elimination.

Source elimination steps

5	Manufacturers initial steps .....Accomplish
Rationale	These steps quickly isolate probable ignition sources based on historical fleet data or analysis. The cockpit crew is expected to take action without delay and without assessment. The steps are placed early in the checklist to immediately isolate probable sources to reduce the risk of event escalation.

Smoke Removal Reminder	At any time smoke or fumes becomes the greatest threat accomplish SMOKE OR FUMES REMOVAL checklist. Page x.x.
Rationale	Smoke removal should be accomplished only when the smoke/fumes are the greatest threat or when the source is confirmed extinguished. Smoke removal may change the airflow and make the situation worse by fanning an ignition source or it may mask the source. Smoke removal steps must be clearly identified and be easy to find. The removal steps may be left out of the checklist to keep the checklist uncluttered and short.
Issue	All manufacturers need to review the smoke removal checklist to ensure compatibility with this new SFF checklist.

6	Source is immediately obvious and can be quickly extinguished: If Yes, Go to Step 7. If No, Go to Step 9.
Rationale	This step is an immediate assessment of the source and situation without waiting for the effect of initial actions. The crew must determine if the source is extinguishable. The outcome of the assessment is a decision to extinguish the source or initiate a diversion.

7	Extinguish the source. If possible, remove power from affected equipment by switch or circuit breaker on the flight deck or in the cabin.
Rationale	After source is identified the crew should use all available resources to actively extinguish the source. This step comes after the source is identified.

Flight Safety Foundation Template

8	Source is visually confirmed to be extinguished: If Yes, Consider reversing initial manufacturer steps Go to Step 17. If No, Go to Step 9.
Rationale	The crew must confirm that the source is extinguished. The outcome of the assessment is a decision the source is extinguished or to continue the checklist. This step is placed early in the checklist to prevent escalation of the event.

9	Remaining minimal essential manufacturer action steps (do not meet initial step criteria) but are probably ignition sources based on historical fleet data or analysis.
Rationale	Additional manufacturer action steps that do not meet the "initial actions" criteria outlined in the SFF philosophy. For example, steps that make the cabin dark or may interfere with source identification. No further assessment should be made prior to diversion

10	Initiate a diversion to the nearest suitable airport while continuing the checklist.
Rationale	The cockpit crew should not delay a diversion if the source remains unknown or cannot be extinguished. The step is placed here to get the airplane headed toward a suitable airport.

Warning	If the SFF situation becomes unmanageable consider an immediate landing.
Rationale	The purpose of this warning is to remind the crew an immediate landing may be required if the situation deteriorates. The step is placed here after the initial probable source elimination steps have been accomplished, but before the additional source elimination steps which may be lengthy.

Additional source identification/elimination steps

11	Landing is imminent: If Yes, Go to Step 16. If No, Go to Step 12.
Rationale	If landing is imminent, the crew should stop the checklist and focus on landing the airplane without the added workload and distraction of doing this checklist. This step is placed here because all probable source isolation steps have been accomplished.

12	XX system actions ..... Accomplish [Further actions to control/extinguish source.] If dissipating ..... Go to Step 16.
13	YY system actions ..... Accomplish [Further actions to control/extinguish source.] If dissipating ..... Go to Step 16.
14	ZZ system actions ..... Accomplish [Further actions to control/extinguish source.] If dissipating ..... Go to Step 16.
Rationale	Additional source identification and isolation guidance may be required when the airplane is far from a suitable landing site. These system steps are presented here to systematically isolate an unknown source. These steps come late in the checklist after a diversion was initiated because they may take time. The sequence of these steps is determined by the greatest hazard they pose to the airplane.

15	Smoke/fire/fumes continue after all system related steps are accomplished: **Consider Landing Immediately** Go to Step 16.
Rationale	This is the final assessment step in the checklist. The outcome of the assessment is an immediate landing or landing at a suitable airport if the additional steps identified the source.

Follow-up actions

16	Review operational considerations.
Rationale	Operational considerations provide information to support crew decision making. The cockpit crew may need to be reminded to review considerations that may affect continued flight operations and decisions. Operational considerations may vary by airplane model and may be lengthy so should be provided outside of the checklist.

Flight Safety Foundation Template

PHILOSOPHY AND DEFINITIONS
Industry Checklist Template for Smoke/Fire/Fumes

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

General

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

Initial Steps for Source Elimination

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

Timing for Diversion/Landing

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

Smoke or Fumes Removal

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

New Format Checklist

EXAMPLE OF AN INTEGRATED, NON-ALERTED SMOKE, FIRE, AND FUMES CHECKLIST
United Airlines A319/A320 Aircraft

QRC

SMOKE, CABIN/COCKPIT

- Oxygen masks and regulators ..... On, 100%
- Crew and flight attendant communications ..... Establish
- Cabin fans switch ..... Off
- Blower switch ..... Override
- Extract switch ..... Override
- Galley/galley and cabin switch ..... Off
- Cabin signs ..... On
- Descent ..... Initiate

WARNING: *Do not delay descent or diversion to find the smoke source.*

CONTINUED FROM QRC

If dense smoke at any time, accomplish reverse side.

REFERENCE ACTION:

If cabin or galley equipment smoke/fire is suspected:

- Emergency exit light switch ..... On

If commercial switch installed:

- Commercial switch ..... Off

If commercial switch is not installed:

- Bus tie switch ..... Off
- Generator 2 switch ..... Off

Just before landing gear extension:

- Generator 2 switch ..... On
- Bus tie switch ..... Auto

END OF CABIN OR GALLEY EQUIPMENT SMOKE

If air conditioning smoke is suspected:

- APU bleed switch ..... Off
- Blower switch ..... Auto
- Extract switch ..... Auto
- Pack 1 switch ..... Off

If smoke does not decrease:

- Pack 1 switch ..... On
- Pack 2 switch ..... Off
- Cargo heat aft isolation valve switch ..... Off

If smoke persists:

- Pack 2 switch ..... On
- Blower switch ..... Override
- Extract switch ..... Override

END OF AIR CONDITIONING SMOKE

If electrical or avionics smoke is suspected:

Accomplish AVIONICS SMOKE ECAM or Flight Manual procedure 14.20.39.

END OF ELECTRICAL OR AVIONICS SMOKE

UNITED

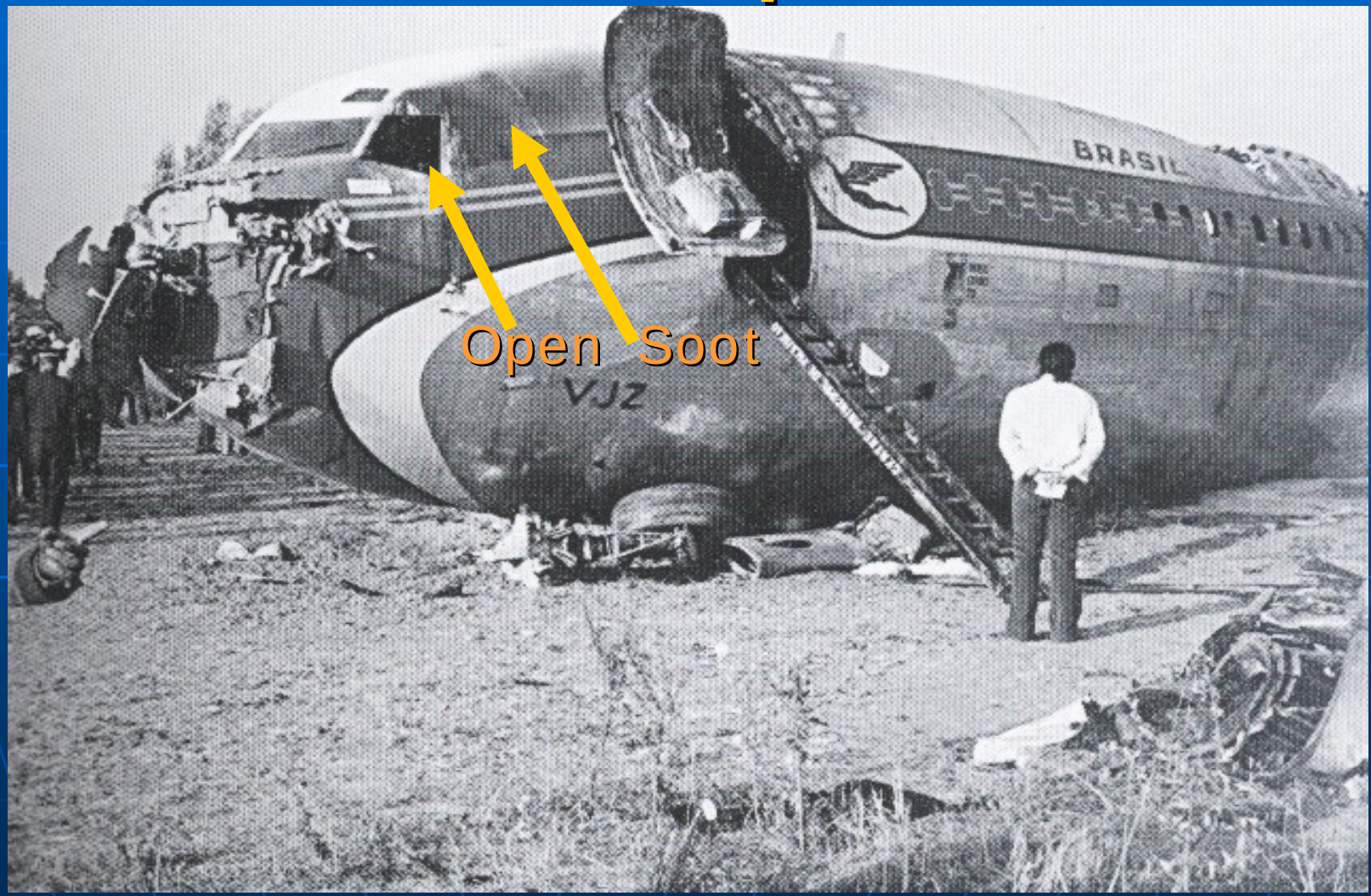
A319/A320 FLIGHT MANUAL OPERATIONS

A319/A320
1 OCT 04

16.50.5
Emergency Procedures
Fire

United Airlines A319/A320 "SMOKE CABIN/COCKPIT" drill — Front Page.

Ventilation and Open Windows



Open Window

- 70 Seconds from Runway
- Open Window did NOT Provide Sufficient Visibility
- High Noise
- Reverse Air Flow
  - Cabin Air into Flight Deck
- Visibility is Proportional to Increase Flow Rate
  - Double the rate double the visibility

Conclusions

- There are going to be in-flight fires
- Multiple layers of mitigation are necessary
- Implementation
  - FAA NPRMs
    - Wiring & Fuel Tank

Conclusions

- Fire is an unexpected event
- Fire is a very high stress event
- Fire may be from an unexpected source

Most Recent Examples

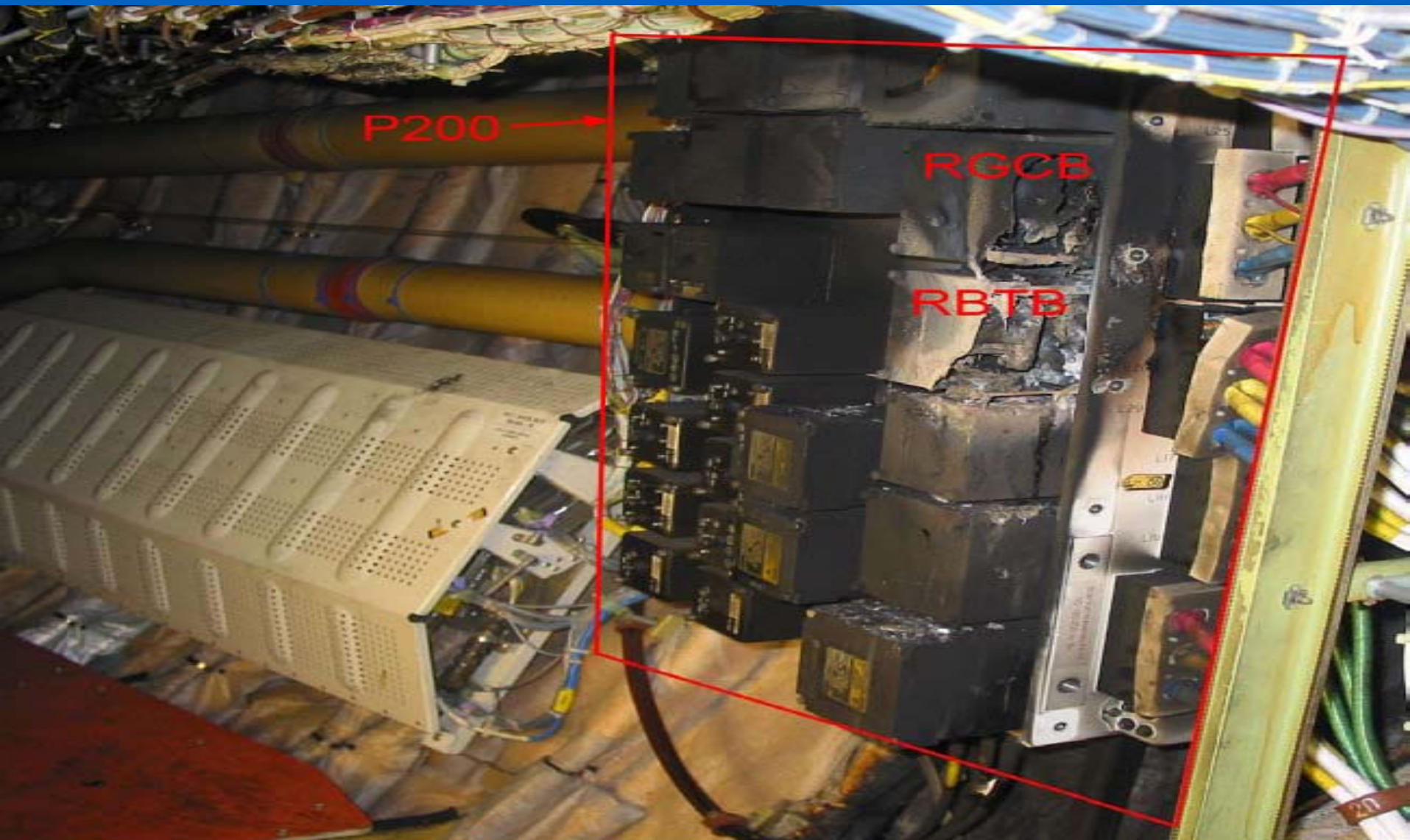
RAF Nimrod
September 2006
Afghanistan

Repo

board

February 27, 2007
United 955

February 27, 2007
United 955



February 27, 2007
United 955

February 27, 2007
United 955

February 27, 2007
United 955

February 27, 2007
United 955

February 27, 2007
United 955


What are we going
to do about it?

Implementation

- Operators
  - FSF checklist template
    - Eliminate open window
  - Retrofit arc fault circuit breakers
  - Improved wiring maintenance
  - Improved thermal acoustic blanket maintenance
  - Vision assurance
  - Improved flight crew training
  - Mark location of minimum damage for crash ax

Implementation

- Manufacturers
  - Adopt FSF checklist template
    - Eliminate open window
  - Install arc fault circuit breakers
  - Improve wiring maintenance
  - Improve acoustic blanket maintenance
  - Install vision assurance technology
  - Improve flight crew training

Implementation

- Regulators
  - Require arc fault circuit breakers
  - Improved wiring maintenance
  - Improved thermal acoustic blanket maintenance
  - Require continuous flight deck smoke testing


It is up to us