Smoke within UPS Flight 006 Report

4.12 SR 36/2013:
The FAA in co-operation or in coordination with EASA to mandate the implementation of vision assurance devices or technology for improved pilot visibility during continuous smoke, fire, fumes in the cockpit emergencies. This could include off the shelf devices or developing mask mounted thermal imaging cameras with the capability to see through smoke/fumes with sufficient clarity to view the primary cockpit instrumentation.

4.16 SR 40/2013:
The FAA in co-operation or in coordination with EASA to mandate a certification requirement for continuous smoke testing for flight deck smoke evaluation tests where the smoke is required to be continuously generated throughout the test for cockpit smoke clearance and develop a mitigation procedure through regulation on how to effectively manage continuous smoke in the cockpit.

1. Page 10

A cargo on the main cargo deck had ignited at some point after departure. Less than three minutes after the first warning to the crew, the fire resulted in severe damage to flight control systems and caused the upper deck and cockpit to fill with continuous smoke.

The crew then advised Bahrain East Area Control [BAE-C] that the cockpit was ‘full of smoke’ and that they ‘could not see the radios’, at around the same time the crew experienced pitch control anomalies during the turn back and descent to ten thousand feet.

The smoke did not abate during the emergency impairing the ability of the crew to safely operate the aircraft for the duration of the flight back to DXB.

Due to the consistent and contiguous smoke in the cockpit all communication between the destination [DXB] and the crew was routed through relay aircraft in VHF range of the emergency aircraft and BAE-C.

2. Page 24

Note: PACK 1, in fire suppression mode provides positive air pressure to the cockpit to prevent smoke/fumes from entering the cockpit area. There is no other effective smoke barrier to prevent smoke/fumes ingress into the cockpit and occupied areas.

[18] Boeing MOM 1-1708015942 issued after the accident includes an advisory note to the revised non-normal checklist. Either air conditioning pack 1 or pack 3 must remain operating to prevent excessive smoke accumulation on the flightdeck

3. Page 26

The flight was approximately 4 minutes into the emergency. The aircraft was turning and descending, the fire suppression has been initiated and there was a pitch control problem[22]. The cockpit was filling with persistent continuous smoke and fumes and the crew had put the oxygen masks on.

15:17[04]:Smoke in the Cockpit-Reduced Visibility Due to Smoke

The penetration by smoke and fumes into the cockpit area occurred early into the emergency[23]. The cockpit environment was overwhelmed by the volume of smoke. There are several mentions of the cockpit either filling with smoke or being continuously 'full of smoke', to the extent that the ability of the crew to safely operate the aircraft was impaired by the inability to view their surroundings.

Due to smoke in the cockpit, from a continuous source near and contiguous with the cockpit area [probably through the supernumerary area and the ECS flight deck ducting], the crew could neither view the primary flight displays, essential communications panels or the view from the cockpit windows.

The crew rest[24] smoke detector activated at 15:15:15 and remained active for the duration of the flight. There is emergency oxygen located at the rear of the cockpit, in the supernumerary area and in the crew rest area. Due to the persistent smoke the Captain called for the opening of the smoke shutter, which stayed open for the duration of the flight.

The smoke remained in the cockpit area.

- 15:17:18|CAPT: UPS six we are full… the cockpit is full of smoke, attempting to turn to flight to one thirty please have…standing by in Dubai

15:18[05]:Flight Management Computer [FMC] Inputs

There was a discussion between the crew concerning inputting the DXB runway 12 Left [RWY12L] Instrument Landing System [ILS] data into the FMC. With this data in the FMC[25] the crew can acquire the ILS for DXB RWY12L and configure the aircraft for an auto flight/auto land approach.

The F.O. mentions on several occasions difficulty inputting the data based on the reduced visibility. However, the ILS was tuned to a frequency of 110.1 (The ILS frequency for DXB Runway 12L is 110.1[26]), the Digital Flight Data Recorder [DFDR] data indicates that this was entered at 15:19:20 which correlates which the CVR discussion and timing.

- 15:18:00|CVR|CAPT: Try and get Dubai in the flight management computer.
- 15:18:02|CVR|F.O: I can't see it [the FMC]

 15:19:04|CVR|BAE-C: UPS six expect one two left proceed direct to ah final of your discretion
- 15:19:08|CVR|CAPT: Alright we're doing our best. Give me a heading if you can I can't see.

15:20[07]:Crew Oxygen System Anomalies – Captain and First Officer

At approximately 15:20, during the emergency descent at around 21,000ft cabin pressure altitude, the Captain made a comment concerning the high temperature in the cockpit. This was followed almost immediately by the rapid onset of the failure of the Captain's oxygen supply[27].

Following the oxygen supply difficulties there was confusion regarding the location of the alternative supplementary oxygen supply location. The F.O either was not able to assist or did not know where the oxygen bottle was located; the Captain then gets out of the LH seat.

This CVR excerpt indicates the following exchange between the Captain and F.O concerning the mask operation and the alternative oxygen supply bottle location. The exchange begins when the Captain's oxygen supply stops abruptly with no other indications that the oxygen supply is low or failing.

- 15:20:02|CVR|CAPT: I got no oxygen I can't breathe.
- 15:20:12|CVR|CAPT: Get me oxygen.
- 15:20:19|CVR|F.O: I don't know where to get it.
- 15:20:23|CVR|CAPT: You fly
- 15:20:41|CVR|CAPT: I can't see

Note: the supplementary oxygen mask and the goggles on the accident flight were two separate units; when being worn by the pilot, in order to remove the mask, the goggles have to first be removed, followed by the mask. The oxygen bottle to the aft of the cockpit area is the only portable oxygen bottle with a full face mask.

At this point on the CVR, all of the associated recorded information including the conversation and ambient sounds indicate the Captain moved the seat back, got out of the seat and then moved to the aft of the cockpit area.

The Cockpit Voice Recorder [CVR] passages following the Captains decision to leave the seat and move out of the cockpit indicate that the environment was full of continuous blinding smoke, and that a breathing apparatus or protective eye wear capable of displacing smoke was required. This is the zone contiguous with the probable location of the fire breach in the cargo lining.

4. Page 32

1.3.1 The aircraft – airframe, systems and available living space - were subject to significant thermal loading caused by fire, resulting in material degradation and damage. This resulted in the exposure of primary structural elements, components and assemblies to significant heat damage and the cockpit area

5. Page 37

1.6.4 Boeing 747 Class E Cargo Compartment
Class E cargo compartments are certified for cargo aircraft only. There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station. There are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment.
There are means to exclude hazardous quantities of smoke, flames, or noxious gasses from the flight crew compartment. The required crew emergency exits are accessible under any cargo loading condition

6. Page 45

1.6.16 Environmental Control Systems
Air Conditioning Packs
Positive pressure supplied by one pack is used to reduce the effect of smoke in the cockpit and supernumerary area after the fire suppression sequence has been activated.

7. Page 46

1.6.19 Lower Lobe Cargo Compartment Fire Protection Systems
Smoke Detection
The forward lower cargo compartment has eight smoke detectors, and the aft compartment has eight smoke detectors. Each smoke detector has a beacon lamp which supplies a smoke (fire) indication to flight crew when smoke is present in the air. The flight crew will be notified of fire and fault condition by master fire light, fire bell, warning, and status EICAS messages.
Fire Suppression

The lower cargo compartment fire extinguishing system is designed to fill the forward or aft cargo compartment with a fire extinguishing agent when smoke is detected. The system is electrically controlled by switches on the P5 pilot's overhead panel.

1.6.20 Flight Deck Smoke Evacuation Shutter

The smoke shutter attaches to the fuselage structure above the flight compartment door. The pilots use a tee handle to open and close the smoke shutter in case of smoke in the cockpit. The tee handle is between the P7 Overhead Circuit Breaker Panels.

The tee handle attaches to a cable which attaches to the smoke shutter.

The shutter assembly is installed on the aft control cabin ceiling. The smoke shutter function is to remove the smoke from the flight compartment of the aircraft.

8. Page 64

1.7.2 Sunrise Sunset Table for OMAL/DXB September 03, 2010.

One factor concerning the ambient lighting and the reduction of the visibility in the cockpit is the available light in the cockpit.

The flight was airborne shortly before dusk, the airport elevation is at sea level. The ambient light would have remained available to the crew as the climbed in altitude and travelled west. However, as a cockpit visibility factor, the return to the east and the subsequent descent reduced the available ambient light and the cockpit lighting has minimal advantages to the crew in a completely smoke filled environment.

9. Page 66

During the emergency descent from the Bahrain FIR into the Emirates FIR, communication between the ATC at Bahrain, the UAE and the accident aircraft were complex due to the flight crew's inability to change the radio frequency due to the smoke in the cockpit.

10. Page 67

When the aircraft turned back to DXB, the flight crew of the aircraft advised BAH-C that they would stay on the BAH-C frequency due to smoke in the cockpit as it was not possible to change radio frequencies from BAH-C to the UAE ATC frequencies required for the return back through the UAE FIR and to DXB.

11. Page 97

1.14.1 In-flight Phase

As detailed in other sections of this report, a cargo fire originating on the main cargo deck breached the cargo compartment liner, severely damaging the control cable support trusses, oxygen system and other essential systems impairing the ability of the crew to safely operate the aircraft for the duration of the flight from the time of the first fire indication.

Due to the cargo compartment liner failing to operate as an effective fire and smoke barrier, the supernumerary and cockpit areas filled with continuous smoke. The smoke did not abate for the duration of the emergency.

12. Page 98

Several aspects of the investigation centred around the CVR statements from the crew concerning the amount and volume of continuous smoke or fumes entering the cockpit area and the increasing temperatures in the cockpit area. The inability by the crew to view the instruments or any of the radio panels had a direct consequence of the survivability of the flight.

13. Page 106

1.16.11 Boeing 747 Synthetic Training Device, Anchorage, USA

Anchorage Simulator Observations – Session #1 and #2

The investigation participated in an observational study at the operators training facility in ANC on September 13, 2010. The purpose of the study was to familiarize investigators with checklists and procedures related to smoke and fire scenarios that may occur in-flight. The simulator used for the observations as an FAA certified level D, B747-400 simulator. Three pilots who were type rated, current and qualified on the B747-400 participated in this study. In addition there was a simulator instructor and 4 observers from the operations/human performance group.

Selected observations from the sessions include:

The pilots involved in the exercise indicated that with the smoke goggles donned, it was difficult to find the switch to clear the goggles of smoke.

The instructor informed the crew that they should have completed the smoke fire and fumes checklist prior to completing the smoke removal checklist. Asked who would be in charge of communicating with ATC, both pilots indicated that the PM would do this.

If this was a single pilot operation, pilot #2 stated that the situation would have been “mind boggling” and he would have foregone the checklist. He also believed it would have been difficult to fly the approach without being able to see the instruments and having specific headings and altitudes.

The instructor who participated stated that he believed the smoke fire and fumes checklist to be the most complicated checklist and the scenario presented would have been a lot for any crew to do.

When the main deck’s cargo fire arm switch was armed, packs 2 and 3 were shut off. If pack 1 was turned off, pack 3 came back on as long as the pack 3 switch was still in the “norm” position. Page 8-10 of the smoke, fire, or fumes checklist stated to turn the pack 2 and 3 selectors to off. If this was completed and pack 1 failed without the crew recognizing this, pack 3 would not come back on.

It took approximately 28 seconds for the crew to don both the oxygen mask and smoke goggles. It took an additional 6 seconds for the crew to establish crew communications. The scenario was run two times and both times the headset was knocked off when donning the oxygen mask.

Pilot #3 stated that the smoke, fire or fumes checklist had lots of branches and was long. He said using the goggles and mask made it more difficult.

The full report on the Simulator Observations is in Appendix to this report.

14. Page 109

1.16.14 Alternative Vision Systems for Smoke/Fumes in the Cockpit

Continuous smoke resulting from large inflight cargo fires as seen with this accident can lead to a situation where the operability of the aircraft and the safety of the crew can be compromised to such an extent that the possibility of recovering the aircraft cannot be a reasonable certainty.

The certification standards as the currently exist do not have a certification standard for continuous smoke removal

Regardless of the certification requirements, as a result of several inflight fires with continuous smoke events, there are alternative vision systems available to assist with smoke/fumes events

The investigation team tested various systems that enable a crew to view the immediate cockpit area and the PFD’s

Two types of system are currently available:

Emergency Vision Assurance System [EVAS] is a self-contained system that includes a battery powered blower which draws smoke in through a filter, filtering out the visible particles, and out to a flexible air duct which is connected to an inflatable transparent envelope, called the Inflatable Vision Unit (IVU). EVAS, the static Inflatable Vision Unit [IVU], a clear plastic closed loop pressurised system that provides a clear channel through smoke that allows the crew to view the
The pilot leans forward, placing his smoke goggles in contact with the EVAS clear window, providing an view of both primary flight displays instruments and the outside world.
Thermal Imaging Cameras. Two types were assessed, a thermal imaging camera and an infrared camera. Both camera types can be helmet mounted as integral equipment for a full face smoke mask. The advanced systems have a small viewing screen mounted at eye level.
Currently there are no approved helmet mounted thermal/infrared integrated cameras for full face mask/goggles for use in commercial aviation. Further research and development would provide a useful alternative to the problem of viewing instruments in a smoke filled cockpit.

15. Page 113

1.18.2 Smoke in the Cockpit - Characterising the Problem
Smoke as a factor in emergency situations is a quantitative problem based on density, volume and flow rate. What defines smoke and fumes as an obstruction to normal operation in a cockpit can be a subjective, other than the fact that smoke is indicative or either a symptom of another failure, usually electrical or there is a cargo fire.
In this accident, the smoke was continuous and of sufficient density and rate of flow to prevent viewing the flight displays, radios panels and the view outside the cockpit.
As an indication of the smoke in the cockpit problem, the pictures below are of an FAA test of an EFB1/Laptop battery fire. The test is a good indication of the lack of visibility encountered when a cockpit is full or filling with smoke. [59]

Picture 5 - Loss of pilot vision - ensuring pilot vision in the presences of continuous smoke.

The visibility should be sufficient to view the attitude indicator or primary flight display and to see outside the aircraft for landing. In addition, it is imperative that the crew be able to view the instruments to navigate and they must be able see to program the flight management computer and the audio control panels.
The checklist must be visible so that procedures can be followed to prepare for landing and manage the smoke/fire/fumes problem. Adequate visibility on the flight deck should be maintained during a smoke/fire/fume event.

16. Page 114

Smoke Generation by a Continuous Source Involving Smoke Cockpit Penetration with no Method of Fire Suppression or Smoke Clearance
Smoke migration is a result of a spreading fire. As a fire burns, heat is created and the products of combustion begin to migrate. Minimising the spreading of smoke and fumes into the flight deck is critical for continued safe operation of the aircraft.
Smoke is a factor in the inability to view the instruments. The composition of the smoke based on the residue found at the accident site was the result of black smoke, typically containing carbonized particles. The Pyrolysis of the burning material, especially incomplete combustion or smouldering without adequate oxygen supply, also results in production of a large amount of hydrocarbons. Heavier hydrocarbons may condense as tar; smoke with significant tar content is yellow to brown.
In addition to the above, the following conditions are considered unsafe:
There is a deficiency in certain components which are involved in fire protection or which are intended to minimise, retard the effects of fire, smoke in a survivable crash, preventing them to perform their intended function; for instance, deficiency in cargo liners or cabin material leading to non-compliance with the applicable flammability requirements.

17. Page 118

i) *Protection of the flight crew compartment from smoke and fumes*.
1) For aeroplanes of a maximum certificated take-off mass in excess of 45 500 kg or with a passenger seating capacity greater than 60, means shall be provided to minimize entry into the flight crew compartment of smoke, fumes and noxious vapours generated by an explosion or fire on the aeroplane.

18. Page 119-20

The requirements for Class E cargo fire suppression are defined in 14 CFR 25.857(e) as follows:
e) Class E. A Class E cargo compartment is one on aircraft used only for the carriage of cargo and in which—
• There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station;
• There are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment;
• There are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and
• The required crew emergency exits are accessible under any cargo loading condition.

There is no certification requirement for active fire suppression.

19. Page 123

1.18.13 Smoke in the cockpit
Smoke in the cockpit under the current certification standards is predicated around the assumption that smoke in the cockpit is temporary. The Non Normal Check lists for SFF events are based around presumptions on the emergency scenarios considered relevant. An emergency scenario, uncontained, can escalate rapidly to an abnormal situation where the assumed safety gates are no longer valid.
The FAA attempted to address the loss of pilot vision by requiring the one-time reduction of a small amount of temporary smoke; there is no certification standard for ensuring pilot vision in the presence of continuous smoke. The current requirement is that smoke should be reduced within three minutes such that any residual smoke (haze) does not distract the flight crew nor interfere with operations under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR).
The single significant safety factor with smoke in the cockpit is the ability of the crew to safely operate the aircraft. This should not be impaired by loss of vision due to smoke from a continuous source in or contiguous with the cockpit.

20. Page 124

124 1.18.15 Controlling Smoke Penetration
Boeing uses a two-step approach to exclude hazardous quantities of smoke and noxious gases from entering the flight deck or other occupied compartments.
1) The flight deck and supernumerary compartments are maintained at a higher pressure relative to adjacent compartments that may contain smoke or noxious gases during Class C or E fire suppression mode.
2) Airflow is reduced and the cabin depressurised.

21. Page 126

1.19.1. Airbus A330 Synthetic Training Device,Abu Dhabi, UAE: Smoke/Fire/Fumes Vision Assistance Testing[72]
Additional crew performance and CRM analysis was performed in a Smoke, Fire, Fumes [SFF] environment to further analyse crew vital actions in a continuous and completely smoke filled cockpit environment where a crew has access to vision enhancement equipment supplied by a manufacturer[73].
The testing used type specific line captains from a local airline with no prior experience of either completely smoked filled cockpits or the vision assistance.
Crew interaction, the vision assistance system operation, task management, crew coordination and critical decision making in complex high task orientated environments that are not routinely included in normal emergency training were observed with crew based recommendations noted regarding CRM and task prioritisation.
<u>A full description of this testing is included in the Appendix G.</u>

[73] Emergency Vision Assurance System (EVAS) provided the equipment and the smoke generator. The system provides a clear space of air through which a pilot can see flight instruments and out of the front windshield for landing. The pilot still relies on the oxygen mask for breathing, smoke goggles for eye protection and employs approved procedures for clearing smoke from the aircraft.

22. Page 128
The primary factors involved in this occurrence include the following:

- The condition that resulted in the ignition source
- The flammable materials that were available to be ignited, sustain, and propagate the fire
- The location of the fire
- The single point of failure that compromised the critical systems
- The subsequent fire-induced material failures that exacerbated the fire-in-progress
- The lack of detection equipment to enable the crew to accurately assess the source and significance of the initial smoke
- The lack of appropriate in-flight fire fighting measures required to deal successfully with the smoke and fire.
- The decision making in the first stage of the accident event sequence
- The emergency procedures available to the crew
- Alternative vision systems – suitable use of and safety enhancements

23. Page 129

According to the FAA, 14 CFR part 25 certification, smoke and fume elimination procedures are designed primarily to evacuate the cabin of foreign pollutants. These procedures are not designed to eliminate the cause of the pollutant but rather to increase the aircraft's airflow to evacuate the pollutant. If the cause of the pollutant is a fire and the fire has not been extinguished, it is possible to worsen the situation by increasing airflow through the area where the fire or smouldering condition exists. For this reason, it is important to extinguish the fire[74]
The FAA Advisory Circular [AC] for Large Aircraft: 25-9A, Continuous Smoke in the Cockpit section calls for the conduct of certification tests relating to smoke detection, penetration, and evacuation, and to evaluate related Aircraft Flight Manual (AFM) procedures. The FAR does not require the consideration of continuous smoke generation/evacuation, the FAA recommends that the airframe design address this situation but it is not mandatory.
With no mandatory requirement to assess continuous smoke in the cockpit, collecting test data on the problem followed by deriving a practical mitigation strategy would seem problematic if not mandated by the regulator.
There is no requirement for carriers to have an alternative vision assistance capability. In the case of this accident the inability to view the primary flight displays or radio panels was a causal factor in the event sequence.

24. Page 134

15:17:19 (ATC) - Captain informed ATC that cockpit was full of smoke
- 15:17:39|RDO-CAPT: UPS six we are full,- the cockpit is full of smoke attempting to turn to flight to one thirty please have (men and equipment) standing by in Dubai.

15:17:38 CAPT - Comment about inability to see intra-cockpit
- 15:17:39|CVR|CAPT: Can you see anything?
- 15:17:40|CVR|F.O: No, I can't see anything.

25. Page 136

There are several references to the smoke in the cockpit, the inability to view inside or outside the cockpit, the increasing heat, lack of oxygen supply and that the PF cannot see the primary flight displays speed or altitude indicators.

26. Page 149

Three events occurred rapidly and in quick succession following the start of the turn back which diverted the crew's attention.
I. The cockpit filled with smoke. The smoke was present at the start of the sequence, but it rapidly became noticeable in the CVR statements that the volume and the density of the smoke has increased significantly. Within two minutes neither crew member could view the panels or out of the cockpit.

II. At about the same time, the pitch control problem became apparent which diverted the F.O's attention as the Captain asked the F.O to 'figure out what was going on'. The F.O was already managing a number of other problems, including the FMC input and the checklist

III. The Captains oxygen supply stopped, the Captain asked for oxygen, the portable oxygen bottle was behind the Captains seat next to the left hand observer seat. The First Officer was not able to assist the Captain. The Captain, one minute after the oxygen supply stopped, got out of the seat and went back into the aft cockpit area. The Captain was heard to say 'I cannot see', the is no further CVR recording or interaction of the Captain.

Seven minutes into the emergency, the F.O is PF and the Captain is incapacitated. Almost immediately, the first relay aircraft contacts the accident flight to relay information. The F.O establishes communication with the relay, this distraction and the requirement to complete the escalating task load precluded the F.O from enquiring as to the location of the Captain.
This aircraft was on the AP, heading on a direct track to DXB at around 380 KTS. The F.O does not attempt to contact the Captain or mention the incapacitation during the radio transmissions.
There are numerous references to the cockpit visibility problems while the PF is talking to the relay traffic. The following workload factors were considered significant when analysing and demonstrating the basic workload functions for the flight crew.

2.1.2 Basic Workload Functions
(1) Flight path control.
o AP from FL220, heading direct to DXB. AP off and manual control from the right turn after the over flight until the end of the data. It is possible due to the smoke and lack of visual clues available spatial disorientation was a factor after the unanticipated bank to the right confused the PF.

27. Page 150

(5) Operation and monitoring of aircraft engines and systems.
• The inability of the PF to view the instruments was a causal factor in the accident. Had this problem been resolved with either an effective smoke abeyance procedure or the fire suppression procedure extinguishing the pyrolysing materials, then only other alternative in a continuously smoke filled cockpit is a vision assistance mechanism

(7) Checklist Interruption.

• Only the initial portions of the Fire Main Deck NNC were completed. As the crew began to experience smoke obscuration and flight control difficulties, the NNC was not completed. In the early stage of the emergency the rapid escalation of the cascading failures occurred while other vital actions were being performed, notably, the Fire Main Deck non-normal checklist. The contact change of prioritisation to deal with the number of problems that were presented to the crew prevented a thorough review of the problems that would be occurring in the near future, for example, tuning one of the radios to the destination frequency.

28. Page 158

At 15:13:31, the crew commanded a right turn and descent. Approximately 30 seconds later, the first indications of smoke and control issues became evident to the crew. From the onset of the emergency the crew reacted to the normal drills required, the Captain assumed control of the aircraft and the F.O reverted to Pilot Not Flying [Pilot Monitoring] duties which included running the QRH Fire Main Deck checklist.

29. Page 160

However, it is clear that a major difficulty faced by the crew was a consequence of the course change back to DXB. Once the smoke prevented the crew from changing radio frequencies, the communications, navigation, and surveillance difficulties increased. On a course to Doha, the flight would have been in direct contact with BAE-C, and if relays were required as the airplane descended toward the airport, direct landline communication between BAE-C and Doha Approach would have greatly simplified the radio communication. ATC radar surveillance and coordination would also have been simplified. The SSR data would have been available to the ATCO and there would have been more available ambient light due to the longitude of Doha.
Analysis of the diversion to DOH and the likely outcome is speculative as the crew incapacitation and smoke/fumes in the cockpit would have prevailed as the rate of failure on the timeline of the failures was linear regardless of the destination. In addition, the aircraft control was seriously compromised by the fire and consequential events, a factor that was not apparent to the crew as they could not view the primary instruments, or the and alert and notification display. The likely outcome of the diversion to DOH is therefore inconclusive, although the communication and task saturation issues experienced by the remaining pilot would have been negated by a DOH diversion. The communications difficulties with the relay aircraft/BAH-C/EACC/DXB chain of events was the result of the course change toward DXB.

30. Page 169

The flight crew was able to restore Pack 1 operation at climb 12,200 ft (UTC 15:00:03) by accomplishing a reset per the PACK 1,2,3 non-normal procedure. All three packs were on at the time of the FIRE MAIN DECK indication (UTC 15:13:46). Pack 2 and Pack 3 were then shutoff. This is the expected result of the crew performing the FIRE MAIN DECK non-normal procedure. Pack 1 was the only remaining source of flight deck ventilation per system design. However, FDR indicates that Pack 1 stopped operating at UTC 15:15:21. The shutdown of Pack 1 resulted in loss of all ventilation to the flight deck, which compromised flight deck smoke control. Furthermore, with no packs operating, the Forward Equipment Cooling System automatically reconfigured into the “closed loop” mode, which changed the cooling air to the flight deck instruments from pack air (outside “fresh” air) to recirculated air via the equipment

cooling fan. Consequently, any smoke that would have migrated to the E/E Bay would have been drawn into the Forward Equipment Cooling System and supplied to the flight deck instruments.
The system is capable of automatically restoring Pack 3 operation if Pack 1 is detected off. However, this capability does not exist if the Pack 3 selector is in the OFF position. Because the FIRE MAIN DECK non-normal checklist instructed the flight crew to select off Pack 3, it was not able to be automatically restored upon the loss of Pack 1 at UTC 15:15:21. Boeing subsequently revised the crew procedure to eliminate the instructions for selecting off Pack 3.

31. Page 174

There is no system or risk methodology available to a cargo crew to recognise when a fire is sufficiently suppressed to stop combustion and at what point in an emergency it is safe to descend.
In the case of this accident, the descent to 10,000 feet at the start of the return to Dubai may have contributed to the rate and volume of smoke produced.
Without active fire suppression and a method to determine if a fire is sufficiently extinguished, the decision to descend from 25,000 feet could potentially directly contribute to the problem of fire propagation and smoke generation combined with a risk to the critical systems and the eventual outcome of the flight.

32. Page 175-7

2.13 Smoke Penetration – Upper Deck Cockpit and Supernumerary Area
Smoke/Fumes Barriers
The accident aircraft was not required to be equipped with a cockpit door or screen.
When the cargo compartment liner was breeched, the smoke penetration into the rear of the supernumerary area was unavoidable.
This type of aircraft is exempt from the cockpit door requirements [according to CFR 121].
Smoke Density/Soot Deposits
In the absence of any recording systems to verify the smoke density it is possible using an established evidence reference data to gauge the smoke density by observing the level of deposited material on surface area or objects ejected from fire zone 1[88] in the debris field, or clear of the fire zones in all debris fields.

Using the Ringelmann scale[89] to compare the deposited residue on the retrieved components from parts of assemblies recovered from the supernumerary area, the Ringelmann scale value were between #4/80% and #5/100%.

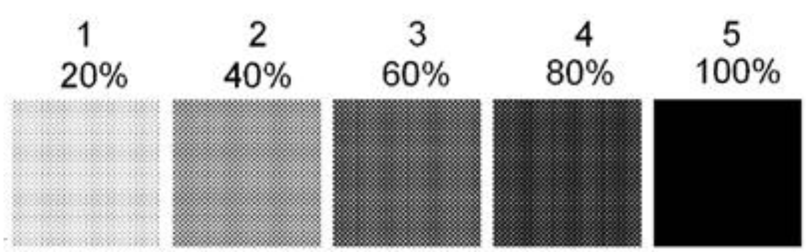

Figure 60 - The Ringelmann Scale: The smoke composition and density scale

Smoke and Toxic/Noxious Gases

The unsafe condition of continuous, unstoppable smoke entering and accumulating in the cockpit was a contributing cause to the incapacitation of the Captain following the mask removal when the oxygen flow had stopped. Controlling the smoke penetration is a crew survivability issue.

2.14 Smoke and Reduced Cockpit Visibility

The lack of verifiable CRM data lead to the investigation team establishing a quantified test and validation exercise using a B747-400 Simulator.[90]

The testing was devised by an NTSB behavioural scientist, who observed, recorded and analysed the data and simulator crew performance.

The objective were to run simulations of the scenarios encountered by the accident crew to establish definitive baseline CRM data on communications, checklists, handling and auto flight conditions

A report on the exercise is contained in the appendix . The exercise concluded:

- It is imperative that when cockpit visual clarity is compromised, clear and defined task and role differentiation between the PF and PM are understood and reinforced through adequate training.
- Crews should be very familiar with the functioning of the oxygen mask selectors and the switching options, including the mask venting function.
- Turning off the dome light aids text differentiation in smoke + twilight conditions.
- EICAS messages that cannot be read are a fundamental flaw in the smoke filled cockpit checklist design philosophy.
- Reversion to a variation of single pilot operation appears to be a standard reaction to a lack of communication in multi crew operating environments. It would be advisable that if a crew member goes into a single pilot operation state of cognitive functioning, that the actions performed are enunciated (as per normal) to provide a clue to the PM, or non-handling pilot, that a command decision has been made and the PM should revert to a passive or
- Training for worst case scenario emergency flight management should be predicated on the requirement to perform an immediate landing with degraded cockpit visibility and communications. This should be a rehearsed procedure with the decision points clearly established through repetitive training.
- Checklists should be fully representative of the reality of the emergency they are attempting to mitigate.

33. Page 177

2.15 Pilot Incapacitation

The incapacitation of the Captain early in the event sequence was a significant factor in the investigation. Based on the elevated temperature testing results and incidental CVR comments, it is now understood why the oxygen flow stopped after the PVC hose connector had failed, the direct effect of this failure on the crew survivability and subsequent events in the accident timeline.

At 15:19:15, the Captain says ‘it’s getting hot in here’, at 15:19:56 there is the first indication that the Captains oxygen supply was compromised.

The Captain’s incapacitation was possibly preventable as there was additional supplemental oxygen available in the aft of the cockpit area and in the supernumerary area. The Captain requested oxygen from the F.O. several times over approximately one minute. The First Officer due to possible task saturation was either not aware of the location of the supplementary oxygen bottles or able to assist the Captain. It is not known if the Captain located either of the oxygen bottles although they were within 2 meters of the Captains position.

The Captain removed the oxygen mask and separate smoke goggles and left the seat to look for the supplementary oxygen. The Captain did not return. The Captain was in distress locating the supplementary oxygen bottle and could not locate it before being overcome by the fumes. The Captain was incapacitated for the remainder of the flight. A post-mortem examination of the Captain indicated that the cause of death was due to carbon monoxide inhalation.
The F.O had limited time on type and eight minutes into the emergency was in a single pilot environment having to manage a smoke compromised cockpit environment and numerous cascading failures.
The protection of critical systems for two crew flights should be reviewed in conjunction with the operator modifying their training system to advise the practicalities of locating the alternative supplies and single crew CRM operating procedures.
The key to avoiding serious problems from the incapacitation of one pilot in a multi crew aircraft is the availability of appropriate SOPs and recurrent training which encourages their use if necessary.

34. Page 180

2.19 Protection of Critical Systems
Several aspects of the investigation centred around the CVR statements from the crew concerning the rate and volume of continuous smoke or fumes entering the cockpit area and the increasing temperatures in the cockpit area.
The protection of critical systems for the area above the class E cargo compartment is predicated on the cargo liner remaining intact as a physical and as a thermal barrier.

35. Page 181-2

2.21 Crew Training – Smoke, Fire, Fumes
Serious in-flight emergencies are uncommon events, particularly an in-flight emergency of the scale experienced the crew of this Boeing 747-4AF.
Evident in the cockpit analysis is confusion due to the smoke and visibility problems as the crew managed the deteriorating cockpit environment as the aircraft was not responding to the crews attempts to control the abnormal situation.
The sequential failure of the aircraft systems, in conjunction with the deteriorating cockpit environment and consequential incapacitation of the Captain in conjunction with the complicated and confused CRM environment are not events that can be trained for with any degree of realism.
Elements of these emergency factors are practices in isolation, for example smoke in the cockpit evacuation, crew incapacitation and multiple systems failure.
A completely obscured smoke/fumes cockpit is a unique environment, simultaneously rendering normal cockpit management problematic is predicated on the ability to view and communicate in the limited living space of an aircraft cockpit, into a confusing and non-synchronous situation where valuable time is used to perform normal cockpit functions. This can be a distraction from the problem solving required to effectively manage a developing series of emergency actions or tasks.
The training environment for non-normal and emergency training procedures for large freighter aircraft is not realistic concerning the risk and crew mitigation options with continuous smoke in the cockpit.
Specialised risk based training in fixed ground training devices could be an advantage to prepare crews to manage the problems associated with continuous smoke filled cockpit environments.
Other examples of this type of environment exist in aviation, for example off shore rotary operations require crew training in a crew simulator that can be submerged in water, rotated 180° and also be used in conditions of low light: these are the realistic emergency conditions which an off shore crew could

experience and the simulator is used to provide a real time exercise that provides the crew with instinctive cognitive reactions, which due to the limited human endurance when submerged [approx. 180 seconds without exertion], can be the difference between a successful or unsuccessful cockpit egress.

This type of emergency training approach should apply to dedicated aerial freighter operations, in particular with the unique three level architecture of the B747-400F series of aircraft, with the cockpit position directly above a main cargo deck.

Based on a derived cockpit environment analysis, there are several safety lessons to be learned and communicated to the aviation industry.

Simulator training today largely focuses on how to fly the aircraft and how to respond to an emergency. It has not progressed to a fully 'evidence based' training in which we use objective flight data to develop training scenarios from known accidents, incidents and FOQA events, factoring these into recurrent training processes. [93]

A safety enhancement would be the adaption by cargo dedicated transport companies to have a separate smoke/fire/fumes immersion training device, where crews can experience the limitations of a completely smoke filled environment, with the attendant CRM difficulties of donning oxygen mask, reading checklists in low visibility, establishing communications and the reality of functioning in an emergency situation, where problems of visibility and managing the aircraft can be experienced, awareness increased and mitigation strategies developed at a crew operating level.

36. Page 183

2.23 Communications

The smoke in the cockpit presented several problems to the PF. The communication difficulties between the aircraft, the fixed ground stations and the relays were contributing factors in this accident.

The communication difficulties based on the frequency selection could have been reduced had the PF been able to communicate on the guard frequency direct to the UAE controllers.

Simulator based testing of smoke filled environments highlighted the difficulties inherent in a smoke filled environment.

There are several attempts by the UAE ATC to contact the flight on the guard frequency in conjunction with aircraft relaying information or flights questioning who is transmitting on the guard frequency.

The communication problems could have alleviated had the checklist directed the crew to tune at least one radio to the destination aerodrome or area control frequencies in the transit FIR.

37. Page 183-4

2.24 Checklist – Smoke, Fire and Fumes – Format Improvements

There have been several industry initiatives to alter the perception of risk for smoke, fire and fumes events in commercial transport category aircraft[94]

Large transport category aircraft specifically cargo operators, where there is a large Class E cargo compartment with a large volume and mass of combustible material should have specific smoke, fire and fumes mitigation implemented to support the crews in the event that there is a large cargo fire.

The crew of the accident flight were in a complete smoke filled environment within three minutes of the alarm.

All cockpit vital actions, including flight management and safe navigation through the airways is predicated on the smoke clearance procedures clearing smoke or fumes and that the crew will be able to view the panels, instruments and outside of the cockpit.

If this presumption is not met, all ability to perform the required vital actions are rendered redundant, unless there is an alternative method to view the required panels.
The recommendations in the various working papers and industry review reports are centered around this risk mitigation.
One problem, and it was highlighted by this accident is the QRH checklist. The investigation team set up and ran two different smoke, fire, fumes simulator sessions.
One was in a Boeing 744 simulator to perform several verification and observation sessions of the crew vital actions and measure and record the CRM and decision making processes in reduced visibility
The second was in an A330, an envelope protected aircraft with a high degree of automation, and relatively hands free.
In each case, the regardless of the aircraft's technical sophistication, the crew are required to read from a QRH.
It is counterintuitive if the primary problem is the requirement to view objects, that the requirement to achieve critical tasks is based on the crews ability to read, comprehend and perform the required vital actions if these are not memory items.
The numerous checklist enhancements regarding font, size and background colour should be implemented at a regulatory level; particularly where large transport aircraft are concerned.
The simulator sessions results and conclusions are in the Appendices.

38. Page 184-5

2.25 Audible Checklists – Smoke, Fire and Fumes

A smoke filled cockpit with a smoke/fumes saturation which is non-dissipating limits the ability of the crew to view the primary flight instruments and the hard copy versions of the QRH.
Several air accident reports cite examples of crews unable to function in a smoke/fumes environment where flight performance and management of vital actions cannot be accomplished as the QRH checklists cannot be read.
From an operability, cockpit ergonomics and human factors perspective it is counter intuitive to require a crew in an emergency situation to acquire functioning information by reading a checklist if the primary obstacle to completing the task is the inability to view the checklist due to smoke in the cockpit.
The implementation of audible checklists, crew activated and monitored would resolve the smoke filled cockpit viewing problem.
Cargo fires can produce dense, toxic, black smoke with heavy particulates and produce liquid residues which can render vision through goggles difficult, even if the object is in close proximity.
Aircraft manufacturers and their respective regulatory oversight organizations should investigate the possibility of audible checklists to assist in smoke, fire and/or fumes events.
The audible checklists solve several problems in a smoke filled cockpit:

- Initiation
  - Triggering can be through the mic or intercom switches
  - Could be managed through an electronic checklist or EFB adaption
  - Can be used during smoke/fume events where there is a continuous source of smoke or fumes near and contiguous with the cockpit area obstructing normal viewing

- Audible checklists could be a QRH hands free application, allowing the pilot to check and confirm vital actions
- All crew can be aware of the checklist progress, enhance the team concept for configuring the plane by keeping all crew members in the CRM loop.

• The ergonomics of handling a QRH/NNC checklist and functioning is simplified.
• Verification ○ Challenge-Response is completed through the aircraft system

• Completion ○ All crew can be aware of the checklist progress

• Interruptions and Distractions ○ High task load functions will not contribute to checklist interruption
○ Checklist flexibility to manage priority tasking or a high demand workload factors

Several working studies have assessed the scope of the task and there have been industry funded studies to collect and analyze data, for example a recent peer reviewed paper comparing the effects of simulated, intelligent audible, checklists and analog checklists in simulated flight[95]
An ICAO working group or an equivalent organization could be established to assess the requirements, develop a research process and present the information at an industry forum for further discussion and support.

39. Page 188-93

(Findings)

11. FAA Advisory Circular 25-9A *Smoke Detection, Penetration, And Evacuation Tests And Related Flight Manual Emergency Procedures* does not require the consideration of continuous smoke generation for cockpit smoke evacuation, the FAA recommends that the airframe design address this situation but it is not mandatory.

23. By the time that the smoke in the cockpit and fire damaged controls became apparent, diverting to Doha was no longer a feasible option.

31. Consequently, the damaged cargo compartment liner exposed the supernumerary and cockpit area to sustained and persistent smoke and toxic fumes.

47. Within three minutes of the fire alarm, smoke enters the cockpit area. This smoke in the cockpit, from a continuous source near and contiguous with the cockpit area, entered with sufficient volume and density to totally obscure the pilot’s view of the instruments, control panels and alert indicating systems for the duration of the flight.

50. The crew made several comments concerning their inability to see anything in the cockpit. The crew in the smoke environment had reduced visibility and could not view the primary instruments such as the MFD, PFD, Nav Displays or the EICAS messages.

54. The Captain called for the smoke evacuation handle to be pulled as the smoke accumulated in the cockpit. The smoke evacuation handle when pulled opens a port in the cockpit roof, which if the smoke is sustained and continuous, will draw smoke through the cockpit as the pressure is reduced by the open port venturi effect compounding the problem. The smoke evacuation handle remained open for the remainder of the flight.

55. There are several instances of checklist interruption at critical times at the beginning of the emergency. The speed and quick succession of the cascading failures task saturated the crew. The smoke in the cockpit, combined with the communications problems further compounded the difficult CRM environment. With the incapacitation of the captain, the situation in the cockpit became extremely difficult to manage.

58. The Captain instructed the F.O. to input DXB RWY12L into the FMC. This action was completed with difficulty due to the smoke. There was no verbal confirmation of the task completion, however, the the aircraft receivers detected the DXB Runway 12L glide slope beam when approaching Dubai.

68. The cockpit environment remained full of smoke in the cockpit, from a continuous source near and contiguous with the cockpit area for the duration of the flight.

69. As the flight returned towards DXB, the crew were out of VHF range with BAE-C and should have changed VHF frequencies to the UAE FIR frequency 132.15 for the Emirates Area Control Center [EACC]. Due to the smoke in the cockpit the PF could not view the audio control panels to change the frequency selection for the duration of the flight.

70. The flight remained on the Bahrain frequency 132.12 MHz on the left hand VHF ACP for the duration of the flight. To solve the direct line of communication

73. The PF requested from the relay aircraft immediate vectors to the nearest airport, radar guidance, speed, height and other positional or spatial information on numerous occasions to gauge the aircraft's position relative to the aerodrome and the ground due to the persistent and continuous smoke in the cockpit.

85. There is no requirement for full immersion smoke, fire, fumes cockpit training for flight crews.

95. The aircraft was not equipped with an alternative viewing system to allow the pilot(s) to view the instruments and panels in the smoke filled environment.

40. Page 194

(Causes)

3.2.6 The rate and volume of the continuous toxic smoke, contiguous with the cockpit and supernumerary habitable area, resulted in inadequate visibility in the cockpit, obscuring the view of the primary flight displays, audio control panels and the view outside the cockpit which prevented all normal cockpit functioning.

41. Page 195-6

(Contributing Factors)

3.3.11 Task saturation due to smoke and multiple systems failures prevented effective use of the checklist by the crew.

3.3.14 Task saturation due to smoke and multiple systems failures prevented effective use of the checklist by the crew

3.3.15 The incapacitation of the Captain early in the event sequence, resulted in a single pilot scenario. The numerous cascading failures and smoke in the cockpit resulted in task saturation and an extreme workload for the remaining pilot.

3.3.16 The crew was not equipped with an alternative vision system or method for managing a smoke filled cockpit that would allow the crew to view the primary instruments.

42. Page 198-201

(Safety Recommendations)

4.11 SR 35/2013:
The FAA in co-operation or in coordination with EASA to require the use of Evidence Based Training Programs [EBTP] in line with the requirement of ICAO Document 9995 - Manual of Evidence Based Training. In particular, require operators to implement the development of evidence based simulator training using objective FOQA accident and serious incident data of smoke filled cockpit environments for crew emergency training.

4.12 SR 36/2013:
The FAA in co-operation or in coordination with EASA to mandate the implementation of vision assurance devices or technology for improved pilot visibility during continuous smoke, fire, fumes in the cockpit emergencies. This could include off the shelf devices or developing mask mounted thermal imaging cameras with the capability to see through smoke/fumes with sufficient clarity to view the primary cockpit instrumentation.

4.13 SR 37/2013:
The FAA in co-operation or in coordination with EASA to develop or redesign all transport aircraft checklists pertaining to Smoke Fire Fumes events to be consistent with the Integrated, Non-alerted Smoke Fire Fumes Checklist template presented in the Royal Aeronautical Society's specialist document Smoke, Fire and Fumes in Transport Aircraft: Past History, Current Risk and Recommended Mitigations, second edition 2013, prepared by the Flight Operations Group of the Royal Aeronautical Society.

4.14 SR 38/2013:
The FAA in co-operation or in coordination with EASA to review the capability of Portable Electronic Device (PED) Electronic Flight Bags (EFB) which are used for non-alerted smoke fire fumes events to be viewed in smoke filled cockpits.

4.16 SR 40/2013:
The FAA in co-operation or in coordination with EASA to mandate a certification requirement for continuous smoke testing for flight deck smoke evaluation tests where the smoke is required to be continuously generated throughout the test for cockpit smoke clearance and develop a mitigation procedure through regulation on how to effectively manage continuous smoke in the cockpit.

4.20 SR 44/2013:
The FAA in co-operation or in coordination with EASA to require operators to implement smoke, fire, fumes training in a dedicated smoke simulator/full immersion training device allowing crews to experience actual levels of continuous smoke in a synthetic training device or other equivalent ground-based training device as an integral process in crew emergency recurrent training.

4.30 SR 54/2013:
ICAO is requested to establish a task force or working group of manufacturers, operators, and regulators to develop a concept and safety case for alternative vision assistance systems for the smoke, fire and fumes events non-normal emergency situations and provide a feasibility working paper for industry consideration on the implementation requirements and required standards.