AIRCRAFT ACCIDENT REPORT 5/2000

Air Accidents Investigation Branch

Department of the Environment, Transport and the Regions

Report on the accident to Boeing 767-322ER, N653UA at London Heathrow Airport on 9 January 1998

This investigation was carried out in accordance with
The Civil Aviation (Investigation of Air Accidents and Incidents) Regulations 1996

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ISBN 0 11 5522662

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Air Accidents Investigation Branch
Berkshire Copse Road
Aldershot
Hampshire GU11 2HH

27 September 2000

The Right Honourable John Prescott
Secretary of State for the Environment, Transport and the Regions

Sir,

I have the honour to submit the report by Dr E J Trimble, an Inspector of Air Accidents, on the circumstances of the accident to Boeing 767-322ER, N653UA, which occurred at London Heathrow Airport on 9 January 1998.

I have the honour to be
Sir
Your obedient servant

K P R Smart
Chief Inspector of Air Accidents

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Appendix G: Reproduction of AAIB Bulletin 10/97 on Incident to Boeing 747-243B, G-VGIN, on 28 April 1997 which involved wiring loom fire damage behind overhead panels in forward cabin. In addition, photographs showing drilling swarf contamination of wiring looms found on another Boeing 747, and tie wrap wire remnants on an Airbus A300.

Appendix H: Trip time requirements for thermal type circuit breakers (MS 22073) and response characteristics of circuit breakers found tripped on N653UA.

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	-	Air Accidents Investigation Branch
A	-	Amperes
AC	-	alternating current
ADP	-	Air Driven (hydraulic) Pump
AFS	-	Airport Fire Service
Al	-	aluminium
AMM	-	Aircraft Maintenance Manual
APU	-	Auxiliary Power Unit
ASB	-	Alert Service Bulletin
ATC	-	Air Traffic Control
Auto	-	Automatic
B	-	Boeing
BMS	-	Boeing Material Specification
BSD	-	backscattered electron detector
BUS	-	busbar (main electrical distribution conductor)
C		carbon
°C	-	degrees Celsius
CAA	-	Civil Aviation Authority
CB	-	circuit breaker
CO	-	carbon monoxide
COHb	-	carboxyhaemoglobin
Cu	-	copper
CVR	-	Cockpit Voice Recorder
DC	-	direct current
DFDR	-	Digital Flight Data Recorder
EDX	-	energy dispersive x-ray
E&E	-	Electronic and Equipment
EEA	-	Emergency Evacuation Alarm
EEC	-	Electronic Engine Controller
EFIS	-	Electronic Flight Information System
EICAS	-	Engine Indication and Crew Alerting System
EMI	-	electromagnetic interference
ER	-	Extended Range
ETFE	-	ethylene tetrafluoroethylene
ETOPS	-	Extended (range) Twin (engine) Operations
F		fluorine
°F	-	degrees Fahrenheit
FAA	-	Federal Aviation Administration
FAR	-	Federal Aviation Regulation
Fe	-	iron
FL	-	Flight Level
FO	-	First Officer
HCl	-	hydrogen chloride
HCN	-	hydrogen cyanide
HF	-	hydrogen fluoride
HF	-	high frequency
HMG	-	hydraulic motor generator
hrs	-	hours
IAD	-	Washington International Airport – Dulles, USA
ILS	-	Instrument Landing System
JAA	-	Joint Aviation Authorities (Europe)
km	-	kilometre(s)
kt	-	knot(s)
LATCC	-	London Area Terminal Control Centre
lb	-	pound(s)
L/E	-	leading edge
mb	-	millibar(s)
MD	-	McDonnell Douglas
MEL	-	Minimum Equipment List
Mg		magnesium
MHz	-	MegaHertz
mm	-	millimetre(s)
MM	-	Maintenance Manual
Mn		manganese
NO_2	-	nitrogen oxides
NTSB	-	National Transportation Safety Board

O_2		oxygen
OVHT	-	overheat
PA	-	Passenger Address (System)
PET	-	polyethylene terephthalate
ppm	-	parts per million
PSEU	-	Proximity Sensors Electronics Unit
PVF	-	polyvinyl fluoride
Pt		platinum
QRH	-	Quick Reference Handbook
SAS	-	Scandinavian Airlines System
SATCOM	-	satellite communication
SCA	-	Senior Cabin Attendant
SED	-	secondary electron detector
SEM	-	scanning electron microscope
SFO	-	Supernumerary First Officer
Si		silicon
SID	-	Standard Instrument Departure
SO_2	-	sulphur dioxide
SSPC	-	solid state power controller
Ti		titanium
TWA	-	Trans World Airlines
µm		micrometre
UA	-	United Airlines
UK	-	United Kingdom
USA	-	United States of America
UTC	-	Co-ordinated Universal Time
V	-	volt(s)
Vref	-	reference threshold speed
VMC	-	Visual Meteorological Conditions
VOR	-	VHF Omnidirectional Radio Range
Zn	-	zinc
ZRH	-	Zurich Airport, Switzerland

Air Accidents Investigation Branch

Aircraft Accident Report No: 5/2000 (EW/C98/1/3)

Registered Owner and Operator:	United Airlines
Aircraft Type and Model:	Boeing 767-322ER
Nationality:	United States of America
Registration:	N653UA
Place of Accident:	London Heathrow Airport
Date and Time:	9 January 1998 at 1522 hrs
	All times in this report are UTC

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) on 9 January 1998 at 1530 hrs and the investigation was initiated that afternoon. The AAIB team comprised Dr E J Trimble (Investigator in Charge), Mr P D Gilmartin (Operations), Mr P T Claiden (Engineering), Mr S W Moss (Engineering-escape slides) and Mr R J Vance (Flight Recorders).

Whilst in cruising flight near Paris during an ETOPS flight from Zurich to Washington, DC, abnormal warnings appeared on the flight deck instrumentation and circuit breakers began tripping. The commander, in consultation with the operator's maintenance control centre at London Heathrow Airport, decided to divert and land at Heathrow. The aircraft subsequently landed safely, but during the landing ground roll the right thrust reverser failed to deploy fully and smoke appeared at the forward end of the passenger cabin. As a result, the commander ordered an evacuation when the aircraft was on the taxiway, adjacent to the landing runway. During the evacuation, the right off-wing escape slide failed to deploy and several minor injuries occurred.

A confusion in communication between the aircraft and various Air Traffic Control units resulted in the Heathrow Airport Tower controller being unaware that the aircraft was landing with technical problems until the evacuation was announced, whereupon the emergency services were alerted.

The investigation identified the following causal factors:

1. The tripping of multiple circuit breakers had been caused by the occurrence of electrical arcing and associated thermal damage to a wiring loom adjacent to the aft/upper inboard corner of the forward galley chiller unit within the Electronic and Equipment (E&E) bay, with resultant thermal damage to an adjacent loom and smoke generation.

2. Prior damage to the wiring loom insulation adjacent the aft/upper corner of the chiller unit had occurred due to contact with such units during associated removal and installation; this chiller unit had been replaced on the day before the accident.

3. Aluminium alloy swarf was present within the E&E bay prior to the accident and had probably assisted the onset of arcing between adjacent damaged wires in the loom.

4. Incorrect installation of the chiller unit, with its heat exchanger exhaust fitted with a blanking plate, would have caused warm exhaust air to discharge from an alternative upper vent which was capable of blowing any aluminium swarf around the wiring looms.

5. The crew were unaware of the potentially serious arcing fire in the E&E bay during the flight due to failure of the bay smoke warning system to activate on the flight deck, because the density of smoke emitted by the arcing wiring in the bay was not apparently sufficient to be detected by the only smoke sensor, which was located in the card and rack cooling system exhaust duct.

6. The jamming of a severely worn latch, associated with the right off-wing slide compartment, prevented that escape slide from operating during the evacuation; such latches exhibited vibration induced wear on other aircraft.

Eleven safety recommendations were made during the course of this investigation.

1 Factual information

1.1 History of the flight

The aircraft was operating a scheduled passenger service, flight UA965, from Zurich (ZRH) to Washington (IAD) with 79 passengers, 3 flight deck and 10 cabin crew. The pre-flight checks and initial start up at Zurich were normal. However, while taxiing for departure from Runway 16, the cabin attendants became aware of a loud 'grinding or whirring' noise from under the floor of the centre cabin. The noise could be heard clearly in the centre and rear sections of the aircraft. The supernumerary first officer (SFO) went into the cabin to check the situation and agreed that the noise was abnormal. The commander stopped the aircraft at a remote holding area and went into the cabin to assess the situation for himself. He decided not to continue the flight and arranged with Air Traffic Control (ATC) to taxi to a remote parking stand where the aircraft was shut down and engineering assistance requested.

During the associated engineering investigation, the source of the noise was traced to the Air Driven Hydraulic Pump (ADP) unit which, together with two electrically driven pumps, powers the Centre hydraulic system. It was found that the pump was operating continuously while selected to the AUTO position when it should normally only operate at times of high hydraulic demand, ie during landing gear and/or flap operation. It was also found that the pump responded normally to OFF and ON switch selections. In consultation with the Operator's Maintenance Control and with reference to the aircraft Minimum Equipment List (MEL), it was agreed that the AUTO function could be placarded as AUTO FUNCTION INOPERATIVE, OPERATE IN 'ON' FOR TAKEOFF AND LANDING, and that the aircraft would then be fit for flight in accordance with the MEL. A limitation was also applied to the effect that the aircraft was to remain within 120 minutes single-engined flying time from suitable diversion airfields, instead of the normal 180 minutes.

The first officer (FO) was the handling pilot for the sector and remained so throughout the flight. The aircraft was again prepared for departure and a normal take off was made from Runway 16 with the ADP selected ON. After gear retraction was completed, while climbing through about 2,000 feet in the turn on the Standard Instrument Departure (SID) and before flap retraction had been completed, a 'LEADING EDGE SLAT DISAGREE' message was generated on the flight deck Engine Indication and Crew Alerting System (EICAS) with the ADP still selected to ON.

The SFO contacted the company Maintenance Control via a satellite link (SATCOM). During this conversation, it was suggested that the ADP should be selected to AUTO in order to check if this had any effect. Selecting the switch to AUTO caused the EICAS message to clear. The flaps and slats were then retracted normally and the aircraft continued its climb to Flight Level (FL) 240. When the ADP was selected to OFF, the same EICAS message reappeared; selection to ON produced the same result. The only available means of clearing the EICAS message was to set the ADP switch to AUTO.

In order to check the flap and slat operation, the aircraft was descended to FL200 and speed reduced below the flap limiting speed. There was then a temporary loss of communication via SATCOM and a high frequency (HF) link was established with Maintenance Control in order to continue the troubleshooting process.

The flaps were selected to 5 degrees using the normal system. It was confirmed that the same EICAS message was generated when the ADP switch was either ON or OFF, but it continued to clear when the switch was in the AUTO position. The flaps were then retracted normally and the crew were confident that the EICAS message regarding the Leading Edge Slat Disagree was incorrect. It was decided to select the ADP switch to OFF and continue the flight with the erroneous EICAS message displayed.

However, a further EICAS message then appeared, 'F/O Pitot Heat'. The appropriate circuit breakers were checked, then pulled and reset by the SFO. It was also noted at this time that two other circuit breakers had tripped. These were the Alternate Flap Drive Motor and the Passenger Services Outlet circuit breakers. An attempt was made to reset the latter, but it tripped again immediately. Two other circuit breakers then tripped, which the crew thought had probably been associated with the Flap Drive System (see section 2.3.3).

At this time, the FO's Electronic Flight Information System (EFIS) screens flashed momentarily, along with both Engine and System screens. Some circuit breakers were then heard to trip, which the crew thought had been another one, or two, Flap Drive System breakers (see section 2.3.3) and a First Officer Pitot Heat (Left). The flight conditions were daylight visual meteorological conditions (VMC).

At this point, the crew became concerned with the situation regarding the circuit breakers and ceased to pull or reset any more of them. After further discussions with company Maintenance Control, the commander decided to divert to land at London Heathrow Airport where there was company maintenance support. At this time, the aircraft was to the east of Paris, about 30 minutes flying time south of London. French ATC were advised of the decision to divert and the aircraft was cleared to route direct to Abbeville VOR, near the northern French coast.

However, the diversion request was not passed to the next French ATC sector and approaching Abbeville the request had to be repeated by the flight crew.

Notification was received at the London Area and Terminal Control Centre (LATCC) from Paris ATC that the aircraft was diverting into London Heathrow. At 1435 hrs, during a telephone conversation between the Paris North Sector Controller and the LATCC Dover/Lydd Chief Sector Controller, the reason stated for the diversion was that the aircraft had a 'technical emergency'. This was then described by the French controller as a 'pressurisation failure' (see section 2.1).

The aircraft came onto the LATCC Lydd Area Sector frequency (128.425 MHz) at 1444 hrs, maintaining FL200 and routing direct to the Biggin Hill VOR radio navigation beacon. The controller sought to confirm the nature of the problem with the aircraft commander, who responded by stating that the aircraft had an 'indicator problem on the flaps'. The controller confirmed with the commander that it was a straightforward 'pressurisation' problem and that no priority would be required. The commander responded that the problem was a 'straightforward flap indicator problem'.

At 1446 hrs, the controller asked if the aircraft could accept normal holding delays for Heathrow of about ten minutes. The commander responded to this by stating that 'we would like to get her on the ground as soon as we possibly could'. The controller acknowledged this by asking 'is that a priority?' to which the commander responded 'yes sir it is a priority'. The standard method of declaring an urgent or emergency situation (using the prefixes 'PAN' or 'MAYDAY' respectively) was not used.

At 1449 hrs, as the aircraft passed over Abbeville VOR in northern France, the controller confirmed his understanding of the situation by stating 'just to put the record straight we'll treat this as an emergency in order that you will get an uninterrupted approach at Heathrow'. The commander responded 'all right sir that's fine'.

By telephone, the controller informed Terminal Control and the LATCC Distress and Diversion Cell of the situation, indicating that the aircraft was being treated as an emergency in order to give it a priority approach into Heathrow, but that there was no other urgent technical reason.

There was no further discussion of the nature of the problem between the aircraft and ATC. The Heathrow Tower controller was not aware that there was any abnormality with the aircraft and the airport emergency services were not alerted to the aircraft's imminent arrival.

Radar vectors were given to position the aircraft for landing on Runway 27L. It was still daylight and the weather was good. The ADP was selected ON for the approach with normal systems being used for landing gear lowering and flap selections. A normal instrument landing system (ILS) approach was flown to a gentle touchdown using a Vref (threshold speed) of 152 kt, using full flap. The aircraft was about 2,000 lb below the maximum permitted landing weight (320,000 lb) at that time.

After touchdown, the FO selected reverse thrust. However, although the left thrust reverser deployed normally, a 'Reverser Unlocked' amber caution light illuminated for the right thrust reverser. The FO therefore cancelled reverse thrust and applied manual braking to over-ride the previously selected Autobrake 2 setting. The aircraft was slowed to taxi speed and control was passed to the commander for nosewheel steering purposes. The aircraft turned off the runway at Block 80 and moved a short distance along the taxiway. The left reverser cancelled normally, but the right 'Reverser Unlocked' caution light remained illuminated.

During the landing deceleration, the flight deck door had opened (probably due to it not having been correctly latched prior to landing); it was immediately re-closed by the SFO. After the aircraft had turned off the runway, the senior cabin attendant (SCA) came into the flight deck to inform the pilots that smoke was coming from the area of seats 1E and 1F in the forward cabin. The smell of smoke was also apparent to the SFO. The aircraft was immediately stopped on Block 89, and the commander made the decision to evacuate since he considered that there was a risk of fire.

The SFO made a Passenger Address announcement to the cabin to 'unfasten seat belts and get out of the aircraft'. The FO informed the Tower Controller of the intention to evacuate and then proceeded to read the Quick Reference Handbook (QRH) procedure. The commander shut down both engines and carried out the items from the Evacuation Checklist. The fire handles were pulled, but the extinguishers were not operated. The Auxiliary Power Unit (APU) was not in operation at the time. Only the battery remained powered after completion of the QRH procedure. The cabin staff in the centre and rear of the aircraft however commented that the Emergency Evacuation Alarm (EEA) had not been audible in those sections, although it was heard in the forward cabin. The aircraft's emergency lighting system operated normally. The flight deck crew then evacuated the aircraft using a forward cabin slide, followed by the last cabin crew member. The evacuation was reportedly completed within 90 seconds.

The Airport Fire Service (AFS) was quickly in attendance once notification of the evacuation had been given to the Tower. There was no fire and no requirement for the AFS to discharge any media. The passengers were assembled into two groups at a safe distance on either side of the aircraft and a headcount was completed. The aircraft cargo holds were inspected, but no fire was apparent.

With regard to operation of the emergency exits, all doors and slides operated normally, with the exception of the right off-wing escape slide. The associated slide compartment door would not open initially, but when finally opened the slide did not deploy. Alternative exits were used.

1.2 Injuries to persons

Several passengers suffered minor evacuation injuries resulting from slide friction burns and the effects of impacting the ground at the bottom of the slides. No passengers were required to remain in hospital overnight.

1.3 Damage to the aircraft

Within the Electronic and Equipment (E&E) bay, the aircraft had suffered arcing and heat damage to one wiring loom, associated heat damage to an adjacent loom and a localised area of heat distress to the external filter of the forward galley chiller unit. Secondary damage had occurred to circuitry on one printed circuit board associated with the thrust reverser indication system for the right engine within the Proximity Sensors Electronics Unit (PSEU). During rectification work, the Air Driven Pump (ADP) was replaced and it was later reported that the 'on-demand' solenoid in the removed unit was defective.

1.4 Other damage

All damage was restricted to the aircraft.

1.5 Personnel information

1.5.1

Commander:	Male, aged 47 years
Licence:	Airline Transport Pilot (USA)
Aircraft ratings:	Boeing 767, 757, 737, 727 NA265, Lear Jet
Simulator check:	29 June 1997
Instrument rating renewal:	29 June 1997
Line check:	1 July 1997
Medical renewal:	13 October 1997
Safety/emergency check:	30 June 1997

	Flying experience:	Total flying:	13,000 hours
		On type:	2,000 hours
		Last 90 days:	150 hours
		Last 28 days	45 hours
		Last 24 hours	2 hours
1.5.2	First officer:	Male, aged 42 years	
	Licence:	Airline Transport Pilot (USA)	
	Aircraft ratings:	Boeing 767, 757, SA-227	
	Simulator check:	21 December 1997	
	Instrument rating renewal:	21 December 1997	
	Line check:	22 December 1997	
	Medical renewal:	12 November 1997	
	Safety/emergency check:	20 December 1997	
	Flying experience:	Total flying:	9,830 hours
		On type:	2,550 hours
		Last 90 days:	65 hours
		Last 28 days	18 hours
		Last 24 hours	2 hours
1.5.3	Supernumerary first officer:	Female, aged 36 years	
	Licence:	Airline Transport Pilot (USA)	
	Aircraft ratings:	Boeing 767, 757, SD-3	
	Simulator check:	24 September 1997	
	Instrument rating renewal:	24 September 1997	
	Line check:	25 September 1997	
	Medical renewal:	6 January 1998	
	Safety/emergency check:	23 September 1997	
	Flying experience:	Total flying:	10,000 hours
		On type:	3,000 hours
		Last 90 days:	157 hours
		Last 28 days	52 hours
		Last 24 hours	9 hours

1.6 Aircraft information

1.6.1 General information

Manufacturer	Boeing Commercial Aircraft Company
Type:	Boeing 767-322ER
Aircraft Serial No:	25391
Year of Manufacture:	1992
Certificate of Registration:	Registered in the name of United Airlines with the FAA on 28 October 1992
Certificate of Airworthiness:	Standard Airworthiness Certificate, Transportation Category, issued by the FAA on 26 October 1992 and valid at time of the accident

Between 27 October 1992 and 9 January 1998, N653UA had accumulated a total of 24,743 hours over 3,776 flights.

1.6.2 Significant aircraft design features

The Boeing 767 aircraft series consists of four models: the Boeing 767-200, 767–200ER, 767-300 and 767-300ER; a 767-400ER model has recently been announced. The principal difference between the -200 and -300 models is a 21 feet 1 inch fuselage extension on the -300 aircraft. The ER designation refers to extended range aircraft, and these have increased fuel capacity and structural reinforcing to accommodate the higher gross weights. The Boeing 767 has been approved for extended range twin operations (ETOPS) which allows the aircraft, depending on airframe and engine combination, to operate up to 180 minutes single engine flying time from a suitable diversion airport. A large cargo door and ETOPS equipment are standard on these models, with equipment such as a fourth electrical generator, increased cargo hold fire suppression capability and cooling sensors for the electronic flight instrumentation system (EFIS) and a more stringent minimum equipment list (MEL).

1.6.3 Electronic and equipment bay

The electronic equipment in the E&E bay is provided with a dedicated cooling system which, in flight, normally operates in the AUTO mode. In this mode the system is configured for closed loop operation during which skin heat exchangers dispose of heat energy. The system is monitored on a flight deck overhead panel where amber lights, in conjunction with the engine indication and crew alerting system (EICAS), indicate such conditions as overheat (OVHT) and smoke (SMOKE). If smoke is detected, override (OVRD) is selected which opens a smoke clearance valve that draws air from the E&E bay, due to differential pressure (cabin to ambient), and expels the air overboard through the valve. This valve is normally open on the ground. There are no smoke detectors installed in the E&E bay of the Boeing 767-300, but one is installed in the ducted cooling system, primarily to detect smoke generated within the E1/E2 racks and various card file panels located in the bay. Some ambient air from the E&E bay is, however, entrained into this system. The smoke detector will generally signal an alarm when it registers a drop of some 12% in the transmissibility of light through this cooling air. It is understood that certification tests demonstrated that this occurred some 12 seconds after the centre aft end of the E&E bay was completely filled with high density smoke. The crew of this aircraft did not observe an associated SMOKE warning at any time during this flight. Boeing 767 aircraft have been making ETOPS flights on a regular basis since 1985.

The E&E bay on this aircraft was located immediately below the forward vestibule/forward galley area, as on most jet transport aircraft types. On the longer range versions of the Boeing 767, ie the -300 and -300ER models, food stored in the galley is refrigerated by a chiller unit housed in a rectangular shaped box some 30 inches long, 17 inches wide and 12 inches in height. This unit weighed 86 lb. with its centre of gravity biased towards its aft end, as installed. The chiller was located in the E&E bay on a simple support structure mounted from the right side of the lower fuselage structure. Space is limited in this part of the aircraft by the physical dimensions of the airframe, with equipment racks, electrical distribution panels and wiring looms allowing only minimal access passageways for maintenance personnel. Suspended from the roof of the bay in the area of the chiller were seven main wiring looms, aligned mostly in the fore and aft direction, several of which divided and re-formed with wires from adjacent looms to form other looms which ran down close to, and roughly parallel with, the chiller aft face as shown in Appendix B, Figure B-1.

1.6.4 Off-wing escape slide system

1.6.4.1 Slide system operation

A diagram of the off-wing escape slide system is shown in Appendix F-1.

The off-wing inflatable escape slides allow passengers exiting through the over–wing escape hatches to reach the ground from the wing trailing edge with minimal risk. Each off-wing escape slide is stored, when not deployed, in a compartment located in the wing/fuselage fairing above the wing and below the window belt. This compartment is closed by an over-wing door, hinged about its lower edge. When operated, an inflatable chute deploys and covers the inboard spoiler (No 6 left wing, No 7 right wing) at the trailing edge and from where it provides an inflated slide to the ground.

The slide is inflated from a high pressure gas bottle located below the wing in the aft wing-to-body fairing, and is activated by the opening action of the over-wing compartment door which pulls a cable connected to the inflation cylinder regulator. The door is powered open by two actuators which are operated by expanding gas from two pyrotechnic squibs. These are fired mechanically at the completion of the full travel of several connecting rods, arranged in series, which interconnect the four door latches located along the top edge of the door. This motion is transmitted through a system of bellcranks to the squib firing pins in the door opening actuators.

These connecting rods are operated by a latch-opening actuator, powered from an electrically fired squib, which pulls on an integrator mechanism which in turn pulls on the connecting rods, thus releasing the latches. The integrator also provides the means to open the slide door for maintenance. By using a socket wrench to turn a cam on the integrator, sufficient travel of the latch rods should be achieved to unlock the door without firing the squibs. It is also necessary to disconnect the cable to the slide gas bottle to prevent this discharging as the door opens. The latch-opening actuator squib on each side is triggered when either of the two over-wing escape hatches on the same side of the aircraft are opened by operation of the emergency PULL handles from inside the aircraft. This causes the auto-arm and auto-fire switches in the hatch frame to be moved to FIRE. However, as the hatch is opened electrical signals are first sent to the spoiler DOWN relays, to retract the inboard spoiler, followed some 2 seconds later by the signal to the latch-opening actuator squib. Should hydraulic power not be available to retract the spoiler, then another squib located in a separate 'spoiler down' actuator is fired. This actuator then physically retracts the inboard spoiler to ensure that the escape slide can deploy without obstruction.

Electrical power for these squibs is supplied by dedicated emergency batteries, one for each off-wing slide, which are continually charged by the aircraft's electrical system. During normal operation, the left battery provides power to the left escape system, and the right battery to the right system. If the BACKUP ARM and BACKUP FIRE switches (located within the hatch frame) are used to deploy the escape slide, then the opposite side emergency battery is used to fire the squib.

1.6.4.2 Door latch description

The design of the off-wing escape slide door latches is such that a set of jaws, which are spring loaded closed and contained within a housing that is attached to the aircraft structure, are arranged to grip an appropriately shaped fitting mounted on the door (see diagram of a latch at Appendix F-2). The latch system is designed so that, when closing and locking the door, it simultaneously grips the fitting and pulls it inboard, ensuring that the door is a tight fit against its frame. A flat horizontally oriented cam plate containing a shaped slot runs through the centre of both the housing and jaws, and engages with a vertically oriented stepped pin which forms the pivot about which the jaws open and close. The extremities of this pin are of a smaller diameter than the central section, and engage with linear slots in the upper and lower faces of the latch housing. The end faces of the larger diameter section abut the inside faces of the housing.

Horizontal translation of the cam plates in the door opening sense, causes the jaws assembly to move outboard under the influence of the pin in the cam plate. As it does so, ramp profiles on the inner edges of the jaws abut against one of two vertical tubes which hold the housing together and through which the latch is attached by bolts to the aircraft structure. This has the effect of opening the jaws against the spring, thereby releasing the door mounted fitting. As this occurs, the pivot pin extremities slide along the slots in the housing. The four latches are inter-linked by control rods such that movement of the integrator, either manually for maintenance, or by the latch opening actuator in an emergency situation, causes all four to move together.

1.6.5 Recent maintenance

Maintenance records showed that the forward chiller unit in N653UA was replaced on the day before the accident during a stop-over at Washington Dulles, DC. The method by which the chiller should have been replaced was detailed in Section 25-33-01 of the Boeing 767-300 Maintenance Manual (MM), as shown at Appendix C. This required the operation to be carried out by two engineers using a 'fishpole' hoist and a temporary ramp in the E&E bay, so that the replacement chiller could be slid onto its support structure with greater ease in the confined working environment of the bay. One person was required to use the hoist to raise the chiller into the bay whilst the other positioned the unit onto the ramp and slid it into place. Also contained within the MM were warnings to the effect that the chiller weighed 86 lb, that care should be taken to avoid personal injury, and that immediately below the chiller was the crew emergency oxygen bottle with the attendant risk of an explosion should this be contaminated with oil or other flammable materials. No specific warnings were included relating to the possibility of wiring loom damage.

1.7 Meteorological information

The aircraft landed at 1522 hrs. The Heathrow 1520 hrs meteorological observation recorded a surface wind from 200° at 9 kt, visibility 40 km, scattered cloud base 15,000 feet, temperature +14°C, dew point +8°C with a mean sea level pressure 1022 mb.

1.8 Aids to navigation

Not relevant.

1.9 Communications

Transcripts of radio transmissions between the aircraft and ATC were available for the final 45 minutes of the flight, including the evacuation. Transcripts were also available for the telephone conversations between the various ATC units that were involved in controlling the aircraft's arrival into London Heathrow.

1.10 Aerodrome information

Runway 27L was used for landing. The full landing distance of 3,658 metres was available and there were no relevant unserviceabilities.

1.11 Flight recorders

The aircraft was fitted with a 25 hour duration digital flight data recorder (DFDR), which recorded almost 300 parameters, and a 30 minute duration cockpit voice recorder (CVR). Both recorders were fully serviceable and the information recovered was used to assist in the reconstruction of the history of the flight and with the analysis of the crew response to events.

Figure A-1 shows a plot of the time histories of the DFDR parameters relevant to the investigation. The important features of the plot are the series of slat disagree warnings and the cycling of the ADP that began almost immediately after take off and which caused the crew to discontinue the climb, reduce altitude to FL 200 and then to recycle the flaps. Despite the number of recorded parameters, the DFDR contained no information that was of assistance in determining the cause, or the time of initiation, of the electrical failure.

The CVR contained a time history of the flight deck audio, beginning prior to the aircraft's descent into Heathrow Airport. In addition to providing information on the crew's response to the in-flight situation and on the emergency evacuation of the passengers after landing, the recorded background noise levels on the four CVR tracks increased as the recording progressed. The cause of the increased background noise was consistent with the electrical disturbance that occurred as a result of the wiring fire.

1.12 Aircraft recovery and examination

1.12.1 Actions taken before AAIB arrival at Heathrow Airport

The aircraft came to a halt in Block 89 and was obstructing one of the normal routes for aircraft clearing from Runway 27L after landing. At the request of the Airfield Fire Service, ground power was applied to the aircraft by the operator's maintenance personnel so that the cargo doors could be powered open to check for evidence of fire, as no adapter was available to manually open these doors. However no evidence of fire was found within the cargo compartments and the doors were subsequently re-closed. At about this time it was noticed that, with the battery still connected, sparks were emanating from a wiring loom within the forward E&E bay. All electrical power was promptly removed from the aircraft, but fire suppression was not required and so no extinguisher media were used. Later analysis of the DFDR showed ground power to have been applied for some 6 minutes, and this also confirmed that no further power applications were made until after the arrival of the AAIB at Heathrow Airport.

1.12.2 Subsequent actions

The aircraft was initially examined by the AAIB where it had stopped, approximately 1 hour after landing and after the battery had been disconnected. In order to clear the aircraft manoeuvring area, it was agreed that the aircraft should be towed to a remote stand where further initial examination could take place. During this period, ground power was inadvertently again connected to the aircraft by maintenance personnel seeking to open the cargo doors in order to remove baggage containers. Hot spots and stable arcing were observed by AAIB personnel for several seconds in the damaged section of the wiring loom in the E&E bay at this time. Electrical power was then quickly removed and, as far as could be ascertained, no additional circuit breakers (CB's) appeared to have been tripped by this application of power. After cargo and personal possessions had been removed, the aircraft was towed to the operator's maintenance area where the detailed examination, and subsequent repair, took place. The CB's found tripped at this time are listed below:

Location	Circuit Breaker/Part No	Rating
Fwd Equipment Ctr P33 panel	Bus Sect 2 Gnd Service BACC18X20	10A
Flt Deck Overhead panel P11	T/R Ind BACC18Z1R R Eng T/R Ind Altn BACC18Z1R	1A 1A
Flt Deck P6-4 Panel	Pitot Heat - L Aux Phase C BACC18Z5R Pitot Heat - F/O Phase B BACC18Z5R Passenger Service Outlet BACC18AC10 Altn Slat Outbd Pwr BACC18AC10 Altn Flap Pwr BACC18AE15 Altn Slat I/B Pwr BACC18AC3 R TRU 10-60806-1020	5A 5A 10A 10A 15A 3A 20A

During repairs to the aircraft, all CBs were judged to be serviceable and remained fitted to the aircraft.

1.12.3 Detailed aircraft examination

1.12.3.1 General

It was apparent that a failure had occurred within one of the looms adjacent to the inboard side of the aft face of the chiller unit and that the immediately adjacent loom exhibited evidence of heat distress. At the failure location, these looms were some 2.95 inches and 3.25 inches clear of the chiller aft face, at their closest point as installed. In addition, the thin foam plastic filter covering the chiller heat exchanger matrix facing these looms exhibited a small localised region of heat damage. There was evidence of copper spatter on this filter in this area and locally on the chiller top surface directly above. The location of this damage was several inches outboard from the loom containing the failure, but no evidence was observed to indicate that any wire had arced onto the chiller. No other areas of thermal distress were apparent in the E&E bay.

1.12.3.2 E&E bay examination

The condition of the E&E bay was examined with specific attention to the overall condition of the wiring looms and general cleanliness. Within the limitations of a simple visual non-intrusive examination, the condition of all accessible looms appeared to be generally satisfactory in that no evidence was found of wire insulation damage resulting directly from cable ties or their attachments to the airframe. Several wires were discovered, however, with minor 'nicks' in their outer insulation layer in areas that could be considered vulnerable to damage during maintenance activities. All looms appeared to be clean and free from dirt and dust deposits or general grime, as were several other Boeing 767 aircraft examined of a similar calendar age which belonged to a different operator.

Removal of the light blue painted chiller allowed access for inspection. This indicated that the primary event appeared to have occurred within one loom and that arcing and burning of wires around the inner surface of the curved section of this loom had occurred over a length of some 6 inches, as shown in Figure B-2. There was also copious evidence of copper spatter from the failed wires on the filter, on other wires and also on airframe insulation blankets below this area. A general examination of the unaffected wiring looms above and around the chiller location revealed a few minor nicks and areas of insulation abrasion but in one area, on a loom directly outboard of the failed loom, the insulation of three wires had been sufficiently damaged to expose their underlying insulation. The surface of an adjacent glass fibre sleeve also showed signs of damage in this area. The damage, the location of which coincided with the plane of the chiller top surface, is illustrated in Figure B-3 where it may be clearly seen to have been caused by 'mechanical' rather than 'electrical' means.

1.12.3.3 Chiller examination

Examination of the chiller unit revealed no evidence of damage, other than that described above. It was determined, however, that it had been wrongly configured for the forward galley position. When correctly installed the chiller interfaces with two air ducts, one at the forward end where a split duct circulates chilled air around the stored food in the galley, and one at its outboard side where warm air from the condenser heat exchanger is ducted away from the E&E bay and into the region above the forward cargo bay. To facilitate the installation of the chiller at the rear galley position, and on other aircraft types, an alternative warm air exit is provided on the top surface of the chiller box which in this forward installation should have been closed off with a blanking plate. This blanking plate was capable of sealing either aperture. With the chiller removed, it was evident that this plate incorrectly sealed off the side exit and that the top exit was open to the E&E bay. Because of this error in blanking plate position, any smoke drawn through the heat exchanger from the overheated filter and wire insulation in the failed section of the loom, together with the warmed air, would have been recirculated back into the bay. Several placards were present on the chiller box which warned that damage could be caused to the chiller unit if the blanking plate was incorrectly fitted for any particular installation.

Tests were subsequently carried out on an identical chiller in another of this operator's Boeing 767 aircraft with the blanking plate incorrectly fitted in the same manner as that found on N653UA. In this configuration the upwards blast of the condenser exhaust air impinged on the underside of the floor panels, floor support structure and several wiring looms, and it was apparent that a proportion of this flow was re-circulated through the inlet of the condenser heat exchanger. It was demonstrated that the velocity of the airflow was quite sufficient to disturb small items of debris lying loose amongst the cabin floor structure, such as drilling swarf, and that it was possible for such debris to be carried along by the airflow.

Information was sought from the aircraft manufacturer regarding the likely effects that an incorrectly fitted chiller blanking plate would have in service. The associated response is summarised as follows:

> Air is ingested into the unit at ambient temperature and flows through the condenser heat exchanger and over the fan motor and compressor. As it is expelled, it typically experiences a temperature rise of 25°F. The chiller manufacturers' rate their equipment to perform to specification up to 85°F and at a reduced capacity up to 110°F. Although it will still operate up to temperatures approaching 130°F, the efficiency of the heat exchange through the condenser is greatly reduced. The chillers have overheat protection in the compressors that will cause the system to shut down at these higher temperatures. The exact temperature limit is dependant on refrigeration system load. The heaviest duty/high ambient temperature periods are limited to ground operations and a short period following take-off. The worst case temperature of condenser discharge air is about 155°F however in the cruise it is usually in the region of 90°F.

The blue painted cover for the chiller unit was made from a single sheet of aluminium folded to form the top and two sides of the box, and its attachment flanges. A natural consequence of this construction was that where the top corner folds intersected, as illustrated in Figures B-4a and B-4c, it was necessary for a small corner bend relief hole to be drilled (and de-burred) in this location to prevent tearing or cracking at what would have been an otherwise impossibly tight bend radius. The general design rule for the diameter of such corner relief holes was that they should be three times the thickness of the associated sheet material. Examination of these corners on the chiller unit, which appeared to conform to this design standard, revealed an understandable level of handling damage, with small areas of missing paint and bruised edges on the aluminium sheet. However, one edge of the sheet at the upper/aft outboard corner was 'burred' in such a way as to form a sharp edge, as illustrated in Figure B-4b. It was also evident that this edge would have been 'leading' whenever the chiller had been moved in an outboard direction, such as when being installed. It was also evident that the position of the damaged insulation on the wires illustrated in Figure B-3 was adjacent to this corner of the chiller when in the installed position.

Evidence of similar mechanical damage of wire insulation to that on N653UA was found on other Boeing 767 aircraft examined; in one case on a UK registered aircraft smears of light blue paint were observed across several wires adjacent to a wire with such insulation damage.

1.12.3.4 Damaged wires

In order to expedite the required wiring repairs on N653UA and the return of the aircraft to service it was necessary to remove the damaged section of loom, but without cutting wires that would not otherwise require repair. In addition, in the interests of the subsequent detailed examination it was considered necessary to retain the damaged section of loom intact and with the minimum of disturbance possible. To this end a cradle, approximately twice as long as the damaged section of loom, was constructed from welding wire shaped to match the bend profile of the loom and fitted with saddles placed at certain points to match the cross section of the loom. Some 38 wires were selected from the failed loom and tied to the cradle at each end before being cut. Six wires within the failed section of loom were discontinuous and exhibited evidence of arcing damage.

Repairs to the wiring in this part of the aircraft were completed by the operator at Heathrow over a period of some nine days. During this process it became apparent that a group of wires, which were segregated into a discrete bundle within a flexible woven glass fibre sleeve and which was adjacent to the arced/burnt wires, had been very effectively protected by the sleeve material from the damaging high temperatures which had been generated by the electrical arcing. These wires exhibited severe heat distress to their insulation, but there were no signs of exposed conductors or arcing, and all had continued to function as wires, at least for the period of this particular flight. Lists of all the wires removed from the two looms and of those which required repair are included in Appendix E, which refers to wire type and associated system with comments on wire condition.

After the repairs had been completed and the electrical systems re-powered, several EICAS messages relating to the right engine thrust reverser could not be cleared. Subsequently, heat damage to several tracks and components was discovered on a circuit board within the proximity sensors electronics unit (PSEU). A visual examination of this card (Part No 8-535-03, s/n 2830) carried out by the manufacturer showed that the circuitry which supplied power to the right engine thrust reverser indication system had been damaged. Replacement of this board cleared these messages.

1.12.3.5 Air driven pump (ADP)

Subsequent to the wiring repairs and replacement of the damaged card in the PSEU the EICAS message 'L/E SLAT DISAGREE' was no longer present. The ADP, however, still failed to operate correctly in AUTO but did function satisfactorily when selected to ON or OFF. After attempted trouble shooting, the ADP was replaced and, with the replacement unit installed, the system functioned correctly. A problem was later reportedly identified on this pump with the 'on-demand' solenoid, which was defective, and which would have allowed the pump to run continuously as experienced both before the aircraft took off and after the post accident repairs had been completed.

1.12.3.6 Conductive debris

Examination of the area below the chiller, and generally throughout the E&E bay, revealed the presence of debris in the form of small coins, stainless steel locking wire, strands of copper wire, plastic cable ties and, in one confined area close below the chiller, a puddle of water approximately 1 inch deep on top of an insulation blanket.

All other areas inspected in the bay showed no apparent signs of present or past contamination by spillage of liquids or condensation, although the general condition of the insulation blanket material suggested that water had been present for a long time. The chiller was fitted with a water/condensation drain which emerged from the chiller lower surface towards its front end. The condensate was collected in a small trough mounted on the chiller support structure, which then drained overboard through a plastic tube. It was noted, however, that the trough was located close to the same frame station as the pool of water.

Further metallic debris was also found in the form of small curled aluminium swarf, typical of that produced from the drilling of holes. Samples of this swarf were found not only in the lower parts of the airframe, but in areas above the chiller, on ledges formed by the structure of the airframe, in the roof of the bay and on top of, and within, some electrical distribution boxes. Examples of this debris are shown in Figure B-5, together with an elemental spectrum of a typical piece of such swarf derived from a scanning electron microscope (SEM) examination. (This and other SEM tests are described later in section 1.12.3.8).

1.12.3.7 Wiring loom examination

Owing to the fragile nature of the failed section of loom it was initially examined in-situ, with the minimum of disturbance, in order to identify each failed and damaged wire by type and system. The configuration of the loom and location of the failed area with respect to the chiller were also documented at this time.

A sketch of the cross-section of the loom is shown in Figure B-2, along with photographs of the damaged loom before disturbance, where it may be seen that it was comprised of individual wires, small bundles of wires laced together and two major bundles contained within separate woven glass fibre sheaths. Apart from separating discrete groups of wires within the loom, it was evident that these sheaths conferred an extra measure of physical protection to the wire group. It was also evident that many of the individual wires around the inside surface of the curved section of this loom had suffered various failures over a length of some 4 to 5 inches, and that two main areas were present where arcing of conductors had taken place. The apparently more extreme arcing event was located towards the lower limit of the damage, some 2 to 3 inches below the level of the chiller top surface, where several 22 gauge wires terminated at the same point with molten and re-solidified ends to their conductors. This was coincident with a 'hot spot' on the surface of the woven glass fibre sleeve embedded within the loom and to which globular deposits of copper had adhered. This location was also co–incident with a green plastic cable tie, the remnants of which had remained attached to the loom by several melted and re-solidified ends.

For a distance of approximately 2 inches above this point, many of the affected smaller gauge wires were missing, as was the insulation of several heavier 12 gauge wires spanning this gap. It was evident that the exposed conductor of one of these wires was continuous (identified as W272-10-12 115V AC ground service bus) and this had been melted and re-solidified into a 'solid bar' in this region. There was a noticeable difference in the arrangement of the wire ends at the upper region of the failed section, in that most had terminated at different locations.

1.12.3.8 Laboratory examination of the damaged loom

The primary aim of the laboratory examination of the failed loom was to identify the likely initiation point and cause of the electrical failure. This was attempted by searching for evidence of pre-existing physical damage to the wire insulation, and for traces of material(s) not normally used in the construction of the wires and which may have contributed to, or possibly initiated, the failure. This was performed partly by using optical microscopy, but mostly by the use of SEM with

Energy Dispersive X-ray (EDX) analysis, some of the results of which are illustrated in Appendix D.

Note: Many of the SEM micrographs were taken using the Backscattered Electron Detector (BSD), which images regions of varying atomic weights as differences in grey level with heavier elements appearing brighter than lighter elements. Such images have the notation 'Detector = QBSD' in the datazone. Other SEM micrographs were taken using the Secondary Electron (SE) detector, which gives a high resolution image, showing good topography ; these images have the notation 'Detector = SE1' in the datazone. X-ray element maps are presented of some areas and show the distribution of selected elements across the imaged area.

Most of the wire samples were taken from the area in the vicinity of the severely damaged section of the loom, and all samples examined are listed below:

Description of Sample	Location	Type	Sample No.
Debris sucked up in vacuum cleaner	Area under failure site - 20 ins below	Various types of particulate material	1
Damaged filter	Aft face of chiller unit	Foam plastic with adherent particles	2
Particles picked up directly onto SEM stubs	Centre of fire damaged area on chiller	Particulate material	3
Water sample	Liquid from fuselage near chiller unit	Water with impurities	4
Blue paint fragment on metal chip	Sample from chiller unit lid	Used for purposes of comparison	5
Wire sheath material	Taken from damaged section of loom	Woven glass plus adherent particles	6
General debris	Below damaged loom, below floor panel	Assorted debris including swarf, locking wire and coins	7
General debris	Taken from shelf below damaged loom prior to vacuuming	Assorted debris including visible copper globules	8
Sections of three wires	Outboard, non fire damaged loom	Physically damaged insulation, ref. Figure B-3	9
Clamp	Immediately above damaged section of loom	Heat affected	10
Cradle containing damaged wires	Burnt/arced section of loom	Originally, a bundle of insulated wires held in place on a skeletal frame. Selected wires later removed for detailed examination	11

In the following text, individual particles examined are referred to by the above general sample number, followed by an identification number within that sample.

Examination of particulate matter, samples 1, 3, 7 and 8:

From all the debris recovered within the E&E bay on and around the galley chiller, selected items were individually examined and analysed in the SEM. Particles 1/1 to 1/10 were individually examined and analysed, as were many of the random groups of smaller particles. All globular material found was copper, sometimes with glass. No traces of globular aluminium were found, but aluminium was present in the form of aluminium alloy swarf or shavings, identified here as particles 1/3, 1/4, 1/8 and 1/10. SEM micrographs and EDX spectra of particles 1/8 and 1/10, which were typical of such aluminium debris found in samples 1, 7 and 8 but which contained different minority elements, are shown in Figure D-1. The EDX analyses of these aluminium particles indicated that they fell into two groups when characterised by their copper (Cu) and zinc (Zn) minority metal count. Amongst the debris immediately beneath the failed section of loom was a piece of copper conductor, melted at both ends and with an attached globule from an adjacent conductor. This is shown in Figure D-2.

Examination of water, sample 4:

The conductivity of the water was measured and the value obtained was 60 μS/cm (micro-Siemens/cm). This value was more than an order of magnitude less than that used in conventional wet arc tracking tests, ref: IEC 112, and was therefore considered to be too low to have initiated a significant leakage current, should it have been wetting wires in the damaged region prior to the loom failure. Its purity was consistent with condensate. This sample was filtered to recover impurities seen in suspension and various particles were examined and analysed. One small aluminium particle was found, but this was not spherical in form and therefore did not appear to have been involved in the electrical failure.

Examination of material from the chiller box cover, sample 5:

A fragment of aluminium from the chiller box was analysed to provide comparison spectra with materials found elsewhere; a typical EDX spectrum is shown in Figure D-3a. It can be seen from this spectrum that the peak due to Cu was very small and there was no evidence of Zn. When these EDX spectra from the box material were analysed, the contribution from the Cu and Zn was below 0.1% of the total count, and so each was registered as zero.

Examination of foam filter and glass sheath adjacent to electrical failure, samples 2 and 6:

Several areas from both the foam filter and the glass fibre sheath were analysed, and both were found to be liberally spattered with copper globules. No aluminium or globules of other materials were found on either of the two samples.

Examination of wires from mechanically damaged outboard loom, sample 9:

All three sections of wire examined showed areas of mechanical damage, with scuffing of the insulation in varying degrees of severity. In several cases, aluminium fragments were embedded in the scuffed regions, sometimes together with glass fibre. An area including such debris is shown in Figure D-3b, together with an EDX spectrum of the fragment identified, from which it may be seen that the peak due to Cu is very small and that Zn was not detected.

Examination of wires from the failed section of loom, sample 11:

The ends of the broken conductors were smooth and rounded, and were characteristic of the copper having been in a molten condition. The only evident source of heat capable of producing temperatures in excess of the 1083°C required to melt copper, and the general characteristics of the failed section, indicated that electrical arcing between wire conductors had occurred. Using a low powered optical microscope, two wires were found with mechanical damage similar to, but more extensive than, that exhibited by the three wires removed from the outboard loom (sample 9). Here the insulation had been physically damaged, but had not apparently been involved in an arcing event. Two examples of this are shown in Figure D-4. The damaged area extended some 2 cm along each wire and was approximately 1 cm away from the upper extremity of the blackened region. Each wire had several marks on the insulation, and one mark on each wire appeared to be carbonised. One of these wires was identified as W782-9-24 (EEC data bus), and these carbonised areas on both wires are illustrated in Figure D-5. The nature of this damage suggested that it had resulted from impingement by hot/molten copper onto the insulation rather than by any arcing events.

Several areas of many individual wires taken from the severely damaged and blackened area of the loom (sample 11) were searched for evidence of conducting material, other than copper, that might have been involved in the electrical arcing. In total, fifteen areas of this sample were examined in detail and several areas of these wires had aluminium-rich particles present. Some of these were roughly spherical in form and their general appearance suggested that this material had been in a molten state before solidifying into the observed form. Analysis of the surface of these particles indicated the presence of fluorine, most likely indicative of a reaction with hydrogen fluoride given off when the ethylene tetraflouroethylene (ETFE) insulation material had been heated to a high temperature.

A summary of the significant SEM and EDX results from all the wire samples examined, with associated Figure numbers, is included in the table below:

Loom	Sample	Wire No.	SEM/EDX results	Fig. No
Inboard/failed	11/1	W 782-9-24	Heat and mechanical damage	D-4 and D-5
Inboard/failed	11/2	not visible	Heat and mechanical damage	D-4 and D-5
Inboard/failure	11/3	W 272-14-8	No Al or Fe found	Not shown
Inboard/failure	11/4	W 272-9-20	No Al or Fe found	Not shown
Inboard/failure	11/5	W 254-1-14	Al sphere on insulation	D-6
Inboard/failure	11/6	W 272-8-20	No Al or Fe found	Not shown
Inboard/failure	11/7	W 272-7-20	Al and Cu 'dusting'	D-7a
Inboard/failure	11/8 (two wires)	W 272-10-12 W 272-3-14	Al plus F nodules No Al or Fe found	D-7b Not shown
Inboard/failure	11/9 (bundle)	W 272-2-14 W 272-1-14	Al <u>and Cu</u> spheres on insulation No Al or Fe on insulation	D-8 Not shown
Outboard	9/1	W264-177-18	Mechanical damage	Not shown
Outboard	9/2	W 264-87-18	Mechanical Damage	Not shown
Outboard	9/3	W 264-86-18	Physical damage, embedded aluminium fragment	D-3b

The EDX analyses results on the globular aluminium particles from the damaged wires from the inboard loom, on the aluminium fragments embedded in the mechanically damaged wires in the outboard loom, and on a sample of aluminium from the chiller box were compared with minority metals spectra from the various aluminium alloy particles found in the samples of collected debris. A summary of this comparison is shown in Figure D-9.

A complete list of all the wires affected is presented in Appendix E, in ATA Chapter number order, together with details on the wire type, unique wire identification number, associated system, the type of repair effected and their separation code. In total, 112 individual cables (98 wires) were repaired in the two looms, of which 20 were assessed as acceptable with only discoloured insulation, 10 of which required insulation repairs, 41 of which required wire to wire splice repairs and 40 of which required wire splice-to-pin (plug/socket) repairs.

1.12.4 Right off-wing escape exit system examination

It was evident upon initial examination of the right off-wing escape slide system that its associated compartment door had not opened, despite removal of the forward right over-wing escape hatch. Further examination revealed that although the pyrotechnic squib in the right latch-opening actuator had fired, the piston in that actuator had only partially retracted. This had resulted in the integrator mechanism being neither fully in the 'latches-locked', nor in the 'latches -unlocked' condition.

After making the system safe, initial attempts to manually open the slide compartment door by turning the (maintenance) cam on the integrator failed despite high levels of torque being applied. However removal of a wing fairing panel above the door allowed some examination of the latch mechanism. This showed that all four latches were only partially in the released condition and that further movement of the latch control rods was not possible. The door was eventually opened by prying apart the jaws of each latch in turn, but it was noticed that one latch in particular was very stiff to operate.

This was the third latch from the front (No 3). It could be seen that this latch exhibited significant corrosion deposits (rust) inside the housing assembly. All latches were essentially identical and bore the Hartwell part number 83014/H2052-13.

Examination of the remainder of the system revealed no further significant defects, although there was a difference in the visual appearance of the latch–operating actuator squibs from the left and right side of the aircraft. The degree of outward petalling of the diaphragm on the squib from the right actuator was markedly less than that on the left squib, which raised concerns about its ability to have properly stroked the latch-opening actuator. However, these spent squibs were subsequently examined by the aircraft manufacturer and it was reported that both appeared to have operated normally.

1.12.4.1 Right door latch No 3 examination

After removal from the aircraft, the No 3 latch was examined in detail. This revealed that the latch had effectively jammed at about its mid-travel position as a result of the stepped pivot pin, which normally slides along the slots in the housing, having become displaced as illustrated in the photograph at Appendix F–2. This had occurred because, in the closed and locked position, the major diameter of the steel pin had worn or fretted into the aluminium material of the lower housing, effectively forming a recess in its inner surface. This in turn had allowed the pin to displace progressively in a downward sense. The depth of wear was such that the smaller diameter section at the top of the pin had been able to disengage from its slot and slide under the inner surface of the upper housing, thus canting over and trapping the pin. This is illustrated in Figure F-3.

In this condition, operation of the latch had been restricted by the lower end of the large diameter section of the pin jamming against the lower housing material. Since the four latches were linked in series by their connecting rods, all four latches therefore effectively jammed. Evidence of fretting was also present around the end holes in the cam plate of the No 3 latch through which the connecting rods were attached. Latches Nos 1, 2 and 4 from both sides of the aircraft showed no evidence of wear of the pin against the housing.

Strip examination of the No 3 latch from the left side however did show similar, but much less advanced, wear of the housing by the pin in the locked position. A steel 'target' plate for the compartment door closed/open proximity sensor was mounted on the connecting rod between latches Nos 2 and 3.

Information provided by the operator and manufacturer indicated a history of problems and failures associated with the off-wing slide door latches on Boeing 767 aircraft with this slide installed. The associated defects included worn or broken-out holes in the cam plate, broken connecting rods and pins displaced in the housings. The aircraft manufacturer had issued Boeing Alert Service Bulletin (ASB) No.767-25 A 0174, dated 18 February 1993, which called for latch replacement with a modified assembly. The subject aircraft, however, had this modification incorporated at build.

All five of the latches removed by the AAIB from N653UA, and the remaining three removed by the operator, were forwarded for examination at the manufacturer's laboratories and all eight of the latches on the subject aircraft were replaced before it was released back to service.

1.13 Medical and pathological information

Not applicable.

1.14 Fire

Apart from the burnt wiring and associated effects on the chiller and some insulating blanket material in E&E bay, there was no other fire damage.

1.15 Survival aspects

Apart from minor slide friction burn injuries which occurred to several passengers during the evacuation, there were no notable injuries sustained by the passengers. The failure of the right off-wing slide to deploy did not impede the evacuation in this particular accident and it was reportedly completed within 90 seconds.

1.16 Tests and research

Apart from the laboratory tests conducted on the wiring and other material from the E&E bay (section 1.12.3.8), no other tests or research were undertaken.

1.17 Organisational and management information

Not applicable.

1.18 Additional information

1.18.1 Recent replacement of chiller unit

On 23 February 1998, two mechanics from the aircraft operator who had replaced the forward chiller unit on N653UA on 8 January 1998, the day prior to the accident, were interviewed on behalf of the AAIB by a representative of the National Transportation Safety Board (NTSB).

The information gained from this interview revealed that neither mechanic had previously replaced a forward galley chiller unit on a Boeing 767 aircraft, although one had replaced a few chiller units on other aircraft types, all of which had been located in the passenger cabin and not in the aircraft E&E bays. After they had referred to the MM instructions, they had carried out the task but had decided to install the chiller without the use of the recommended hoist and ramp. The mechanics stated they were unsure whether the latter equipment was available, and other mechanics had previously indicated to them that within the confined space of the E&E bay it was difficult to use this equipment.

In the event, one of the mechanics had helped to pass the chiller unit up into the bay and the other had lifted it into place on the support framework. After this had been done, the bolt holes between the chiller base and framework had not aligned and, in the opinion of one of the mechanics, this misalignment may have been due to obstruction by wires. The chiller unit was then moved forward and outboard in order to align the holes. After completing the installation, the mechanics stated that the wires around the chiller had been inspected using a flashlight. The operation reportedly took between 45 minutes and 1 hour, and neither mechanic reported being aware of any time pressures to complete the task.

1.18.2 Wiring installation and specifications

Wires in the Boeing 767 aircraft are routed through the airframe generally in discrete bundles variously referred to as looms, or harnesses. The wiring installation was designed to comply with the manufacturer's and industry standards which include model unique wiring installation requirements that satisfy Federal Aviation Regulations (FAR) Part 25. Installed wires are required to conform to codes of separation in order to enhance system survivability. These separation codes are intended to ensure that the critical functions of redundant power systems and/or flight essential systems are preserved by preventing all redundant channels of the same system from being damaged by a single threat event. The effects of electrical wiring faults are thus intended to be minimised, with isolation of fault damage and prevention of damage propagation between redundant systems. Wiring separation is also applied on the grounds of electromagnetic interference (EMI) compatibility. The associated wire separation categories defined by the manufacturer are as follows:

Functional (power source) separation category:

Code	Definition
A	APU control and APU generator control and protection
C	Circuits associated with centre Bus and 'C' redundant systems
H	Circuits associated with ETOPS hydraulic motor generator (HMG powered)
L	Circuits associated with Left power Bus
N	Non redundant signal and power circuits with limits (neutral circuits)
R	Circuits associated with Right power Bus
S	Standby Circuits - Circuits powered by the main/APU battery system (Hot battery bus, battery bus, and AC standby bus) and control

EMI Separation Category:

Code	Definition
1	Source of interference circuits and equipment
2	Passive circuits and equipment
3	Sensitive circuits (EMI susceptible and equipment)

Redundancy Separation Category:

A	Group 'A' - Separate from all 'B' or 'C' etc. groups of same category
B	Group 'B' - Separate from all 'C' or 'A' etc. groups of same category
C	Group 'C' - Separate from all 'A' or 'B' etc groups of same category
Etc.	As many characters as necessary to achieve separation, but avoiding repeating letters used for functional (power source) separation

Wiring bundles associated with the above separation categories are identified by using different coloured tying materials, such as 'tie wraps' or lacing tape, in accordance with the codes listed below:

Wire Bundle Code	Tie or wire colour
A	Orange
C	Yellow
H	Purple
L	Red
N	White
R	Green
S	Blue

Wiring with different categories are separated from each other by using the following methods.

Separation by space (preferred method):

In pressurised areas of the aircraft, all wire bundles with functional separation categories L, R, C, A, H or S are separated in space by a minimum of 0.25 inch between the categories. For the same categories in unpressurised areas, 0.5 inch minimum separation must be maintained. In areas where mechanical failures may damage redundant flight essential/critical systems, additional wiring protection and/or increased spacing between bundles is provided. The particular separation distances are defined by appropriate analyses of, for example, engine rotor failures, tyre bursts etc. Category N wires are considered exempt from any separation requirements and may be routed with category L, C, R, H and S wires. In addition, a minimum separation of 2 inches is required between wiring and control cables, lines carrying fuel, oxygen or hydraulic fluid, and 0.5 inch separation between other lines associated with systems such as water and pitot/static.

Separation by wire bundle assignment:

For circuits within the same functional separation category, but which must be further separated from each other for other functional reasons, the wires must be placed in different wire bundle assemblies, which may be routed and clamped together.

Separation by use of connectors:

For circuits which must be separated from each other for functional reasons, wires are routed through separate connectors wherever practical.

Separation by insulating material:

Where physical separation in space is not possible or practical, sleeving or tubing may be used. Typically, in pressurised areas various types of a non-fray flexible fibreglass sleeve are used and in unpressurised areas polytetrafluoroethylene (PTFE) tubing. Fibreglass sleeving is generally used where thermal and mechanical protection is required, and is able to withstand temperatures of 250°C continuously, and up to 750°C for shorter periods.

The loom containing the failure, and the adjacent heat affected loom, were both coloured coded Green, whilst the loom containing the three mechanically damaged wires was coded Blue. This ran adjacent to a Red coded loom.

Wire specifications

Wiring used on Boeing aircraft conforms to one of the Boeing Material Specification (BMS) documents, in this case the Boeing Design Manual 7032. This provides the selection criteria, which includes the functional, environmental and system requirements for all wires and cables. All wires are qualified to BMS or military specifications and in each case are subjected to a series of tests to verify their performance under different conditions. These tests include electrical tests (current overload, insulation resistance, arc tracking resistance, etc), mechanical tests (deformation, dynamic cut-through, wire to wire abrasion, flexure endurance etc) and environmental tests (accelerated ageing, thermal shock, fluid and humidity resistance, smoke and toxicity, flammability, etc). During accelerated ageing or thermal shock tests on general purpose wiring, wires are subject to a temperature of 200°C for some 168 hours. During flammability, smoke and toxicity tests such wire is tested in accordance with the FAA requirements of FAR Part 25, Appendix F, in addition to the manufacturer's own, often more stringent, requirements.

The wires which had failed, or were damaged and required replacement or repair, were classified as 'general purpose' being limited mostly to BMS 13-48D (printed as W48D) and BMS 13-51F (W51F). Other wire types in the vicinity were BMS 13-35 and RG 174, the continuous design maximum temperature rating of all these wires being 150°C. W51 type wire is a copper stranded wire, but is insulated with two layers of a fluoropolymer coated aromatic polyimide tape wound around the conductor.

If wiring insulation material is damaged in some way, for example due to mechanical abrasion or cutting through contact with 'sharp' objects, so that the wire is exposed and a local external conductive path is available, then electrical arcing can occur. A conductive path may arise from adjacent metal ('ground') structure, another exposed conductor, or the presence of a conductive liquid such as water, or moisture. If the electrical current required to form an arc discharge between the damaged wire and the available conductive path is below the current trip threshold of the associated circuit breaker for the wire, a stabilised arc will occur. The intense heat generated by such electrical arcing can break down such polyimide insulation tape and deposit the resultant carbon 'char' as an electrically conductive, thermally stable, graphite. This conductive carbon char will then provide an enhanced current path between the live conductor wire and other exposed wires, or 'ground'. This type of wiring insulation is recognised within the industry to have poor arc-tracking resistance because tracks carbonise quickly into significant conducting paths and is an example of a 'tracking polymer'. In addition aromatic (compounds with carbon rings) polyimide films, amongst other materials, are susceptible to 'flashover' which in this context is taken to be the sudden catastrophic failure due to thermal decomposition of the insulation material.

W48 type wire is a copper stranded wire, insulated by two layers of extruded ethylene tetrafluoroethylene (ETFE). ETFE is an example of a 'non-tracking polymer' where any intense heating of the surface of the material from an electrical arc, for example, results in gaseous products such as carbon monoxide, hydrogen cyanide, hydrogen fluoride, hydrogen chloride, sulphur dioxide and nitrous oxides.

Most of the wires in the wiring looms examined had two identification numbers printed upon their outer surfaces, one identifying the wire type and printed in green, the other identifying the specific wire within a circuit and printed in red. These numbers were repeated at intervals of 6 to 8 inches.

1.18.3 Examination of other aircraft

During this investigation the opportunity was taken to examine the general condition of wiring looms in other large jet public transport aircraft. Indirect assessment of wiring problems in such aircraft was also gained from associated reports. In addition, examination of the CAA database in the UK revealed evidence of numerous wiring/loom failure events which had resulted from wiring damage such as chafing, handling damage and foreign object damage.

In almost all of the aircraft examined directly, conductive and non-conductive debris was found, particularly in the lower parts of the airframes. It was not unusual to find evidence of drill swarf, for example, on and around wiring looms. The E&E bay in one high time Boeing 747 aircraft (which had accumulated a total flying time of 100,000 hours since manufacture in 1970) was examined. The associated wiring looms were covered in dirt, dust and general grime, which was slightly sticky to the touch. Debris similar to that retrieved from N653UA was also found, particularly in the lower part of the airframe.

As part of a current overseas investigation into the loss of a large four engined jet transport aircraft, investigators from the NTSB have examined the condition of wiring looms in new and undelivered aircraft, in addition to aircraft which have been retired from service and placed in storage. Particular emphasis was placed on the state of cleanliness, the condition of looms and individual wires. A summary of their initial findings is reproduced below:

'Airplane wiring was examined in different airplanes for condition and degrees of contamination. The airplanes had been manufactured by Boeing, Airbus and Douglas and operated by numerous airlines, including TWA. The airplanes ranged from new and undelivered to airplanes that had sub-assemblies built in 1969. In all but an undelivered B-737, metal shavings were found on wires and in bundles. Damage to the wire insulation was not noted where metal shavings were on the surface, but cuts in the insulation were found where shavings were between wires in bundles. Lint and other debris accumulations in airplanes of more than a year old ranged from light surface 'fuzz' to accumulations of more than 3/4 inch depth. A range of lint and debris textures were found ranging from syrup-like black residues to fluffy lint. Frequently a combination of types of these materials were found on the wires.

Evidence was also found of worn wire insulation at the edges of nylon clamps and coating of wires with miscellaneous materials that included grease, water and anti-corrosion spray. Cracked wire insulation was found primarily in the sunlit areas near the forward flight engineer panel. Cracked insulation was also found in darker areas.'

Photographs of debris observed in two different retired aircraft examined during the above inspections are shown in Figure G-8.

1.18.4 Significant electrical arcing/fire events

1. A recent wiring loom failure above the passenger cabin trim in a Boeing 747, and reported upon in AAIB Bulletin 10/97 (Appendix G1 to G2), concluded that the most probable cause was that swarf, generated from a structural repair carried out in the region of the failure in a loom, became entrapped within the wire bundle. Subsequently, when wires in the loom were replaced by pulling them through cable ties and clamps, the wire insulation suffered cuts from this swarf which subsequently precipitated the loom failure.

2. In May 1995, a Nimrod aircraft of the Royal Air Force successfully ditched into the Moray Firth, Scotland, as a result of a severe in-flight fire. The report on the investigation of this accident concluded that a defect in the No 1 DC engine wiring loom led to an arcing event and loom failure. Several wires terminated in globular ends and one wire, which was continuous, had a solidified section in the region of the failure over a distance of some 1.5 inches. This led to an uncommanded opening of the air starter valve for the No 4 engine whilst the engine was operating. The single, unloaded, turbine wheel in the starter rapidly ran up to overspeed and, due to a defective retention nut within the unit, was released before blade tip rub and failure could occur as intended by the unit's design. The subsequent release of the intact turbine wheel from the air starter motor punctured an adjacent fuel tank in the wing, resulting in a catastrophic fire. The aircraft was on a test flight following major maintenance during which all four engines had been removed and re-fitted. The initiating fault in the loom was not positively determined, but the associated evidence suggested that it had resulted from either chafing damage from an adjacent steel braided hose, or mechanical abrasion and shorting from conductive debris trapped within the loom. Prior to that accident, there were no maintenance inspections/activities specified for these engine looms and a fleet wide inspection revealed that up to 25% of the engines examined contained defects in looms which required repair. Although the aircraft was lost, all seven crew members escaped with relatively minor injuries.

3. On 24 November 1993, a SAS MD-87 experienced smoke and a subsequent fire upon touchdown. The fire damage was severe, including a one foot diameter hole through the fuselage skin. The subsequent investigation found that two wires, one 115V AC and one 28V DC, had been pinched together and were arcing to the fuselage structure. Neither the 10A circuit breaker (28V line) nor the 15A circuit breaker (115V line) had tripped.

4. On 17 March 1991, a Lockheed L1011 en route from Frankfurt to Atlanta, Georgia, was forced to make an unscheduled landing at Goose Bay, Canada. Approximately 7.5 hours into the flight, flames had issued from the base of a cabin sidewall to a height of about that of the adjacent seatback tray at the last but one row of passenger seats on the left side of the cabin. The fire was extinguished, but the ignition source was not determined; one possible cause appeared to be an electrical fault. Some of the wires in a fifteen-wire bundle located in the area of the fire exhibited evidence of arcing. Five CBs connected to this bundle had tripped. An overtight bend radius of the wire bundle and accumulations of lint, dust and items from the passenger compartment found on the wires, insulation blankets, structure, etc were thought to have been contributory factors.

5. On 18 January 1990, an MD-80 en route from Buffalo to Cleveland was forced to return when the flight deck filled with smoke from overheated electrical wire insulation. The left generator tripped off-line and the commander turned the right generator control switch to the OFF position. He selected emergency power and initially was able to clear the smoke. He then started the auxiliary power unit (APU) and the flight deck again started to fill with smoke. The APU electrical power was then switched OFF and the emergency electrical power was switched back ON. The aircraft subsequently landed back safely at Buffalo. It was found that the left generator phase B power feeder cable terminal, which was connected to a plastic terminal strip, had melted due to extreme arcing affects. The terminal, approximately 15 inches of the cable and the terminal stud had melted. The second source of smoke came from a fire started by the molten metal that had sprayed an area forward of, and below, the terminal strip. The only CB to trip was the cabin temperature control. This incident was caused by improper torquing of the phase B terminal.

6. On 6 September 1995, the commander of an MD-11 aircraft was about to start the engines for departure from Capital Airport in China when the flight crew noticed a significant amount of smoke emanating from the E&E bay. Further inspection revealed that areas of the E&E bay were on fire. Investigators later found that molten metal from arcing wires had fallen onto the fuselage skin insulation blankets under the E&E bay. There was extensive flame propagation from the insulation blankets up into the E&E bay, with associated widespread damage.

7. On 28 November 1998, a Boeing 747-400, VH-OJD, returned to London Heathrow Airport some 45 minutes after departure with an apparent fault in the E&E bay ground cooling airflow exhaust valve (AAIB Bulletin 6/99). After a lengthy troubleshooting process, maintenance crews discovered that a small fire had taken place on the outer film of a bilge insulation blanket, at Station 540, and that this was associated with several failed 24 gauge wires in a small bundle connected to the exhaust valve. These wires had been positioned, incorrectly, beneath the insulation blanket and it was considered most likely that they had inadvertently been damaged by being stepped upon. The fire had affected an area of approximately 18 inches x 6 inches. The insulation blanket had recently been changed for a 'lightweight' item, fabricated by the operator from polyimide foam and a polyester scrim reinforced polyester film. Water, resulting from condensation, was present in the bilge of this aircraft and it was considered that this may have limited the extent of the fire.

In addition to the above significant electrical arcing/fire accidents and serious incidents, many related incidents are reported under the UK Mandatory Occurrence Reporting (MOR) System. Two of these are reproduced below:

Occurrence Number 199907499: Date 1 November 1999: Type Boeing 737-500: 'Burnt wiring loom at E1-3 shelf (avionic rack in E&E bay). Found during investigation of carried forward defect (CFD) "instrument switch light illuminating". Two circuit breakers (IRS nr 2 DC & instrument transfer) found tripped & unable to reset. Further investigation revealed signs of arcing behind E1-3 shelf (avionic rack in E&E bay). On removal of E1-3 shelf (p/n 65C27433-21), a large section of wiring loom found completely charred with many bare cables showing. Technical Services Query Note (TSQN) QN/QA/160 raised for liaison with a/c manufacturer & to action any fleet requirements. Total a/c hours/cycles 16838/20952. The manufacturer was made aware of this wiring damage and the metallurgical analysis concluded that the source of arcing could not be identified. Standard wiring inspection practices have been included in the operator's engineering continuation training. CAA Closure: The hazard is adequately controlled by the operator's actions.'

Occurrence Number 20004125: Date May 2000: Type Boeing 737: CAA Status Open: 'P6-4 panel electrical loom arcing due swarf present in wire bundles. Unusual ticking noise heard from P6-4 panel during inspection following completion of SB 737-24A1118 part 111. Evidence of arcing from the wire looms at the rear of P6-4. Electrical power removed. External power receptacle showed signs of overheating, unable to confirm that this was as a result of P6-4 panel arcing. Investigation found swarf present within the wire bundles at the rear of P6-4 panel. Suspect swarf entered wire loom as a result of work being carried out to complete SB 737-24A1118 (which required anchor nuts to be removed by drilling) and/or inadequate protection of the wire looms. Wire looms should have been protected before metalwork commenced and the area inspected/cleaned before electrical power was applied. Arcing stopped once swarf had been removed.'

The above MORs further illustrate the ongoing occurrence of such electrical arcing problems in service, in addition to the effects of wiring contamination by metallic swarf. The first MOR also indicates how a potentially serious instance of arc induced wiring loom damage can remain undetected and further flight operation be conducted with a related 'carried forward defect', before such wiring loom damage is discovered.

1.18.5 Insulation blanket materials

The airframe thermal and acoustic insulation blankets on the Boeing 767 aircraft, in common with most aircraft, are fabricated by encapsulating a sheet of insulating medium (typically non-flammable or fire retardant glass fibre or foam plastic) within a thin reinforced plastic bag, tailored to fit the appropriate local structure. One of the functions of the bag is to seal the insulating medium against the ingress of water, grime and oil etc, to both enhance the fireworthiness of the blanket and to avoid an unacceptable increase in weight.

All materials used for these blankets are qualified by the manufacturer to the Boeing Material Specification documents BMS 8-48 type III, grade A, class 1 or 2, for the glass fibre insulating medium; and BMS 8-142 type 1, class 3 for the insulation blanket bag. This material on the Boeing 767 may be non-metalised polyethylene terephthalate (PET) film or metalised and non-metalised polyvinyl fluoride (PVF) film, qualification of which includes passing the vertical flammability tests as specified in Federal Aviation Regulation (FAR) 25.853, Appendix F. The insulation blanket material affected by hot copper spatter on N653UA was thought to be metalised PVF.

The FAA Technical Center at Atlantic City published report DOT/FAA/AR-97/58, entitled ' Evaluation of Fire Test Methods for Aircraft Thermal Acoustical Insulation', in September 1997. This report indicated that the primary response to thermal degradation of these materials is for the film to rapidly 'shrink away' from the source of heat. In air, PET film burns with a smokey flame and therefore fire retardant treatments are necessary, making this material resistant to small ignition sources in low heat flux environments. PVF film has similar characteristics. However, it is reported that both will burn readily in fully developed fires. The report questioned the validity of the current 'vertical' flammability tests, and described an apparently more reliable 'cotton swab' test method, which the manufacturer has included in its associated material specifications requirements. Two blanket bag materials that remain in service, but which are no longer produced, are also reported upon: ie metalised PET film, which was considered 'flammable and which possibly could propagate a fire in a realistic situation'; and polyimide film (installed at manufacture in Lockheed L1011 Tristar aircraft) which is currently being re-evaluated for future use as blanket bag material due to its excellent flammability resistance and mechanical properties.

1.18.6 Circuit breaker (CB) characteristics

Circuit breakers perform two functions in aircraft electrical systems. Their primary function is to provide overcurrent protection for the aircraft wiring and their secondary function is to facilitate the isolation of specific circuits that do not contain any other specific switching mechanisms. The detail construction of thermal CBs for aircraft depends on the manufacturer, the rating and the application. The associated 'button' is the manual means of operating such CBs and its position visually indicates its state. This may be pulled out to open the circuit, when a white band is visible on the shaft of the button, or pushed in to close the circuit.

Most CBs employ a bi-metal strip through which the load current flows. When an overload current condition occurs, the electrical resistive heat induces differential expansion of the two metallic elements so that the strip bends far enough to trip a spring-loaded mechanism. This then separates the electrical contacts, and the button extends. Re-setting of the button can be done manually.

Such thermal type circuit breakers, however, do not trip as soon as their notional rated current is exceeded. They operate in accordance with current/time curves, trip times being longer for lower overcurrents. This characteristic is a natural feature of the response of the bi-metal strip to heating, and confers an 'inrush current' capability for motor starting, transformer operation, etc. Such delayed action characteristic of such circuit breakers can result in wiring damage due to excessive currents, before tripping occurs.

Details of trip time requirements for typical CBs (taken from MS 22073) and response curves for the particular CBs found tripped on N653UA are included at Appendix H.

However, the major disadvantage of this type of circuit breaker, as demonstrated in this accident, is that if the insulation of a wire becomes sufficiently damaged to initiate arcing onto some adjacent conductor, stabilised arcing will continue if the required arc sustaining current does not cause the circuit breaker to trip.

1.18.7 Toxicological effects of combustion gases

The effects of the gas given off when materials such as ETFE wire insulation are degraded by heat, and which are generally recognised as the important toxic/irritant components of combustion products, are listed below:

Carbon monoxide (CO)

Carbon monoxide is produced when any combustible material containing carbon or its compounds burns incompletely, or in reduced oxygen conditions. It is always present in uncontrolled fires. When inhaled, it is absorbed by the blood from the lungs and combines with haemoglobin to form carboxyhaemoglobin (COHb). This reaction inhibits the transport of oxygen by blood to the body tissue. 10% - 20% carboxyhaemoglobin in the blood can be tolerated generally with only a slight headache, but higher concentrations may induce a severe headache, weakness, dizziness, dimness of vision, nausea, vomiting and collapse. Concentration above 50% can lead to collapse and death.

Hydrogen cyanide (HCN)

This gas stimulates breathing, and therefore the rate of absorption. Cyanide affects the body by direct absorption into the tissues, affecting certain enzymes, such as cytochrome oxidise. This blocks the uptake of oxygen by cells from the blood stream, and a concentration of only some 200 parts per million (ppm) of HCN will induce rapid collapse and death. Nylon is one material which produces HCN during combustion.

Hydrogen Fluoride (HF)

Hydrogen fluoride, produced by the combustion of fluorinated polymers such as PTFE and ETFE, combines with moisture to produce hydrofluoric acid, one of the most reactive acids. Pathologically, this acid is much more active than hydrochloric acid and causes major oedema within the respiratory tracts. It is also a protoplasmic poison. Burns produced by hydrofluoric acid produce throbbing pain and progressive destruction of tissues with decalcification and necrosis of bone. Combustion of fluorinated polymers may also produce saturated and unsaturated fluorinated hydrocarbons of low molecular weight, which are also extremely toxic.

Hydrogen Chloride (HCl)

Combustion of many fire retardant materials produces hydrogen chloride. This combines with moisture to form hydrochloric acid which has a highly irritant effect on the throat and respiratory tracts. It is an intense irritant to the eyes, throat and respiratory tracts, causing destructive damage to the mucous membranes and pulmonary oedema.

Sulphur dioxide (SO_2)

This gas is produced by the combustion of any compound containing Sulphur. It combines with moisture to produce sulphuric acid which is highly irritant to tissues, including the eyes. It attacks the mucous membranes of the respiratory tracts, causing uncontrolled coughing.

Nitrous oxides (NO_x)

These gases combine with moisture to form nitric and nitrous acids which can be absorbed directly, or with carbon particles of smoke which have adsorbed these acids. They attack the throat, trachea and lung tissues and are highly irritant. Some of the acid may be neutralised by an alkaline reaction within the body tissues, producing nitrate of sodium. Nitrate absorption causes arterial dilation, hypo-tension, headache, vertigo and the formation of methaeoglobin.

1.19 New investigation techniques

None.

2 Analysis

2.1 The flight

The pre-flight checks and initial start up at Zurich were normal. The first indication of any problem with the aircraft came from the cabin attendants who became aware of a loud 'grinding or whirring' noise from under the floor of the centre cabin. The noise could be heard clearly in the centre and rear sections of the aircraft. The supernumerary first officer (SFO) went into the cabin to check the situation and agreed that the noise was abnormal. The commander then stopped the aircraft at a remote holding area and went into the cabin to assess the situation. He correctly decided not to continue the flight and asked for clearance from ATC to taxi to a remote parking stand where the aircraft was shut down and engineering assistance requested.

During the subsequent engineering investigation, the source of the noise was traced to the ADP in the centre hydraulic system. It was found that the pump was operating continuously while selected to the AUTO position on the flight deck when it should have normally only operated at times of high hydraulic demand, such as during landing gear and/or flap operation. It was also found that the pump responded normally to OFF and ON switch selections. In consultation with the Operator's Maintenance Control and with reference to the MEL, it was agreed that the AUTO function could be placarded as 'AUTO FUNCTION INOPERATIVE, OPERATE IN 'ON' FOR TAKEOFF AND LANDING', and that the aircraft would then be cleared for flight. A limitation was also applied to the effect that the aircraft was to remain within 120 minutes single-engined flying time from suitable diversion airfields, instead of the normal 180 minutes. The dispatch of the aircraft in this condition was in accordance with the company MEL for the aircraft.

The aircraft was again prepared for departure and a normal take off was made from Runway 16 with the ADP selected ON. After gear retraction had been completed, while climbing through about 2,000 feet agl in the turn on the SID and before flap retraction had been completed, a 'LEADING EDGE SLAT DISAGREE' message was generated on the flight deck EICAS with the ADP still selected to ON.

The SFO contacted the company Maintenance Control using a SATCOM link. During this conversation, it was suggested that the ADP should be selected to AUTO in order to check if this had any effect. Selecting the switch to AUTO caused the EICAS message to clear. The flaps and slats were then retracted normally and the aircraft continued its climb to FL 240. However when the ADP was then selected to OFF, the same EICAS message reappeared; selection to ON also produced the same result. The only available means of clearing the EICAS message was to set the ADP switch to AUTO. This was a different manifestation of the ADP switching logic problem than that which had occurred prior to departure.

In order to check the correct flap and slat operation, the aircraft was descended to FL200 and speed reduced below the flap limiting speed. There was then a temporary loss of communication on the SATCOM and therefore an HF link was established with Maintenance Control in order to continue the troubleshooting process.

The flaps were then selected to 5 degrees using the normal system. It was confirmed that the same EICAS message was generated when the ADP switch was either ON or OFF, but it continued to clear when the switch was selected to the AUTO position. The flaps were then retracted normally and the crew were confident that the EICAS message regarding the Leading Edge Slat Disagree was incorrect. It was decided to select the ADP switch to OFF and continue the flight with the erroneous EICAS message displayed (the reasons for the ADP failure and this EICAS message are contained in section 2.3.1).

A further EICAS message then appeared, 'F/O Pitot Heat'. The appropriate circuit breakers were checked, then pulled and reset by the SFO (in consultation with company Maintenance Control, in accordance with the company standard operating procedures). It was also noted that two other circuit breakers had tripped. These were the Alternate Flap Drive Motor and the Passenger Services Outlet circuit breakers. An attempt was made to reset the latter, but it tripped again immediately and then two other circuit breakers tripped, which the crew thought had probably been associated with the 'Flap Drive System' (see section 2.3.3).

At this time, the FO's EFIS screens flashed momentarily, along with both Engine and System screens. Some circuit breakers were then heard to trip, which the crew thought had been another one, or two, 'Flap Drive System' breakers (see section 2.3.3) and a First Officer Pitot Heat (Left). The flight conditions were daylight visual meteorological conditions (VMC).

At this point, the crew became concerned with the situation and ceased to pull or reset any more of the circuit breakers. After further discussions with company Maintenance Control, the commander decided to divert to land at London Heathrow Airport where there was company maintenance support. At this time the aircraft was to the east of Paris, about 30 minutes flying time south of London. A landing at Paris Charles de Gaulle Airport would probably have been more expeditious, but at this stage of the flight the commander was not aware of the potential urgency of the situation. The following safety recommendation was therefore made in an AAIB safety recommendation document, containing seven recommendations Nos 98-12 to 98-18, which was issued on 31 March 1998:

> The Boeing Commercial Airplane Company and the FAA should issue advice to pilots that whenever a series of apparently unrelated electrical/electronic system failures occur within a short period of time, the probability of an associated and developing electrical fire or smoke situation should be actively considered, necessitating the declaration of an emergency and initiation of a diversion to the nearest suitable airport. It should also be noted that in such situations, the fire or smoke condition may not be accompanied by any associated direct warning indications on the flight deck; in general, circuit breakers which have tripped should only be reset once, after a suitable cooling period has elapsed, but only then if deemed essential to the safe operation of the aircraft. The FAA should notify other regulatory authorities of its response to these aspects.
>
> [Safety recommendation no 98-12, made 31 March 1998]

In its response to the Draft Copy of this report, Boeing forwarded information from the Boeing 767 Operations Manual revision, dated 20 August 1999, which included the following information on circuit breaker operation in the 'Checklist Introduction, Non-Normal Checklists' section:

' Resetting circuit breakers is not generally a requirement in flight. However, a tripped circuit breaker (other than a fuel pump circuit breaker) may be reset at the captain's discretion, after a short cooling period (approximately 2 minutes). If it trips again, no further attempt is to be made to reset that circuit breaker.'

The three flight deck crew members worked well together in a co-ordinated manner, in order to complete all of the required tasks associated with the diversion and the necessary communication with the cabin crew, passengers, company Maintenance Control and ATC. The presence of the third pilot on the ancillary seat was extremely beneficial in moderating the workload of the two operating pilots at peak times throughout the remainder of the flight.

French ATC were advised of the decision to divert and the aircraft was cleared to route direct to Abbeville VOR, near the northern French coast. However, the diversion request was not passed to the next French ATC sector and approaching Abbeville the request had to be repeated by the flight crew.

Notification was received at LATCC from Paris ATC that the aircraft was diverting into London Heathrow. At 1435 hrs, during a telephone conversation between the Paris North Sector Controller and the LATCC Dover/Lydd Chief Sector Controller, the reason stated for the diversion was that the aircraft had a 'technical emergency'. At this stage it appears that the French controller had assumed, probably because the aircraft had descended from FL 240 to FL 200, that it had some form of pressurisation problem since he then described the technical emergency as a 'pressurisation failure'.

The aircraft came onto the LATCC Lydd Sector, frequency (128.425 MHz) at 1444 hrs, maintaining FL200 and routing direct to the Biggin Hill VOR. The controller sought to confirm the nature of the problem with the aircraft commander, who responded by stating that the aircraft had an 'indicator problem on the flaps'. The controller sought to confirm with the commander that it was a straightforward 'pressurisation' problem and that no priority would be required. The commander responded that the problem was a 'straightforward flap indicator problem'. Since this information was at variance with the earlier information received by the controller, it took several minutes to clarify the ambiguity.

At 1446 hrs, the controller asked if the aircraft could accept normal holding delays for Heathrow of about ten minutes. The commander responded to this by stating that 'we would like to get her on the ground as soon as we possibly could'. The controller acknowledged this by asking 'is that a priority?' to which the commander responded 'yes sir it is a priority'. The standard method of declaring an urgent or emergency situation (using the prefixes 'PAN' or 'MAYDAY' respectively) was not used. Reference to the correct phraseology is contained in the Emergencies/Irregular section of the operator's Flight Operations Manual.

The operator subsequently stated in response to the Draft Copy of this report that 'It is our belief that the flight crew was unaware of the urgency of the situation until landing when smoke finally made its way into the flight deck.' Whilst it was accepted that the urgency of the situation was fully realised by the crew after the landing, the commander's transmissions to ATC quoted above appeared to indicate that the commander was anxious to land his aircraft as soon as possible. It was therefore concluded that his transmissions indicated that he believed he was in an urgent situation.

At 1449 hrs, as the aircraft passed over Abbeville VOR in northern France, the controller confirmed his understanding of the situation by stating "just to put the record straight we'll treat this as an emergency in order that you will get an uninterrupted approach at Heathrow". The commander responded "all right sir that's fine".

At no time was the LATCC controller informed that the aircraft had any electrical system anomalies and the controller regarded the commander's request "to get her on the ground as soon as we possibly could" as a means of obtaining an expeditious priority approach ahead of the normal arrival traffic stream.

By telephone, the controller informed Heathrow Terminal Control and the LATCC Distress and Diversion Cell of the situation, indicating that the aircraft was being treated as an emergency in order to give it a priority approach into Heathrow, but that there was no other urgent technical reason.

There was no further discussion of the nature of the problem between the aircraft and ATC. The Heathrow Tower controller was not aware that there was any abnormality with the aircraft and therefore the airport emergency services were not alerted to the aircraft's imminent arrival.

Had the controller been informed of the dubious state of the aircraft's electrical system, or if the request for a priority approach had been prefixed with a 'PAN', then he would have alerted Heathrow to the situation in order that the emergency services could have been deployed prior to the aircraft's arrival. The commander was however under the impression that having ATC treat the aircraft as an emergency in order to get a priority approach was sufficient to alert the emergency services at Heathrow, and therefore briefed the cabin crew and the passengers to expect to see their presence on landing.

However, the controller treated it merely as a case for an expeditious approach with no other consequences and the alerting at Heathrow did not take place. In the event, the lack of deployment of the emergency services prior to landing did not materially affect the successful outcome of the evacuation.

Radar vectors were given to position the aircraft in the traffic sequence for landing on Runway 27L. It was still daylight and the weather was good. The ADP was selected ON for the approach, with normal systems being used for landing gear lowering and flap selections. A normal ILS approach was flown to a gentle touchdown using a Vref (threshold speed) of 152 kt and full flap. The aircraft was about 2,000 lb below the maximum permitted landing weight (320,000 lb) at that time.

After touchdown, the FO selected reverse thrust. However, although the left thrust reverser deployed normally, a 'Reverser Unlocked' amber caution light illuminated for the right thrust reverser. The FO therefore correctly cancelled reverse thrust and applied manual braking to override the previously selected Autobrake 2 setting. The aircraft was slowed to taxi speed and control was passed to the commander for nosewheel steering purposes. The aircraft turned off the runway at Block 80 and moved a short distance along the taxiway. The left reverser cancelled normally, but the right 'Reverser Unlocked' caution light remained illuminated.

During the landing deceleration, the flight deck door had opened (probably due to it not having been correctly latched prior to landing) but it was immediately re–closed by the SFO. After the aircraft had turned off the runway, the senior cabin attendant (SCA) entered the flight deck to inform the pilots that smoke was coming from the area of seats 1E and 1F in the forward cabin. The smell of smoke was also apparent on the flight deck. The aircraft was immediately stopped on Block 89, and the commander made the correct decision to evacuate since he considered that there was a risk of fire.

2.2 The evacuation

The SFO made a PA announcement to 'unfasten seat belts and get out of the aircraft'. The FO informed the Tower Controller of the intention to evacuate and then proceeded to read the QRH procedure. The commander shut down both engines and carried out the actions on the Evacuation Checklist. The fire handles were pulled, but the extinguishers were not operated (there was no reason for them to be operated in these circumstances). The APU was not in operation at the time. Only the battery remained powered after completion of the QRH procedure. The aircraft's emergency lighting system operated normally. The flight deck crew then evacuated the aircraft using a forward cabin slide, followed by the last cabin crew member.

The cabin crew had carried out a satisfactory evacuation despite some of them having been unaware that there was a potential evacuation situation developing before the evacuation alarm was activated. Those crew members at the rear of the aircraft commented that they were unable to hear the evacuation alarm, but responded to the PA order to evacuate the aircraft. The evacuation alarm was subsequently tested, after rectification of the damaged wiring loom, and was then found to be serviceable. The evacuation was reportedly completed within 90 seconds, the maximum time required for the evacuation certification demonstration.

The forward right over-wing exit was difficult to open and, when it finally did open, the associated slide did not deploy. The aft right over-wing exit opened without a problem but the slide still did not deploy. Neither flight attendant pulled the manual inflation handle. However, there were sufficient other exits available for the evacuation and therefore the loss of these two exits had little affect on the overall evacuation time.

The AFS was quickly in attendance once notification of the evacuation had been given to the Tower. However, there was no fire and no requirement for the AFS to deploy any media.

The passengers were assembled into two groups at a safe distance on either side of the aircraft, and a headcount was completed. The presence of the two groups of passengers had the effect of slightly delaying the headcount procedure while co-ordination of the two groups, on opposite sides of the aircraft, was effected.

2.3 Technical investigation

2.3.1 Air driven pump (ADP)

The first indication to the crew of a fault on the aircraft occurred before take off when a problem was encountered with the operation of the ADP in the centre hydraulic system. When selected to the automatic mode it continued to run after system pressure had been attained but, as it would operate satisfactorily in the manual mode, ie selected ON, the aircraft was dispatched in accordance with the MEL. Subsequent to the wiring repairs and replacement of the damaged card in the PSEU, the EICAS message 'L/E SLAT DISAGREE' was no longer present. The ADP, however, still failed to operate correctly in AUTO, but did operate correctly when selected to ON or OFF. After the ADP had been replaced, the system functioned correctly. The ADP which had been removed was found to have a defective 'on-demand' solenoid.

The appearance of the 'L/E slats disagree' message with the ADP switch at either the ON or OFF position was considered by the manufacturer to have been associated with the degradation of wiring insulation which allowed the 'slat disagree' sensing circuit to sense a false 'low'. With the switch in these positions, a 28V DC signal is removed from the disagree circuitry, but when in AUTO it was likely that the 28V signal, despite the damaged wiring, was sensed as a 'high' thereby removing the warning.

Thus it seemed probable that the initial loom failure occurred just after take off, which appeared to be supported by the fact that no unusual smell or smoke was detected by the flight or cabin crew whilst the aircraft was on the ground.

2.3.2 Chiller installation

The installation of the forward galley chiller unit in the Boeing 767 is slightly unusual when compared with other Boeing types, in that it is located in the forward E&E bay, beneath the forward galley/vestibule area. As illustrated in Figures B-1 and B-2, it is positioned in an area of high wiring loom and equipment density, with several looms routed around and behind this unit. It is physically attached by four bolts to its support frame, and wired to the aircraft by one quick release connector. Access to the chiller may be gained by three ways into the E&E bay, but entry is usually gained through the relatively small hatch in the lower fuselage immediately aft of the nose landing gear, or the hatch in the forward vestibule floor. Compared with other wide body aircraft types, the physical space for maintenance crews within this bay is limited. Thus, as the chiller is one of the more heavy and distant items of equipment from the hatches, replacement tends to be a physically arduous task although relatively straight forward. In an attempt to both ease this process and to avoid possible damage to the chiller, wires and equipment in the bay, the use of installation equipment was specified in the Removal/Installation instructions in the Boeing 767 Maintenance Manual (MM).

Interviews conducted in the USA by the NTSB, on behalf of the AAIB, with the two mechanics who replaced the chiller on the day before the accident when the aircraft was at Washington, revealed that neither had performed this particular task previously on a Boeing 767 aircraft. Although the MM provided step-by-step instructions on this task, they decided to perform it without the benefit of the installation equipment since they were unsure if such equipment was available. In addition, advice from their colleagues had suggested that it was difficult to use the ground equipment in the confined space of the E&E bay.

The failure to correctly position the condenser heat exchanger exhaust blanking plate during this chiller replacement appeared to have been an oversight on the part of the two mechanics, despite the presence of several warning placards on the unit warning of the risk of damage to the chiller if fitted incorrectly. In isolation, this would have amounted to nothing more than an inconvenience as the chiller may have been damaged or shut down by its protection circuits should it have overheated. Also, any possible direct effect of warm air discharged directly on wires in the bay was not considered a factor in their failure since the specification for these wires allowed for operation at ambient temperatures significantly greater than that capable of normally being generated by the chiller. In the context of this accident, however, the physical presence of this incorrect exhaust flow may have been a factor in the failure of the loom, in that it had the potential to disturb any loose conductive debris in the areas around the chiller and adjacent looms.

Examination of the forward E&E bay on N653UA revealed, in addition to general small nicks and areas of abrasion on the surfaces of wire insulation, mechanical damage to the insulation of several wires, in two different looms, in regions adjacent to the installed position of the top/aft area of the chiller. This damage was not associated with arcing of wires, but at several locations wire conductors had been exposed. At one specific location, a small piece of aluminium was found embedded in the damaged surface of the insulation and later SEM analysis of this indicated that it was similar to the material from which the chiller cover was made, ie mostly aluminium and magnesium, but with no zinc or copper present. Areas of such mechanically induced insulation damage were also found within 10 mm of the upper extremity of the blackened region of the failed loom, on two separate wires.

After this accident, similar damage was observed on wires in the vicinity of the chillers on several other Boeing 767-300 aircraft, including one from a different operator where this particular damage was associated with a smear of light blue paint across adjacent wires. The chiller from N653UA had a small sharp edge at the top aft outboard corner which had been formed as a result of the way in which the material had been folded at the corner; this corner exhibited local bruising damage. The orientation of this edge and the location of the insulation damage on the various wires, in relation to the likely movement of this corner of the chiller when the unit had been installed, was such that it was both possible and probable for it to have caused the mechanical damage found on the wires. It also remains possible, however, that these wires could have been damaged on a previous occasion.

Thus the evidence gained during the investigation strongly suggested that all 'mechanical' damage to wiring insulation found around the aft end of the chiller, as installed, had been caused during chiller replacement operations, with the possibility that most, if not all, of this damage had occurred during the last replacement. In view of these serious findings, the following three safety recommendations were included in the previously mentioned AAIB safety recommendation document which was submitted to the FAA and the manufacturer (with copies to the CAA, JAA, NTSB and the operator) on the 31 March 1998:

> The FAA should require an immediate inspection of all wiring looms around the forward galley chiller unit installation within the electronic and equipment (E&E) bays on Boeing 767-300 aircraft to check for damage to loom wiring and general freedom from metallic debris and moisture.
> [Safety recommendation no 98-13, made 31 March 1998]

> The Boeing Commercial Airplane Company should emphasise in the Aircraft Maintenance Manual (AMM) that the appropriate handling equipment must be used whenever a galley chiller unit is replaced within the E&E bay on Boeing 767-300 aircraft, and include a specific warning in the AMM of the risk of potentially critical wiring damage occurring during such chiller unit replacement, in addition to a requirement to inspect for such wiring damage following chiller unit installation.
> [Safety recommendation no 98-14, made 31 March 1998]

The Boeing Commercial Airplane Company should introduce, as soon as possible, additional protection of the wiring looms in the E&E bays of Boeing 767-300 aircraft to prevent potentially critical damage to such looms during installation of forward galley chiller units within such bays.
[Safety recommendation no 98-15, made 31 March 1998]

The manufacturer issued Boeing Alert Service Bulletin 767-24A 0120 in March 1998 which recommended operators to visually inspect the wiring adjacent to the chiller units within the E&E bay for chafing and to wrap associated wiring bundles in protective tape to improve abrasion resistance. In addition, the manufacturer undertook revision of Section 25-33-01 of the Boeing 767-300 AMM to alert operators to the potential risk of wiring loom damage arising from chiller installation/removal, with the addition of a requirement in the MM to check the wiring for damage after installation of chiller units. The special tray tool, which was recommended within this section of the MM for use during such installation/removal, was to be subject to testing and validation.

In a commendably rapid reaction to this accident the FAA issued Airworthiness Directive 98-07-026 on 27 March 1998, which required that all Boeing 767 aircraft that had a similar chiller installation were to have an intensive visual inspection of wiring adjacent to the chiller units for evidence of damage, and for corrective actions to be taken if such damage was found. In addition, re-routing of adjacent wiring bundles was required if inadequate clearance between such wiring and chiller units did not exist, with either a repeat inspection when a chiller was replaced or a 'one time' wrapping of wiring with protective tape, or sleeving, to prevent chafing. In addition, Boeing introduced increased protection to the wires adjacent to the chiller unit on aircraft production.

It was later reported that some 572 Boeing 767 aircraft worldwide had this galley chiller installed in their E&E bays, of which 231 had been inspected. Of these, some 19 had been found with wiring which had been either damaged or chafed in close proximity to the chiller installation.

2.3.3 Circuit breaker operation

From the general and detailed examination of the chiller unit and the wires removed in the support cradle from this aircraft, it was concluded that the initial failure had occurred within this section of the loom. There was no evidence of arcing from any wires to the chiller, loom supports or airframe. All the evidence indicated that arcing had taken place only between the conductors of the affected loom, with some wires in the immediately adjacent loom suffering severe collateral heat damage which had not induced associated wire conductor failure.

Although the re-application of electrical power to the aircraft after it had landed, but before an initial examination of the loom had taken place, had been inadvertently done for non-investigative reasons, this fortuitously demonstrated that arcing could be sustained within the area of the wiring failure for a period without inducing the associated CBs to trip. The characteristics of such CBs are well documented, with high overcurrents induced by short circuit events resulting in rapid tripping of such breakers. However, 'soft' or intermittent shorts, sometimes referred to as 'ticking faults', such as those that may be experienced during arcing events, can occur without tripping of related CBs provided that such variables as line impedance, spacing between conductors and ambient conditions are favourable. This can result in sustained or intermittent arcing at relatively low currents, which can extend times before CBs trip, as evidenced in this case and in others such as those highlighted in section 1.18.4.

The causes of CBs tripping in flight are generally unlikely to be evident to flight crew and therefore re-setting of tripped CBs (particularly if such tripping has been induced by an arcing event) can be dangerous. The re-establishment of power to damaged conductors may result in increasingly severe failures of the wire bundle due to additional arcing, possibly for an extended period, before the related CBs trip again. Such apparently successful re-setting of CBs can therefore convey a false impression to the crew that a particular fault has been cleared.

During this flight such arcing within the damaged section of the failed loom not only tripped the CBs listed in section 1.12.2, but had been sustained by other CBs which did not trip in the time available during the flight, as evidenced by the direct observation of arcing after ground power had been inadvertently applied. With regard to those CBs which were found tripped, it was apparent that the associated list in section 1.12.2 included CBs mentioned by the crew, ie F/O Pitot Heat, Alternate Flap Drive (Power) and Passenger Service Outlet, in addition to CBs not specifically mentioned by the crew, such as Alternate Slat Inboard and Outboard Power. In view of these findings, it was considered that the 'Flap Drive System' CBs referred to by the crew were probably those for the Alternate Flap and/or Slat Power. Damaged wiring from these systems was also repaired, as listed in Appendix E.

Localised extreme temperatures within the loom probably existed in flight for at least 30 minutes, supporting the concern that further wiring damage could have occurred to previously undamaged wires should the flight have continued for a longer period of time. (The ETOPS clearance for the Boeing 767-300 is that it should always remain within a distance equivalent to 180 minutes single engined flying time from a suitable diversion airfield. On the accident flight, a restriction had been added to the Despatch Release which stated 'ER operations beyond 120 minutes not allowed').

The operator's Procedural Index contained the instruction to crews that the pulling and resetting of CBs should only be carried out when directed to do so by a Checklist or by company Maintenance Control. It is generally accepted within the industry that the re-setting of a tripped circuit breaker should only be attempted once and after a suitable cooling off period has elapsed, which allows operators a measure of operational freedom following 'nuisance' CB trips. It is considered that this information should be formalised and highlighted to all pilots and emphasised during recurrent training, but only if it is essential to the safe operation of the aircraft. At the time of this accident there was no guidance published for flight crews with regard to situations which involve a developing series of (apparently) unrelated electrical system failures (see section 2.1, safety recommendation no 98-12).

2.3.4 Smoke/heat detection

Throughout the relatively short flight during which the aircraft diverted to London Heathrow Airport there is little doubt that either continuous or intermittent arcing and associated pyrolysis of wire insulation material was occurring in the failed section of the loom within the E&E bay, below the forward galley. Although this progressive electrical failure was generating localised intense temperatures from the arcing in addition to associated smoke within the bay, in the absence of a related smoke warning on the flight deck the only manifestation of the problem to the crew was the tripping of CBs associated with apparently unrelated systems. The CVR contained no evidence from crew comments made during the flight that they had recognised the possibility, from the succession of tripped CBs, that they may have had a critical electrical fire problem.

Further loom damage, PSEU circuit board damage and additional smoke was probably caused when reverse thrust was selected on landing, resulting in only the partial deployment of the right thrust reverser cowl. However, the failure of the right thrust reverser to deploy was not operationally critical on this occasion.

The aircraft manufacturer specifies wire characteristics, such as flammability characteristics, maximum concentrations of particulate matter, toxic gas concentrations and associated test methods, for all wires including W48 type ETFE insulated wires. If this material becomes heated, it should not self-sustain a fire in the absence of the ignition source, although pyrolosis may occur and toxic gases will be released This appeared to have been the case with the arcing event on N653UA.

SEM analysis of a sample of the thin foam plastic filter covering the aft face of the chiller unit showed this material to be 'loaded' with an antimony based compound, which is commonly used as a fire retardant. Thus, although this filter had melted adjacent to the failed section of the loom, and would have been subject to a forced draught by the operation of the chiller, it did not sustain a fire. The relatively small volume of wire insulation and filter that was heated and melted/burnt undoubtedly would have given off toxic gases with their characteristic pungent odours and potential harmful affects, but in this case these would have been in relatively small amounts. The natural flow of conditioned air in the Boeing 767 aircraft is from the cabin area down into the lower section of the fuselage, before exiting through the pressurisation outflow valves. Therefore, in flight any such gases generated in the E&E bay would have been unlikely to enter the passenger cabin. Had they done so, as was the case after the landing when airflow patterns changed as the engines spooled down to idle, then the apparently low concentration of these gases would probably not have represented a direct threat to the occupants but may well have alarmed passengers, which could have adversely affected an orderly evacuation after the landing.

The concentration of smoke in the E&E bay throughout this event had not been sufficient to activate the sole smoke detector for the bay, which was located in the cooling system for the E1-E2 racks and card file panels. This smoke detector was the only means by which the crew could have been alerted to the location of their critical electrical problem, which would have afforded them the opportunity to assess its scale by visual examination through the hatchway to the E&E bay which was located in the floor of the forward vestibule.

Certification data obtained from Boeing indicated that thick smoke in the E&E bay was required to be present for the detector in the E1-E2 racks cooling system to register a SMOKE warning in a reasonably short period of time, suggesting that a more serious arcing event and/or fire would be necessary to generate a warning over the timescale of the events on N653UA. As a result of these findings, the following safety recommendation was included in the AAIB safety recommendation document submitted on 31 March 1998:

> The FAA should require the installation of smoke or heat detectors within the E&E bays of Boeing 767 aircraft and other modern jet transport types, with associated flight deck warnings to alert crews to electrical overheat/fire situations within such bays at the earliest stage, so that appropriate and timely operational action can be taken.
> [Safety recommendation no 98-16, made 31 March 1998]

This recommendation was however not accepted by the FAA, which considered that additional smoke or fire detection equipment within such E&E bays would not improve safety and that the low smoke emission rates likely to be generated by wiring faults would lead to an increase in nuisance alarms due to the low sensing thresholds that would be necessary. The FAA also stated that a smoke detection system is already in place designed to detect events from the most likely source of smoke or fire, ie the electrical equipment. The FAA maintained that the E&E bay smoke warning system on the Boeing 767 had been certificated after its ability to function, when adequate levels of smoke were generated within the bay, had been demonstrated satisfactorily.

However Boeing is currently designing the installation of a sensor to detect smoke in the E&E bay of the Boeing 767-400 aircraft. A bleed from the exhaust of the ambient air extracted by the galley chiller, which is warmed by the condenser heat exchanger and which is ducted away to an area above the forward cargo compartment, will be passed over the new detector before being discharged back into the bay. There are currently no plans, however, to install such a system on Boeing 767-300 aircraft.

Subsequent to the above recommendation and as a result of the accumulating evidence of metallic contamination and damage to aircraft wiring looms generally (see section 2.3.7), including areas remote from such E&E bays, it was concluded that the scope of the previous recommendation should be widened. The following safety recommendation is therefore made:

> Manufacturers such as Boeing and Airworthiness Authorities such as the FAA should investigate the feasibility of installing smoke and/or heat detectors within remote areas of high wiring and equipment density, such as the E&E bays of transport aircraft, with associated flight deck warnings to alert crews to electrical overheat/fire situations within such areas at the earliest possible stage, so that appropriate and timely operational decisions can be taken. [Safety recommendation no 99-50]

2.3.5 Insulation failure/flashover

Under normal conditions, the AC electric strength values of polyimide film quoted by one manufacturer are in the region of 200V per micrometer, and similar values would be expected for ETFE material. Normal maximum operating AC voltage in the wires on transport aircraft is 115V, therefore under normal service conditions there is a considerable safety margin in the design of wire insulation.

Both polyimide and ETFE are materials that can operate at relatively high temperatures and are resistant to most chemicals. Polyimide wire coatings are tough, have a reasonable resistance to mechanical damage and, as a result of their good mechanical and electric strength properties, enable wires to be constructed with thin layers of insulation.

Electrical problems with wires generally arise if their insulation ceases to provide a homogeneous coating over the conductor. Typical examples of problems that can occur in insulation are (micro) cracking or 'crazing' induced by internal stresses or by chemical action, chemical degradation caused during operation at elevated temperatures, and mechanical damage introduced during handling (flexing) or by in-service conditions (vibration). The potential problem of induced cracks in insulation, for example, at over-tight bends in the wire/loom or wherever wires are flexed on a regular basis, is minimised by correct installation (specifying minimum bend radii, for example) and by applying the insulation in a number of layers so that if a crack occurs in one layer, it is unlikely to produce an electrically weak path through the entire insulation wall.

Insulation failure, however, is an electrical failure condition and is often initiated by mechanically induced damage; it is characterised by the catastrophic breakdown of the insulation and is usually attributed to poor arc-tracking resistance associated with carbonisation of the insulation material.

The majority of the wires which failed in the loom were of the W51 type. Such wire consists of a copper stranded wire conductor insulated with two layers of a fluoropolymer coated aromatic polyimide tape wound around the wire. This type of wiring insulation has been used because of its electrical and mechanical properties, in addition to associated significant weight savings in any wiring installation. However, this insulation material is an example of a 'tracking' polymer, where intense heating from an arc will produce a carbon 'char' which is an electrically conductive, thermally stable, graphite. Such conductive carbon char can then provide an enhanced current path between the live wire and other damaged wires, or 'ground'. An insulation is said to have poor arc-tracking resistance if these tracks carbonise quickly into significant conducting paths. Aromatic (compounds with carbon rings) polyimide films, amongst other materials, are susceptible to 'flashover' where this is taken to represent (in this context) the 'sudden' catastrophic failure and thermal decomposition of the insulation material. The precise origins of such insulation failures are difficult to diagnose because the rapid catastrophic nature of the event destroys most, or all of the original evidence. As a consequence of this characteristic, the specific origin of the failure within the loom on N653UA was not determined. As the majority of the wires which failed in the loom were to the W51 specification, an initial arc struck between conductors would have resulted in the formation of this highly conductive char which would have been deposited over the surrounding wires. It is considered that the inevitable collateral damage to the insulation of the wires immediately adjacent to the failure origin on this loom, arising from the locally intense arcing temperatures generated, would then have triggered the series of failures found in the surrounding wires.

There was a relatively low number of W48 specification wires in the failed section of the loom. W48 type wire is a copper stranded wire, insulated by two layers of extruded ethylene tetrafluoroethylene (ETFE). ETFE is an example of a non–tracking polymer where any intense heating of the surface of the material, from an electrical arc for example, results in such gaseous products as carbon monoxide, hydrogen cyanide, hydrogen fluoride, hydrogen chloride, sulphur dioxide and nitrous oxides. It was considered that damage to the insulation of these wires had probably resulted, at least initially, from the catastrophic failure of the polyimide insulated wires, which formed the majority of the wires in this loom.

2.3.6 Moisture/fluids

Although the conductors of a wire may be exposed by mechanical damage, or pinhole flaws/cracks, in the insulation it may not necessarily arc immediately as the operating voltage may not be high enough, or the distance between the conductors small enough, to allow an arc to form. Additional factors may be required such as the presence of moisture (or any slightly conductive fluid), or conductive metallic debris. In the early stages of breakdown of 'tracking' polymer insulation, a layer of moisture on the wire could bridge the gap between two (or more) damaged wires, or to ground, and if it were sufficiently conductive could cause a small leakage current to flow. This type of situation produces the 'classical' wet tracking phenomena where the (low) current passing through the surface moisture causes localised heating, with evaporation and formation of very narrow dry bands within the film. As one of these bands forms, it has most of the voltage between the conductors concentrated across it and a small, but locally intense, flashover will occur. This tiny arc cannot be sustained, usually because of the high resistance of the moisture, but in a typical situation dry bands and arcs will continually and randomly occur in a process known as 'scintillation'. Carbonised tracks quickly develop in small non-uniform areas along the discharge path on the surface of the insulation, and these are generally likely to be highly conductive in comparison to undamaged insulation. This is a slow process and relies upon the liquid film being reconstituted at regular intervals, until such time as sufficient areas of char link up, when a catastrophic flashover will occur.

The general examination of the E&E bay on N653UA revealed no particular evidence that condensation, moisture, or spillage of liquids had occurred on or around the failed loom. Unless the aircraft had been parked in a powered down state in a cold moist atmosphere for a significant period of time shortly before the event, which was not the case, the general environment in the E&E bay was likely to have been warm. The loom in question, in common with most wires in this part of the aircraft, was remote from the aircraft skin where condensation was most likely to form and could self-generate 'warmth', albeit at a low level, from the various currents present in the large numbers of wires comprising the loom. In addition, the incorrectly fitted blanking plate on the chiller unit allowed a blast of air, warmer than ambient, to circulate amongst these wires. Despite the presence of a pool of water in the lower part of the bay, which was likely to have been caused by condensation generated from the 'cold' end of the chiller, it was considered unlikely that moisture had formed on the wiring looms around the chiller to act as the catalyst for the failure.

2.3.7 Conductive debris

Conductive debris of the type found in N653UA and other aircraft examined may precipitate flashover. Should adjacent defects exist in the insulation of two adjacent wires such that the conductors are exposed, then an arc may be struck by direct contact between the two exposed conductors, or by a particle or piece of conductive debris directly coming into contact with both exposed conductors. Alternatively, should the debris be sharp-edged, such as metallic 'swarf' or locking wire, then it could settle onto the surface of a loom, or possibly become embedded within the loom between wires. This would have the potential, under the influence of vibration over sufficient time, or movement of the loom during maintenance activity, to mechanically abrade through the layers of insulation and induce an arc between conductors.

Examination of numerous aircraft in the USA by the NTSB and in the UK by the AAIB revealed many to have wiring looms contaminated with conductive debris, and drill swarf in particular. In the context of this accident, another possibility was considered to have existed in that the cover for the chiller, manufactured from aluminium alloy sheet, had a sharp edge formed as a result of minor damage to the top aft outboard corner. From the SEM analysis, it appeared that a small sliver of conductive debris had been shed from this box, probably from this bruised corner, and had become embedded in the insulation of a wire in the outboard loom. Although this had not precipitated arcing at this location and there was no evidence of arcing directly between any wires of this loom and the chiller unit, it demonstrated the possibility that if such debris were to become embedded deep enough in the insulation of a wire to touch the conductor, then such a 'live' spot could more readily make contact with an adjacent exposed conductor, or ground, and trigger a loom failure.

As there seemed little doubt that most, if not all, of this observed mechanical damage to the insulation of the wires had been caused by the act of installing the replacement chiller unit, it was considered likely that similar damage had existed on the insulation of wire sections destroyed by the arcing events. The main difference between the wires from the two ends of the failed section of loom was that at the upper end the discontinuous wires terminated at slightly different locations, suggesting that the arcing of wires at the upper end were isolated events, whereas at the lower end the majority of the wires terminated at the same point. This was co-incident with the position of a cable tie, suggesting that all these wires had failed in one event. In view of the fact that this upper region of wire terminations was at a similar height to the top aft edge of the chiller, where mechanical damage to the insulation of at least two wires in this loom was found close to the failed section, it was considered likely that the origin of the loom failure had been in this upper area.

A sustained arc, or arcs, appeared to have occurred between adjacent wires and then travelled in a downwards direction. In one clear example, wire W272-10-12 (12 gauge 115V wire supplied through the P33 Bus Sect 2 Gnd Serv. CB, found tripped, and shown in Figure B-2), the conductor had remained intact but the individual strands had melted and fused back together to form a solid section of wire. This characteristic effect, also exhibited by a conductor in the failed loom referred to in the report on the loss of the RAF Nimrod (section 1.18.4), appeared to have resulted in this case from a sustained arc between the subject wire and several smaller gauge wires associated with the right thrust reverser indication system, where the heavier gauge wire was more able to remain physically continuous as the lighter wires melted away. As this wire had not disintegrated and was the only continuous wire in the group with such pronounced characteristics of a 'travelling arc', it was considered likely that this wire had supplied the power for the arc(s) until such time as its CB tripped.

Examination of the circuit diagrams containing the wires that were severed showed in all cases that power was supplied to these wires from the P6 power distribution panel, located on the right/rear side of the flight deck. When sustained arcing occurs between wires in a loom, it is a natural characteristic that the 'live' end of the severed wire 'burns' back to the source of power, assuming that the adjacent wire is at ground or a significantly different potential and the CB does not trip. In this case, however, although it might have been expected that the travelling arc would have moved upwards along the wires back towards the P6 panel, it was considered that it had in fact moved in a downwards direction, with the power from the continuous 12 gauge wire finding a path to ground, partly through circuitry connected to the smaller gauge wires. These travelling arcs appeared to have continued until the restriction of a cable tie was reached, whereupon this region of arcing ceased.

The aircraft had flown one sector after the chiller had been replaced and before the accident flight (Washington to Zurich). No CBs were reported to have tripped during this flight, or whilst the aircraft had been on the ground at Zurich, or for approximately 30 minutes after the next take off. The wire bundles in the E&E bay were generally fairly stiff and securely tied, and because of this it was considered unlikely that the initial arc had been struck between two adjacent wires with exposed conductors. The SEM examination of the wires revealed the presence of aluminium particles on the carbonised surface of the insulation of several failed wires, close to the upper region of wire terminations. All such particles identified by this method were small, soot covered and would not have been identified by optical microscopy; all had the appearance of having been molten and re-solidified. The elemental mapping and EDX spectrum analyses of these samples revealed them to be unlike the material from the chiller cover, but much more like one of the two types of aluminium alloy which comprised the swarf samples recovered from the E&E bay. All had been attacked to some extent by fluorine, presumably volatilised when the ETFE insulation pyrolised, indicating that these particles were unlikely to have contaminated the wire ends during, for example, removal from the aircraft and general handling. It was therefore evident that pieces of aluminium alloy, probably drill swarf, were associated with the arcing of these wires.

It could not be determined if such particles had directly triggered the initiating flashover by bridging the gap between two conductors exposed by mechanical damage to their insulation, or if such debris had been embedded within the loom and had cut through the insulation of two or more wires, or was merely embedded within the loom and was caught up in the arcing event. The fact that conductive debris contaminated the E&E bay of N653UA, and many other aircraft examined, and was found amongst the wires of the loom which failed on the Boeing 747 referred to in Appendix G, and has been found on and within the looms of many high time aircraft examined by the NTSB, indicated that this is a widespread problem affecting all aircraft. Contamination of aircraft by such debris would appear to occur mostly during 'airframe' maintenance when in service, but several instances of debris were reported in new build and low time aircraft.

In the case of N653UA, it was established that mechanical damage to wire insulation exposed conductors in the region of the loom failure and that disturbance of looms, and possibly of swarf, occurred in this area during chiller replacement on the day before the accident. The failure in the loom occurred to wires around the inside radius of the curved section, a location upon which it would be difficult for items of conductive debris to settle and initiate a failure between exposed conductors. However, there was a powerful abnormal circulation of warm air from the top to the rear of the incorrectly configured chiller, which had the potential to disturb loose lying debris and which was more than capable of transporting particles of swarf, should any have become caught up in this airflow.

It was considered most likely, therefore, that the initial arc in the failure sequence was struck by a section of aluminium alloy swarf making contact with the exposed conductors of at least two wires towards the upper end of the failed section of loom. Therefore, in addition to the previous recommendations made with respect to inspection and protection of wiring looms in the area of the forward galley chiller (section 2.3.2), the following safety recommendation is made:

> Manufacturers such as Boeing and Airworthiness Authorities such as the FAA should require that all operators and maintenance organisations should ensure that before maintenance activities take place which are likely to generate conductive debris, wiring looms and electrical equipment in the working area are provided with temporary protection against associated contamination, and that at the end of the maintenance activity such areas are specifically inspected to be free from such contamination.
> [Safety recommendation no 99-51]

2.3.8 Copper spatter

There was evidence within and around the failed section of loom of another important characteristic of such failures, molten copper spatter. In the specific case of this accident, damage was seen from impingement of molten copper on the insulation of wires not directly involved with the loom failure, and in at least one case the conductor had been exposed. Although this did not appear to have precipitated any flashovers in the adjacent loom, it was notable that most of the spattered material had (fortuitously) travelled forward and slightly outboard, missing this loom, and had impinged mostly onto the aft face of the chiller unit, melting the plastic foam filter. It was evident, therefore, that the loom immediately adjacent to that containing the failure had been at serious risk of associated wire insulation damage, and possible flashover, had this been sprayed with copper spatter since there was no physical barrier or sufficiently large separation between them. The two looms affected were both bound by the same green coloured cable ties (Figure B-1), which identified all wires as belonging to right generator and right redundant non-power circuits. In this particular case, therefore, any failure of the adjacent loom would not have compromised system redundancy philosophy, as intended by the separation requirements detailed in section 1.18.2. However, any such failure in the adjacent loom would have produced additional arcing, heat, smoke and the tripping of more CBs.

Elsewhere in the E&E bay, looms of different 'colour' identification were routed in close proximity. For example, the 'blue' loom outboard of the failure location contained wires associated with standby power circuits, battery dependant circuits, 'hot battery' and standby busses, and the three physically damaged wires reported upon. This blue loom was routed in close proximity (approximately 0.25 inch) to a 'red' loom which contained wires associated with the left generator circuits, left redundant circuits and non-power system circuits (Figure B-2). In specific areas of the aircraft where clearly identified 'threats' exist to wires, for example from tyre bursts, rotor failures etc, specific consideration is given to wire bundle separation, or protection. However, such considerations do not apply generally and the minimum separation required by the manufacturer between wire bundles within the pressure shell was 0.25 inch. Demonstrably, this distance may be easily traversed by molten copper globules ejected by an arcing event.

Many solidified copper globules of various sizes up to approximately 0.1 inch in diameter were recovered from the E&E bay local to the loom failure. Damage to the insulation of at least two wires (Figure D-5) and airframe insulation blankets beneath this area was directly attributable to impingement by molten copper. Hot copper globules were also found to have impinged upon the inner films of insulation blankets immediately below the failed loom location and the film had shrunk away from each point of contact to leave large roughly circular holes, an effect which accorded well with the observations contained in the FAA report referred to in section 1.18.5. There was no evidence of fire at these locations but, in view of the fact that there have been many instances of insulation blanket fires which have occurred on aircraft with differing types of insulation blanket bag materials, and which have been initiated by both electrical failures and hot drilling swarf, it was considered that there had been a risk of such a fire in this case as a result of molten copper spatter ejected during the period of arcing.

In Boeing Alert Service Bulletin 767-24A 0120 (section 2.3.2), operators were recommended to wrap wiring bundles adjacent to the chiller units in protective tape to improve abrasion resistance, and this was intended to be a permanent installation. This process also had the incidental benefit of increasing the protection of wires contained in such wrapping against the effects of any adjacent loom electrical failures, thereby enhancing the intent of the segregation philosophy of the different electrical/electronic systems on the aircraft in this area. In addition, these wrapped loom sections would also be shielded from any conductive debris generated in the future during maintenance activities and would further minimise the risk of copper spatter impingement onto wires, insulation blankets and equipment should a failure occur within the wrapping.

This Alert Service Bulletin specified several types of wrapping tape that could be used, but was specific only to the looms immediately adjacent to the chiller unit. It was readily apparent, however, that the glass fibre sheathing in the failed loom provided excellent protection for the wires that it contained. Although the insulation of those wires immediately abutting the wall of this sheath adjacent to the arced areas had been damaged by heat, it had not failed. Elsewhere on N653UA, and in other aircraft examined, this sheathing was also seen to have protected wires from mechanical damage. In consideration of this, and the apparent widespread contamination by conductive debris found in aircraft generally, the following safety recommendation is made:

> Boeing and other aircraft manufacturers should devise simple additional methods for the physical protection of all wiring looms installed in areas of high maintenance activity, with the ultimate aim of protecting all wiring looms in order to minimise insulation damage from conductive debris, maintenance activities and collateral damage from any adjacent catastrophic loom failures. [Safety recommendation no 99-52]

2.3.9 Improved circuit breakers and electrical system monitoring

The major disadvantage of the simple type of bi-metal circuit breaker which is generally used in the aircraft industry, as demonstrated in this accident, is that if the insulation of a wire becomes sufficiently damaged to initiate arcing onto some adjacent conductor, stabilised arcing will continue if the required arc sustaining current does not cause the circuit breaker to trip. Such continued arcing can then lead to a cascade of thermal damage to adjacent wires, with arcing escalation, progressive loss of electrical systems and the danger of a rapidly developing fire situation which may involve non-electrical systems and materials.

The increasing reliance on electrical power on modern and future public transport aircraft for flying control, engine and flight management systems with the associated increase in the use of computers, in addition to passenger services and entertainment systems, makes such aircraft more vulnerable to electrical fires and their potential affects, particularly if the flight crew do not receive timely warnings of electrical fire initiation.

Recent advances within the electrical industry in the design of electrical power systems have led to the development of solid state power controllers (SSPCs) which may offer many benefits over the simple thermal type CBs thus far used within the aircraft industry. In addition to higher reliability, compact size, lower power dissipation, faster 'smart' circuit breaking operation and lower cost, the use of SSPCs permits self test and improved computer interfacing.

Whilst the overcurrent characteristics of SSPCs can be designed for particular installations, their adoption would not prevent stabilised arcing of associated wiring where the arc sustaining currents were within the normal rating of the SSPC. However, the computer interfacing capability of SSPCs would allow improved circuit monitoring systems. Such systems might be capable of being programmed to react to particular characteristics of arcing, to sense abnormal current patterns or to identify and react to groups of tripped SSPCs induced by progressive loom(s) failure. As a result of such findings and considerations, the following safety recommendation is made:

> In view of the increased dependency upon electrical and electronic systems in modern jet transport aircraft, Boeing and other major manufacturers should conduct an assessment of the technology which may be available, currently and through research, to provide enhanced computer management/monitoring of such systems. The aim of the assessment would be to improve upon present protection against arcing/fire occurrence within dense areas of wiring looms, particularly within Electronic and Equipment Bays, and to provide fully reliable and timely warning systems for associated overheat/fire situations in such bays, and other zones of high electrical system density. [Safety recommendation no 99-53]

2.3.10 Right off-wing escape slide

The failure mode of the No 3 latch fitted to the slide compartment door of the right off-wing slide was a known problem to the manufacturer, and attempts had been made to improve latch performance generally by the issue of Boeing Alert Service Bulletin No 767-25 A 0174 in 1993. This called for latch replacement with a modified assembly, which had been incorporated into N653UA at build. As far as could be ascertained, all eight latches fitted to this aircraft were original fit. The fretting and wear exhibited by the jammed latch, and to a lesser extent by the opposite No 3 latch, indicated that these units and, most likely, the whole area of the off-wing slide compartment experience marked vibration whilst in flight. The obvious difference between the installation of the No 3 latch and the others is that a target plate for the door open/closed proximity sensor is mounted on the connecting rod, close to the No 3 latch. It was considered that this mass could have influenced the vibration characteristics of the rod and possibly induced the unacceptable levels of wear exhibited by the No 3 latch. Because of the likelihood that this problem is not limited to this aircraft, and the potentially serious consequences of an off-wing escape slide failing to deploy when required in any future emergency evacuation, the following safety recommendations were included in the AAIB safety recommendation document which was issued on 31 March 1998:

> The FAA, in conjunction with the manufacturer, should require operators of the Boeing 767 aircraft, equipped with off-wing slide systems, to visually inspect the slide door latches for signs of wear, with particular attention to the inside of the slot in the lower housing.
> [Safety recommendation no 98-17, made 31 March 1998]

> The Boeing Commercial Airplane Company should expedite action to improve the functional reliability of off-wing slide door latches on Boeing 767 aircraft which are so equipped.
> [Safety recommendation no 98-18, made 31 March 1998]

In response to this accident, and in view of the previous problems with these latches, Boeing issued Alert Service Bulletin (ASB) 767-25A0260 on 9 July 1998 which dealt with the inspection of all off-wing slide compartment door latches on aircraft with more than 6,000 flight hours. Repeat inspections were required every 6,000 hours or at 18 month intervals, whichever was later, and the manufacturer requested that operators reported on the outcome of such inspections. The inspection established a latch operation torque, measured at the integrator, and which if above a value of 175 lb inch required all latches if worn or damaged to be replaced. Part of the summary contained in the Service Alert Bulletin is re-produced below.

> 'Six operators have reported worn off-wing slide compartment door latches. Four operators have reported that these conditions have prevented off-wing slide compartment operation. This has caused non-deployment of one slide during an emergency evacuation and non-deployment of one slide during a test. On two other airplanes, an off-wing slide compartment door could not be opened for maintenance. A total of 58 latches have been found with slider (cam plate) end holes that were worn more than the maximum design dimension. On two latches, the edge of the hole had broken and the latch control rod was disconnected. On two latches, the slider jammed and would not allow operation of the latch mechanism to release the off-wing slide compartment door.'

The manufacturer stated an intention to review the design of these latches following receipt of the associated feedback data from operators after they had implemented this Alert Service Bulletin. In its later response to the Draft Copy of this report, Boeing stated that SB 767-25A0275 was scheduled for release in April 2000 (see later) and would require replacement of the off-wing escape slide disconnect housing. In addition, the manufacturer stated that the improved housing would be incorporated on new production aircraft.

The FAA responded to the above safety recommendations and ASB 767–25A0260 with the issue of a Notice of Proposed Rulemaking (NPRM) on 22 December 1999 which was applicable to certain models of the Boeing 767–200 and -300 series:

'This proposal would require repetitive inspections to detect wear or damage of the door latches and disconnect housings of the off-wing escape slide compartments. If wear or damage is found, the proposed AD would require replacement of these discrepant components with new components. This proposal is prompted by reports of worn and damaged door latches and disconnect housings of the off-wing escape slide compartments. The actions specified by the proposed AD are intended to ensure deployment of an escape slide during an emergency evacuation. Non-deployment of an escape slide during an emergency could slow down the evacuation of the airplane and result in injury to passengers or flightcrew.'

In a later response dated 22 August 2000, Boeing stated that SB 767-25A0275 was still awaiting approval by the FAA and that the FAA was not intending to raise an AD on this later SB, since the FAA considered that the AD action on ASB 767-25A0260 would be sufficient. This response raised the question that worn or damaged latches might only be required to be replaced if the latch operation torque check, measured at the integrator, was not passed satisfactorily. AAIB concern remains that such torque checks may not necessarily identify worn latch mechanisms.

3 Conclusions

(a) Findings

1 The flight crew was properly licensed, medically fit and adequately rested to operate the flight.

2 The decision to dispatch the aircraft from Zurich with the ADP 'Auto' function inoperative was in accordance with the requirements of the aircraft operator's Minimum Equipment List.

3 The decision to contact company maintenance control in order to seek advice on handling the aircraft systems problems in flight was the correct course of action.

4 The decision to cease any circuit breaker operations after the reset of the Cabin Services Outlet circuit breaker and the subsequent multiple circuit breaker trips was prudent and probably prevented further in-flight difficulties.

5 The commander's method of communicating the nature of the aircraft's technical problems to Air Traffic Control units was not in accordance with standard international procedures, or the company Operations Manual. This caused some confusion at LATCC and Heathrow over the nature of the problems and resulted in the Heathrow Emergency Services not being alerted to the fact that the aircraft had technical problems prior to the initiation of the evacuation on the taxiway.

6 A partial electrical failure of a wiring loom, involving arcing, had occurred at a location close to the upper aft face of the forward galley chiller unit located in the forward E&E bay and caused collateral heat distress to some wires in an adjacent loom, tripping of multiple circuit breakers and the generation of smoke.

7 Smoke from the arcing fire in the E&E bay was not detected by the associated warning system during the flight but was observed, after the landing, by cabin crew at the forward right seat row position.

8 Mechanical damage to the insulation of wires in two looms close to the aft upper edge of the forward galley chiller unit had been present before the flight and had probably been caused by contact with the forward galley chiller unit during its replacement prior to the preceding flight.

9 Although many circuit breakers had tripped as a result of the electrical shorting of wiring within the E&E bay, other circuit breakers had not tripped and had allowed travelling stable arcing to continue in flight and subsequent to the landing, before electrical power was removed from the aircraft.

10 A variety of conductive debris, particularly aluminium alloy swarf produced by previous drilling operations, was recovered from the region around the chiller unit, and generally within the E&E bay. In addition, the chiller unit had been wrongly configured for the forward location in the Boeing 767 causing the blast of warm exhaust air from the condenser heat exchanger to vent into the E&E bay, up against the underside of the cabin floor structure, and this air movement may have redistributed alloy swarf amongst the wiring.

11 Evidence of small re-solidified aluminium alloy globules, consistent with the type of alloy determined to comprise some of the drilling swarf recovered from the E&E bay, was found on several wires close to their severed ends indicating that drilling swarf had contaminated the wiring before the arcing event.

12 Molten copper globules up to 0.1 inch diameter had been ejected from the arcing wires and had impinged upon, and caused damage to, otherwise undamaged wire insulation in the area of the arcing, and to the chiller unit foam filter and the airframe insulation blanket material below the chiller, illustrating how such arc-induced copper 'spatter' could rapidly spread overheating/fire affects to adjacent areas, including thermal acoustic insulation blankets.

13 Excessive fretting/wear had occurred to the No 3 latch of the off-wing escape slide compartment door, causing it to jam the door release linkage when the slide had been commanded to deploy during the evacuation. Such vibration induced latch wear had been found on other aircraft and so Boeing issued Alert Service Bulletin 767-25A0260 on 9 July 1998 requiring inspection and reporting on latch wear to assist a latch design review.

(b) Causal factors

The investigation identified the following causal factors:

1 The tripping of multiple circuit breakers had been caused by the occurrence of electrical arcing and associated thermal damage to a wiring

loom adjacent to the aft/upper inboard corner of the forward galley chiller unit within the Electronic and Equipment (E&E) bay, with resultant thermal damage to an adjacent loom and smoke generation.

2 Prior damage to the wiring loom insulation adjacent the aft/upper corner of the chiller unit had occurred due to contact with such units during associated removal and installation; this chiller unit had been replaced on the day before the accident.

3 Aluminium alloy swarf was present within the E&E bay prior to the accident and had probably assisted the onset of arcing between adjacent damaged wires in the loom.

4 Incorrect installation of the chiller unit, with its heat exchanger exhaust fitted with a blanking plate, would have caused warm exhaust air to discharge from an alternative upper vent which was capable of blowing any aluminium swarf around the wiring looms.

5 The crew were unaware of the potentially serious arcing fire in the E&E bay during the flight due to failure of the bay smoke warning system to activate on the flight deck, because the density of smoke emitted by the arcing wiring in the bay was not apparently sufficient to be detected by the only smoke sensor, which was located in the card and rack cooling system exhaust duct.

6 The jamming of a severely worn latch, associated with the right off-wing slide compartment, prevented that escape slide from operating during the evacuation; such latches exhibited vibration induced wear on other aircraft.

4 Safety recommendations

It is recommended that:

4.1 The Boeing Commercial Airplane Company and the FAA should issue advice to pilots that whenever a series of apparently unrelated electrical/electronic system failures occur within a short period of time, the probability of an associated and developing electrical fire or smoke situation should be actively considered, necessitating the declaration of an emergency and initiation of a diversion to the nearest suitable airport. It should also be noted that in such situations, the fire or smoke condition may not be accompanied by any associated direct warning indications on the flight deck; in general, circuit breakers which have tripped should only be reset once, after a suitable cooling period has elapsed, but only then if deemed essential to the safe operation of the aircraft. The FAA should notify other regulatory authorities of its response to these aspects.

[Safety recommendation no 98-12, made 31 March 1998]

4.2 The FAA should require an immediate inspection of all wiring looms around the forward galley chiller unit installation within the electronic and equipment (E&E) bays on Boeing 767-300 aircraft to check for damage to loom wiring and general freedom from metallic debris and moisture.

[Safety recommendation no 98-13, made 31 March 1998]

4.3 The Boeing Commercial Airplane Company should emphasise in the Aircraft Maintenance Manual (AMM) that the appropriate handling equipment must be used whenever a galley chiller unit is replaced within the E&E bay on Boeing 767-300 aircraft, and include a specific warning in the AMM of the risk of potentially critical wiring damage occurring during such chiller unit replacement, in addition to a requirement to inspect for such wiring damage following chiller unit installation.

[Safety recommendation no 98-14, made 31 March 1998]

4.4 The Boeing Commercial Airplane Company should introduce, as soon as possible, additional protection of the wiring looms in the E&E bays of Boeing 767-300 aircraft to prevent potentially critical damage to such looms during installation of forward galley chiller units within such bays.

[Safety recommendation no 98-15, made 31 March 1998]

4.5 The FAA should require the installation of smoke or heat detectors within the E&E bays of Boeing 767 aircraft and other modern jet transport types, with associated flight deck warnings to alert crews to electrical overheat/fire situations within such bays at the earliest stage, so that appropriate and timely operational action can be taken.

[Safety recommendation no 98-16, made 31 March 1998]

4.6 Manufacturers such as Boeing and Airworthiness Authorities such as the FAA should investigate the feasibility of installing smoke and/or heat detectors within remote areas of high wiring and equipment density, such as the E&E bays of transport aircraft, with associated flight deck warnings to alert crews to electrical overheat/fire situations within such areas at the earliest possible stage, so that appropriate and timely operational decisions can be taken.

[Safety recommendation no 99-50]

4.7 Manufacturers such as Boeing and Airworthiness Authorities such as the FAA should require that all operators and maintenance organisations should ensure that before maintenance activities take place which are likely to generate conductive debris, wiring looms and electrical equipment in the working area are provided with temporary protection against associated contamination, and that at the end of the maintenance activity such areas are specifically inspected to be free from such contamination.

[Safety recommendation no 99-51]

4.8 Boeing and other aircraft manufacturers should devise simple additional methods for the physical protection of all wiring looms installed in areas of high maintenance activity, with the ultimate aim of protecting all wiring looms in order to minimise insulation damage from conductive debris, maintenance activities and collateral damage from any adjacent catastrophic loom failures.

[Safety recommendation no 99-52]

4.9 In view of the increased dependency upon electrical and electronic systems in modern jet transport aircraft, Boeing and other major manufacturers should conduct an assessment of the technology which may be available, currently and through research, to provide enhanced computer management/monitoring of such systems. The aim of the assessment would be to improve upon present protection against arcing/fire occurrence within dense areas of wiring looms, particularly within Electronic and Equipment Bays, and to provide fully reliable and timely warning systems for associated overheat/fire situations in such bays, and other zones of high electrical system density.

[Safety recommendation no 99-53]

4.10 The FAA, in conjunction with the manufacturer, should require operators of the Boeing 767 aircraft, equipped with off-wing slide systems, to visually inspect the slide door latches for signs of wear, with particular attention to the inside of the slot in the lower housing.

[Safety recommendation no 98-17, made 31 March 1998]

4.11 The Boeing Commercial Airplane Company should expedite action to improve the functional reliability of off-wing slide door latches on Boeing 767 aircraft which are so equipped.

[Safety recommendation no 98-18, made 31 March 1998]

E J TRIMBLE
Inspector of Air Accidents
Air Accidents Investigation Branch
Department of Environment, Transport and the Regions
August 2000

All safety recommendations are required to be taken into consideration and where appropriate, acted upon without delay. Regulation 14 of the Civil Aviation (Investigation of Air Accidents and Incidents) Regulations 1996 sets out the statutory responsibilities of any undertaking or authority to which a safety recommendation is communicated.