Boeing 737-236 series 1, G-BGJL: Main document

Aircraft Incident Report No: 8/88

Report on the accident to Boeing 737-236, G-BGJL at Manchester International Airport on 22 August 1985

Contents

Operator:	British Airtours
Aircraft Type:	Boeing 737-236 series 1
Nationality:	British
Registration:	G-BGJL
Place of Accident:	Manchester International Airport Latitude 53° 21' N Longitude 002° 16' W
Date and Time:	22 August 1985 at 0613 hrs All times in this report are in UTC

SYNOPSIS

The accident was notified to the Air Accidents Investigation Branch(AAIB) on the morning of 22 August 1985 and an investigation began that day. The AAIB team comprised Mr D F King (Investigator in Charge), Mr M M Charles (Operations), Mr S W Moss (Engineering,Powerplants), Mr C A Protheroe (Engineering, Fire), Mr E J Trimble(Engineering, Evacuation/Survival), Mr C J Ford (Operations),Mr D J Mearns (Operations), Mr R A Davis (Cockpit Voice Recorder)and Mr P F Sheppard (Flight Data Recorder).

At 0612 hrs G-BGJL, carrying 131 passengers and 6 crew on a charterflight to Corfu, began its take-off from runway 24 at Manchesterwith the co-pilot handling. About thirty six seconds later, as the airspeed passed 125 knots, the left engine suffered an uncontained failure, which punctured a wing fuel tank access panel. Fuel leakingfrom the wing ignited and burnt as a large plume of fire trailing directly behind the engine. The crew heard a 'thud', and believing that they had suffered a tyre-burst or bird-strike, abandoned the take-off immediately, intending to clear the runway to the right. They had no indication of fire until 9 seconds later, when the left engine fire warning occurred. After an exchange with Air Traffic Control, during which the fire was confirmed, the commander warned his crew of an evacuation from the right side of the aircraft, by making a broadcast over the cabin address system, and brought the aircraft to a halt in the entrance to link Delta.

As the aircraft turned off, a wind of 7 knots from 250° carried the fire onto and around the rear fuselage. After the aircraft stopped the hull was penetrated rapidly and smoke, possibly with some flame transients, entered the cabin through the aft right door which was opened shortly before the aircraft came to a halt.Subsequently fire developed within the cabin. Despite the prompt attendance of the airport fire service, the aircraft was destroyed and 55 persons on board lost their lives.

The cause of the accident was an uncontained failure of the left engine, intitiated by a failure of the No 9 combustor can which had been the subject of a repair. A section of the combustor can,which was ejected forcibly from the engine, struck and fractured an underwing fuel tank access panel. The fire which resulted developed catastrophically, primarily because of adverse orientation of the parked aircraft relative to the wind, even though the wind was light.

Major contributory factors were the vulnerability of the wingtank access panels to impact, a lack of any effective provision for fighting major fires inside the aircraft cabin, the vulnerability of the aircraft hull to external fire and the extremely toxic nature of the emissions from the burning interior materials.

The major cause of the fatalities was rapid incapacitation due to the inhalation of the dense toxic/irritant smoke atmosphere within the cabin, aggravated by evacuation delays caused by a door malfunction and restricted access to the exits.

1 Factual Information

1.1 History of events (see Appendix 1)

The two pilots and four cabin crew, (one male purser and three stewardesses), reported for flight KT28M, Manchester to Corfu,at 0500 hrs on the morning of Thursday 22 August 1985, with ascheduled departure at 0600 hrs. The pilots, the commander (a training captain) and a senior first officer, completed their pre-flight preparation. The purser briefed the cabin crew, allocating their duties before boarding the aircraft.

Upon reaching the aircraft, the commander carried out an external check while the co-pilot completed the pre-flight checks on the flight deck. The purser checked the safety equipment in the cabin,which was being prepared for the arrival of the passengers. The aircraft documents on the flight deck were examined and an entry in the technical log (entered on the previous day) relating to slow acceleration of No 1 (left) engine was discussed, the co-pilot having been a member of the crew on that occasion. As there had been no reported problems on the two flights after remedial action had been carried out, the commander signed his acceptance of the aircraft in the technical log.

It had been arranged that the co-pilot would fly the aircraft on this sector and a comprehensive discussion of their respective duties and the actions to be taken in the event of an emergency during take-off, before or after V1* (146 knots (kt)),took place between the pilots as part of the "Captain's Briefing".

The engines were started by the co-pilot and no abnormalities were observed during the start sequence. The commander requested clearance to taxi at 0608 hrs and, when cleared, taxied the aircraft to the holding point of runway 24 (Appendix 2). The cabin crew carried out the safety equipment demonstration to the passengers,after which the purser reported to the commander that there were129 passengers plus 2 infants, a total of 131 passengers on board.A child and one of the infants were seated on their parents' lapsat the aisle seats of row 10 (10C,10D), the row adjacent to the overwing exits, using child lap straps provided by the cabin crew.The two aisle seats of row 11 (11C,11D) were left empty.

The purser and the No 4 stewardess working in the forward partof the aircraft strapped themselves into their seats, each with a full harness. They were sitting on a stowable bench seat inthe left forward galley with their backs to the forward bulkhead,facing rearwards. Stewardess No 4 was in the outboard position adjacent to the left front (L1) door and the purser was in the inboard position nearer the centre of the galley and the cabin aisle; both were forward of a galley bulkhead resulting in a restricted view of the cabin. It is assumed that stewardesses Nos 2 and 3were occupying the crew seats in the rear galley, also on the left side of the aircraft, but facing forward with an unobstructed view of the passenger cabin (Appendix 3 Fig a).

The aircraft was cleared to line up on runway 24, and as fullnose-wheel steering was available only through a tiller on the left (commander's) side of the flight deck, the co-pilot assumed control after the commander had lined the aircraft up on the runway. Limited nosewheel steering is available through the commander's and co-pilot's rudder pedals. The aircraft was then cleared for take-off at 0612 hrs with the wind reported as 250° at 7kt (para. 1.7), and the co-pilot requested take-off power. Thecommander advanced the throttles and commented that the No 1 engine acceleration was acceptable - the first officer agreed that it was better than on the previous day, the auto throttle was selected and the engines achieved the required take-off power. During the take-off run the commander made the routine call of "eightyknots" which was confirmed by the co-pilot, and 12 seconds later a 'thump' or 'thud' was heard.

Immediately, the commander ordered "stop", closed the throttles and selected reverse thrust on both engines. He then checked that the speed brakes (spoilers) were extended. The maximumIndicated Air Speed (IAS) achieved was 126 kt. The commander thought that they had suffered a tyre burst or a bird strike.

Both reverser systems deployed and the right Engine Pressure Ratio(EPR) peaked briefly at 1.32 before settling at 1.25 for approximately5 seconds, after which reverse was de-selected on both enginesat a speed of about 70 kt; only the right engine reverser buckets retracted. The left engine EPR fell to zero within 2 seconds of the 'thud', and it remained at zero thereafter. The left engine high pressure spool speed (N2) decayed more gradually, with the result that the reverser buckets on the left engine were ableto deploy fully. However, by the time reverse was de-selectedthe N2 had decayed to the point where falling engine oil pressure inhibited the reverser operating system, locking-out the left engine system with the buckets fully extended.

The co-pilot had applied maximum wheel braking, however, because the commander considered a possible cause of the 'thud' to be tyre failure, and as there was considerable runway remaining ahead of the aircraft, he said "Don't hammer the brakes, don't hammer the brakes." The co-pilot responded by modulating the braking effort. At 45 seconds after the start of the take-offrun, 9 seconds after the 'thud', as the aircraft decelerated through 85 kt groundspeed the commander started to inform Air TrafficControl (ATC) by a Radio Telephone (RTF) call that they were abandoning the take-off. The fire bell on the flight deck started ringing almost coincident with the start of this transmission and he added as he cancelled reverse thrust, "it looks as though we've got a fire on number 1". Following a 3 second pause, 19 seconds after the 'thud' and before the crew had inhibited the fire bell, ATC transmitted, "right there's a lot of fire, they're on their way now." Coincident with the end of this transmissionthe fire bell was inhibited and as the ground speed reduced below50 kt the commander queried with ATC whether he needed to evacuate the passengers. The controller replied "I would do via the starboard side." This message was passed 25 seconds after the 'thud', 20 seconds before the aircraft stopped, as it decelerated through 36 kt groundspeed.

Some 6 seconds later, 14 seconds before the aircraft stopped,as the commander initiated the turn into link Delta he warned his crew of an evacuation from the right side of the aircraft by making a broadcast over the cabin address system; "Evacuate on the starboard side please." As the aircraft's groundspeed reduced through 17 kt, 10 seconds before it stopped, the purser opened the flight deck door and said, "Say again", seeking confirmation of the evacuation order. The commander repeated,"Evacuate on the starboard side", 8 seconds before the aircraft came to a halt.

Immediately the aircraft stopped the commander ordered the engine fire drill to be carried out on the left engine by the co-pilot,and as the passenger evacuation was to be carried out on the righthand side, shut down the right engine.

The passenger evacuation drill, a non-memory drill was called for by the commander and was read from the Quick Reference Handbookby the co-pilot. Before they were able to complete the drill the commander saw fuel and fire spreading forward on the left sideof the aircraft, opened the co-pilot's sliding window on the rightside of the flight deck and ordered him to evacuate the aircraft.This the co-pilot did by means of a fabric escape strap secured above the sliding window and he was followed down to the groundby the commander.

Passengers in rows 1-3 appear to have been initially oblivious of the fire which issued from the engine after the 'thud'. However,most of those seated aft of row 5, and in particular those aft of row 14 on the left side, were immediately aware of an intense fire. The flames were seen to cause some 'cracking and melting'of the windows, with some associated smoke in the aft cabin before the aircraft stopped. These effects, with the accompanying radiant heat, caused some passengers to stand up in alarm. A male passenger shouted "sit down, stay calm". Similar calls were then made by others seated mainly on the right side of the aircraft.Many sat down, but some found the pressure to move into the aisle irresistible.

The purser and stewardess seated in the left of the forward galleyarea during the take-off run heard a 'thud' which they too thought was a tyre burst. They were aware that the take-off had been abandoned and that reverse thrust had been selected. There were sounds of distress in the cabin and the purser leaned inboard in an attempt to improve his view and saw passengers standing up. He made a Public Address (PA) announcement for passengers " to sit down and to remain strapped in", released his harness and went into the forward part of the cabin. He saw fire outside the aircraft on the left side coming up over the leading edge of thewing and flowing back over the wing's top surface. There was nosmoke or fire apparent to him in the cabin at that time.

After the purser had confirmed the evacuation with the commander he repeated the evacuation call a number of times over the PA system. Then, as the aircraft was coming to a halt, he went to the right front (R1) door to open it and release the inflatable escape slide. The door unlocked normally but as it was moving out through the aperture the slide container lid jammed on the doorframe preventing further movement of the door. After spendinga short time trying to clear the restriction he postponed further effort and crossed to the L1 door. He cracked it open, ascertainedthat the forward spread of the fire was slow enough to allow evacuation from that door, opened it fully and confirmed the inflation of the slide manually. This was achieved about 25 seconds after the aircraft had stopped and coincident with the initiation of foamdischarge from the first fire vehicle to arrive. Evacuation began on the left side under the supervision of the No 4 stewardess, who had to pull free some passengers who had become jammed together between the forward galley bulkheads in order to start the flow.

The purser returned to the R1 door, lifted the slide pack in order to close the slide container lid, and cleared the obstruction.He succeeded in opening the door about 1 minute 10 seconds after the aircraft stopped and again confirmed the automatic inflation of the slide by pulling the manual inflation handle. Evacuation was carried out from this exit supervised by the purser.
Smoke emanating from the cabin quickly reached the galley area and became rapidly more dense and acrid. When the smoke began to threaten severe incapacitation, the forward cabin crew vacated the aircraft by the slides at their respective doors.

As the aircraft came to a halt and at the instigation of otherpassengers, a young woman sitting in row 10 seat F (10F), beside the right overwing exit, attempted to open it by pulling on her right hand arm-rest which was mounted on the exit hatch. Her companionin seat 10E, the centre seat of a row of three, stood up and reached across to pull the handle located at the top of the hatch marked "Emergency Pull". The hatch, weighing 48 lbs, fell into the aircraft, pivoting about its lower edge to lay across thepassenger in 10F, trapping her in her seat. With the assistance of a man in row 11 behind the women, the hatch was removed and placed on vacant seat 11D. The passengers in 10F and 10E then left the aircraft cabin through the overwing exit onto the wing followed by other survivors. This exit was open about 45 seconds after the aircraft stopped.

During the latter stages of the abandoned take-off, and just as the aircraft turned towards taxiway link Delta, the right rear(R2) door was seen by external witnesses to be open, with the slide deployed and inflated. A stewardess was initially visible in the doorway but the door and slide were obscured by thick blacksmoke as the aircraft stopped. No one escaped through this door.Two passengers remember seeing one of the two stewardesses from the rear of the aircraft struggling to direct passengers in the rear aisle. Neither rear stewardess survived.

The left rear (L2) door was opened by firemen some time afterthe fire had been extinguished.

In total, 17 surviving passengers escaped through the L1 door, 34 through the R1 door and 27 through the overwing exit including1 infant and 1 child in arms.

The air and ground movements controllers in the tower had seen the fire and smoke trailing behind the aircraft (Appendix 4) and had initiated 'full emergency' action. The air controller activated the alarm siren connected directly to the aerodrome fire servicestation (Manchester International Airport Fire Service - MIAFS),and gave brief details of the emergency to the MIAFS watchroom over the direct telephone link. The ground movements controller alerted the emergency telephone operator at the Manchester International Airport Exchange.

Members of the MIAFS who were on duty at the time, heard a bang and saw an aircraft decelerating on runway 24. Black smoke and flames were trailing from the left side of the aircraft and the firemen had already initiated their response when the crash alarmsiren sounded.

Two Rapid Intervention Vehicles (RIVs) attended first, one arriving at the aircraft coincident with, the other just after the L1 doorhad opened and its slide deployed, as passengers were about to start to evacuate. About 30 to 40 seconds later, as two major foam tenders took up position, the R1 door was opened fully and its slide deployed.

The MIAFS vehicles were positioned in order to attempt to keepthe escape routes clear of fire, and to attack the source of thefire.

A British Airways crew coach arrived at the accident site after about 4 minutes, carrying a Tristar cabin crew, who rendered first aid and comfort to the survivors and later to an injured fireman.They also led the survivors away from the aircraft and onto coachesfor transportation to a suitable holding area, and then on to hospital. Other ramp and airport authority vehicles also attended.

A third foam tender arrived at the site, some 4 to 5 minutes after the aircraft had stopped, having been retrieved from the paintshop. On arrival the driver saw a hand move above a man trappedin the right overwing exit. He left his cab, climbed onto the wing, and pulled a young boy clear over the body of the man trapped in the exit. This boy, who was the last evacuee to survive the accident, was rescued some 5¤ minutes after the aircraft stopped.

Approximately 7 minutes after the aircraft stopped it became clear that no more passengers were likely to evacuate unaided and firemen equipped with breathing apparatus entered through the R1 door.However, an explosion occurred which blew one of the fireman out of the door and onto the tarmac. Following this, the officer in charge, who was becoming increasingly concerned about the limited amount of water remaining on the fire fighting vehicles, ordered that no further attempts to enter the cabin should be made until a reliable water supply was established. The crew of one of the foam tenders was directed to go to the nearest hydrant on the airfield to refill but this, and several others were tried and found to be dry. (After 10 minutes delay this vehicle returned empty and was redirected to the hydrant at the fire station.)

During the fire, the tail section and the fuselage aft of thewings collapsed onto the ground due to thermal weakening of the structure. Eye-witness accounts of the time at which this occurred varied considerably, from an estimated 35 seconds after the aircraft stopped by the crew of RIV 2 to many minutes later by other witnesses.

At 0621 hours the Greater Manchester Council (GMC) Fire Service arrived at the North rendezvous point (RVP) and, after having waited for an escort which had to be redirected from the WestRVP, arrived at the site at 0626 hours, 13 minutes into the incident.Shortly after this a two man team with breathing apparatus entered the aircraft through the R1 door and reported a number of bodies. About 33 minutes after the aircraft stopped a male passenger was found still alive but unconscious, lying in the aisle near the front of the aircraft. He was the last person to be removed alive but died some 6 days later in hospital.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	2	53*	-
Serious	-	15	-
Minor/None	4	63	1 (fireman)

(* Including the man rescued after 33 minutes who died 6 days later in hospital.)

1.3 Damage to aircraft

The left engine combustion casing was split open, causing substantial secondary damage to the engine and nacelle, and the forward sectionof the No 9 combustor can had been ejected through the damaged engine casing. A fuel tank access panel on the lower surface of the left wing immediately outboard of the engine had been punctured,producing a large hole in the base of the main fuel tank.(Appendix5 fig a) The left engine nacelle and adjacent areas of wing had been damaged by fire and the wing had suffered additional damage caused by an explosive over-pressure within the fuel tank. The right wing and engine were undamaged.

Parts of the rear fuselage left sidewall together with most of the cabin roof were burnt away, and the rear fuselage and tailsection had collapsed to the ground. Most of the cabin interiorwas extensively burnt and the floor in the rear of the passengercabin had collapsed down into the rear cargo hold.

Those areasof the cabin interior which had escaped direct damage by the firewere covered with a thick coating of viscous soot. (Appendix 3photos e-f)

1.4 Other damage

There was some fire damage and fuel spillage on the runway and taxiway link Delta.

1.5 Personnel information

1.5.1

Commander	Male aged 39 years
Licence:	Airline Transport Pilot's Licence valid until 9 March 1986
Last medical examination:	Class 1 Medical Certificate valid until 30 September 1985 with no limitations
Part 1 Pilot-in command ratings:	PA 23, 30 and 39 Trident HS121, HS 748 Boeing 737 Series Certificate of Test: valid until 16 December 1985
Instrument rating:	Valid until 7 December 1985
Route check:	Valid until 29 November 1985
Emergency equipment and procedures check:	Valid until 18 January 1986
Flying experience:	Total all types: 8,441 hours Total Boeing 737: 1,276 hours Total last 28 days: 54 hours 25 minutes
Other ratings and approval:	Authorised by the Civil Aviation Authority (CAA) as a Type Rating Examiner, in respect of Boeing 737 aircraft. Also CAA approved as an Instrument Rating Examiner.
Duty time:	On the day before the accident the commander

was on duty for 4 hours 30 minutes, positioning by surface transport. Prior to this he had had the previous 2 days free of duty. Rest period before reporting for duty on 22 August 1985 was 15 hours 45 minutes.

1.5.2

Co-pilot: male aged 52 years

Licence:		Airline Transport Pilo
		Class 1 Medical Certi
Last medical examination:		30 September 1985, for distant vision an exercising the privil
Part 1 Pilot-in-Command		PA 18, 22, 25, 28 and ratings: Boeing 737-
Certificate of Test:		Valid until 30 Novem
Instrument Rating:		Valid until 25 Marc
Emergency equipment and procedures check:		Valid until 5 March 1
Flying experience:	Total all types:	
	Total Boeing 737:	
	Total last 28 days:	
Duty time:	The co-pilot had, on the day before the accident, flown a total of 5 hours 50 minutes within a flying duty period of 7 hours 09 minutes. The previous 2 days were free of duty, and his rest period before reporting for duty on 22 August 1985 was 17 hours 06 minutes.	

1.5.3 Cabin crew:

1.5.3.1

Purser: Male aged 39 years

	Air steward 9 years.
	Promoted Purser 5 May 1985.
	Safety Equipment and Procedures (SEP) refresher and check undertaken
	3 and 4 January 1985.
	Worked a duty period of
	7 hours 39 minutes the previous day.
Duty time:	Rest period before reporting for the accident flight, 14 hours 36 minutes. The 3 days before the previous duty period were free of duty.

1.5.3.2

Forward Stewardess (No 4):	Aged 26 years
	Employed on a seasonal contract from May 1984 until 31 October 1984. SEP certificate for Boeing 737 and L 1011 TriStar aircraft dated 1 June 1984. Re-employed April 1985,
	SEP certificate Boeing 737 and L1011 TriStar
	aircraft renewed 11 April 1985. Subsequently employed on a permanent basis.
Duty time:	Duty and rest periods were as for the purser. The preceding 2 days were free of duty.

1.5.3.3

Rear stewardess (No 2):	Aged 23 years
	Employed on a seasonal contract February 1985. Initial entry SEP certificate for Boeing 737 and L1011 TriStar aircraft dated 26 February 1985. Aircraft familiarisation for Boeing 737 and L1011 TriStar aircraft was completed on 15 and 16 March 1985 respectively. Previous experience was from May to August 1984 with an independent Boeing 747 operator.

Duty time:	Duty and rest periods were as for the purser. The preceding 7 days were free of duty

1.5.3.4

Rear stewardess (No 3):	Aged 27 years Employed on a seasonal contract February 1985. Initial entry SEP certificate for Boeing and L1011 TriStar aircraft dated 26 February 1985. Aircraft familiarisation on Boeing 737 aircraft completed 2 March 1985. No recorded previous experience.
Duty time:	Duty and rest periods were as for the purser. The preceding 3 days were free of duty.

1.6 Aircraft information

1.6.1 Leading particulars

Manufacturer:	Boeing Commercial Airplane Company.
Type:	Boeing 737-236 Series 1.
Engines:	Two x Pratt & Whitney JT8D-15
Date of Manufacture:	April 1981
Certificate of Airworthiness:	UK Transport Category (passenger) Valid to 2nd April 1986
Certificate of Maintenance Review:	Valid to 26 November 1985
Total airframe hours:	12,977 hours
Total airframe landings:	5,907 landings
Weight and balance:	
Maximum take-off weight	54,200 kg (119,511 lb)
Take-off weight (actual)	52,696 kg (116,195 lb)
Weight at time of accident	52,696 kg (116,195 lb)
Take-off fuel	12,370 kg (27,275 lb)
The weight and centre of gravity were well within the prescribed limits.	
Fuel	Jet A1

1.6.2 Engines

1.6.2.1 General

The Pratt and Whitney JT8D-15 is a two-shaft turbofan engine.The combustion section is can-annular and comprises 9 combustorcans enclosed by a Combustion Chamber Outer Case (CCOC) (Appendix5 Fig b). Compressor delivery air enters the CCOC, where a smallproportion is mixed with fuel in the combustor cans and ignitedto produce the combustion flame. The remainder of the compressorair flows around the inner and outer walls of the cans to providea cooling flow (note: the combustion temperatures are above themelting point of the can materials and thus the cooling flow isessential to maintain can integrity). Whilst the combustor canscontain the combustion process, the CCOC must withstand the compressordelivery pressure (in the order of 240 psi at take-off conditions)and it is therefore essentially a pressure vessel. It is basicallya one-piece tube of AMS 5603 steel alloy with flanges fore andaft which attach to the engine casing by two rings of steel bolts.

The combustor cans themselves comprise a cast Stellite dome, orhead, and 11 liners of Hastelloy X sheet material (Appendix 5Fig c). The dome incorporates swirl vanes which direct the incomingcompressor delivery airflow into the can prior to mixing withfuel from the fuel nozzle which is inserted into the centre ofthe dome. The fuel nozzle also provides radial location of theforward end of the can. Axial location is achieved via an integrallug on the dome which picks up on a mounting pin bolted to thediffuser case. The remainder of the can is constructed from 11rings (liners) of sheet Hastelloy X material of varying diametersto achieve the desired profile of the can. Liner 3 incorporatesthe flame transfer ports to adjacent cans. The liners are resistanceseam-welded to each other. The aft end of liner 11 is a slidingfit in the transition duct bulkhead, which provides radial supportfor the rear of the can but allows movement in an axial directionto accommodate thermal expansion and contraction. Can numbers4 and 7 also have an igniter plug boss incorporated in Liner 2.All cans are fitted with an "air scoop" over the topof liner 2, as part of a programme to reduce the engine's smokeemission.

Cooling of the liners is achieved by directing the relativelycool compressor delivery air over the outside surfaces of thecan and onto the inner surface through small film-cooling holesadjacent to each liner joint. Since there is a pressure differentialof about +3% of compressor delivery pressure from outside to insideof the can, cooling air will flow inwards. Larger holes in theliner also allow larger volumes of air to flow in locally to cooland adjust the combustion gas flow pattern inside the can.

The combustor cans fitted to G-BGJL's engines were to Pratt andWhitney modification standard 5192, ie. the latest standard applicableto the JT8D-15 at the time of the accident. The modification wasintended to overcome various problems encountered on the previousstandard of can, including cracking of the seam weld between linernumbers 2 and 3. This was felt to be particularly undesirablebecause it occurred under the air scoop and could only be detectedby radiographic techniques. It was stated by the manufacturerthat this modification standard would provide a combustor canof "improved durability".

The combustion section is further enclosed by an aluminium alloyfan case which forms the by-pass duct and is the externally visiblepart of the engine casing in this area.

Each engine was fitted with a thrust reverser system typical ofreverser systems fitted to this category of aircraft, comprisinga pair of clam-shell doors which swung on linkages from theirstowed position (around the exhaust duct) into a position aftof the engine, where they deflected the exhaust gases sidewaysand slightly forwards to provide reverse thrust (Appendix 6 Figa).

Boeing 737 installations differed from the norm however, byhaving the 'split plane' of the reverser doors inclined at approximately45° to the horizontal, with the lower door inclined outboard,so as to limit the ingestion of debris blown up by the reversedexhaust efflux. The thrust reverser door actuating system wasinhibited below a critical engine oil pressure, nominally 35 psi.

1.6.2.2 History of the engines fitted to G-BGJL

(a) Engine serial number P702868 (Left)

This engine was delivered new to British Airtours in April 1980whilst fitted to aircraft G-BGJG. In the winter of 1983/1984,the engine was removed and stripped for a sample layout (see paragraph1.17.2). At that time a Light Maintenance Inspection (LMI) wasperformed and the engine was re-assembled with repaired combustorcans from another engine, serial number P702946. This engine hadbeen prematurely removed, having run 7482 hours/3371 cycles sincenew, in September 1983 due to a pilot report of high exhaust gastemperature and visible compressor damage. The engine was strippedand it was found that a failure of the 13th stage compressor outershroud had caused damage to the 13th stage compressor blades.It was considered economically advantageous to perform an LMIat this shop visit, thus the combustor cans were inspected andrepaired as necessary - this work being completed on 16 November1983. Although the actual lengths of cracks found in the canswere not recorded, the Engine Strip Report for P702946 noted that"5 off combustion chambers (combustor cans) exhibited considerableburning and cracking to the 3rd liners adjacent to cross-overtubes". After the accident to G-BGJL, it was possible todetermine the crack lengths from radiographic plates which hadbeen retained. These radiographs had been taken to inspect forcracking in the 2/3 liner area (ie under the air scoop) but, fortuitously,the film also covered the area up to liner 5, specifically the3/4 liner joint.

Examination of the radiographs showed that the can exhibitingthe most cracking in the 3/4 liner joint was can No 9, serialnumber TS351 (installation position was the same on both engines).A circumferential crack 160 mm in length extended in the thirdliner from the male flame transfer tube around the outboard faceof the can, in the area of the seam weld to the fourth liner.A second crack 25 mm in length, barely discernible from the radiograph,was seen about 50 mm further round from the main crack (Appendix5 Fig d).

Can No 7 exhibited cracking in a similar area to the main crackin can No 9 but only some 75 mm in length. Can No 6 also had acrack of about 60 mm in this area. The remaining cans had eitherminor circumferential cracking of less than 50 mm in length or,in three cases, no discernible circumferential cracks.

It was also noted from detailed examination of the radiographsof the can set that can No1 had a distinctive area of multiple"branchy" cracking in the 3rd liner area - some of thecracks having joined together and liberated a small triangularpiece roughly 2.5 mm along each side. The length of the circumferentialcracking was, however, only some 35 mm.

All the above mentioned cracks in the cans were addressed by directfusion weld repairs during the LMI. Pre-weld Solution Heat Treatment(SHT) and post-weld stress relief (see paragraph 1.17.2) werenot carried out.

The cans were installed in engine P 702868 which was fitted toG-BGJL on 2 February 1984 and ran a further 4,611 hours/2,036cycles before the accident flight. The total hours/cycles runon the cans were thus 12,093/5,397, whilst the engine itself hadrun 14,503 hours/6,552 cycles.

(b) Engine serial number P 702841 (Right)

This engine was delivered new to British Airtours in January 1980whilst fitted to aircraft G-BGDE. It had had three unscheduledremovals in September 1982, August 1983 and October 1984. It wasfitted to G-BGJL on 7 February 1985. At the time of the accidentit had run 9,946 hours/7,172 cycles since new. There are no indicationsthat the performance of this engine played any significant partin the sequence of events which led up to the accident.

1.6.2.3 Entries in the aircraft's technical log concerning performanceof the left engine and associated rectification action

The aircraft's technical log and technical records were examinedto determine the number and nature of crew-reported defects onthe left engine since the installation of engine serial No P702868in February 1984. Of particular interest were flight crew reportsof slow acceleration, slow start and throttle stagger (see paragraph1.17.2). A large number of these were found as detailed below:-

Throttle Stagger	Slow Acceleration	Slow Acceleration & Throttle Stagger	Slow Start
25.9.84	18.2.84	11.2.84	11.7.85
14.6.85	6.5.84	16.6.85	16.7.85
	6.5.84	20.8.85	
	6.11.84	21.8.85*	
	29.12.84		
	29.12.84		
	16.1.85*		
	17.1.85		
	25.1.85		
	29.7.85.		
	5.8.85		

Dates marked with an asterisk * indicate where the flight crewalso commented on a low ground idle N2.

Slow acceleration is based on the time taken for the engine toreach the "stand up" setting of 1.4 EPR from groundidle.(" stand up" - both throttle levers moved to thevertical)

"Throttle stagger" refers to a mismatch in the positionof the pilot's throttle levers when the EPR for both engines arematched. In all cases where throttle stagger was reported, theleft engine lever was forward of the right engine lever to achievethe same EPR.

The three log entries for the month of August, 1985 are discussedin greater detail later in this section. The other 16 entrieswere dealt with in a variety of ways, including times when thecrew were asked to accept the aircraft and to report further onthe symptoms - on occasions no further crew comment was made.Where actual work was performed on the aircraft, it was alwaysof a minor nature (eg checking the PS4 line for leaks and moisturecontamination, checking engine bleed air for leaks). This rectificationaction appeared to cure the symptoms and, consequently, at notime was the engine combustion section checked for a disruptedgas path. Trim runs (see paragraph

1.17.2.3) were performed on16 February 1984 and 18 June 1985 but the log merely records thatthey were carried out with no indication of any Fuel Control Unit(FCU) adjustment having been performed. Following the "slowacceleration" report on 17 January 85, the ground crew reportedthat they found the left engine ground idle N2 speed to be 1%low and adjusted the FCU accordingly.

The following is a verbatim extract from the Technical Log forthe 5th, 20th and 21st August 1985 (Engine related reports only):-

Date	Defect	Action
5.8.85	No 1 (left) engine very slow to accelerate both forward and reverse	No 1 FCU damper versilubed (lubricated) PS4 line blown through
20.8.85	No 1 engine slow to spool up on take-off and about 1¤-2 inches throttle stagger at 1.4 EPR	PS4 pipes checked for leaks. Fuel system bled. Please give further report.
21.8.85	No 1 engine does not accelerate for 5 or 6 secs with thrust lever halfway up quadrant. Ground idle is very low: 28% N1 and 50% N2. Autothrottle drops out due to the amount of stagger at first. In the air, No 1 engine slower than No 2 as well.	ADD* raised for full trim run with test set to be carred out on No 1 engine. PS4 filter water drain trap removed - some water found. Ground idle adjusted 1 turn increase. Now matches No 2 engine but still seems slow to No 2 engine. Would crews please report further. (*Acceptable Deffered Defect)

The aircraft flew a further two sectors, a total sector time of7 hours 14 minutes, arriving back at Manchester at 0431 hourson 22nd August 1985. No flight crew comment was made in the AircraftTechnical Log regarding the condition of either engine.

Statements made by the two technicians tasked with attending tothe log entry on 21st August confirm the information containedin the "action" column above. Having consulted withBritish Airtours Base Engineering at Gatwick, they elected toremove and replace the PS4 filter water-drain trap and adjustthe ground idle trim screw by one turn in the 'increase RPM' direction.Both engines were then started normally and it was observed thatboth N2 gauges were reading 58%. The throttles were advanced toa point where the EPR gauges began to register a change. Theyreported that there was still about 0.5 inches of throttle staggerat the top of the levers when the EPR readings matched but wereevidently satisfied that the acceleration times of both engineswere similar and acceptable. Subsequent examination of the aircraft'sFlight Data Recorder indicates that the left engine acceleratedat about the same rate as the right but did not achieve the samelevels of N2 and EPR during the ground run. This is consistentwith the comments regarding throttle stagger and "still seemsslow compared with No 2" (right) ie if both throttles wereadvanced together, then the right engine would achieve higherRPMs and EPRs than the left engine.

The ground crew also raised an ADD entry in the log to performa trim run at the next visit to Gatwick (where a trim test-setwas held). It would also appear that, had the flight crews remaineddissatisfied with the performance of the engine, the aircraftwould have been re-rostered into Gatwick on the 22nd August forthis work to be performed.

1.6.3 Engine fire warning and suppression systems

The aircraft was fitted with separate FIRE and OVERHEAT detectionsystems designed to alert the crew to excessive temperatures withinthe engine nacelles. Flight deck indications were by means ofwarning captions and indicators, augmented in the case of a FIREwarning by an audio warning (bell sound). Built-in test equipmentenabled serviceability checks to be carried out on both fire andoverheat systems before each flight.

G-BGJL was typical of Boeing 737 (and other current commercial)aircraft in being equipped with a conventional "two shot"main engine fire suppression system.

1.6.4 Fuel system

Fuel was carried in three fuel tanks, all of which were integrallyformed within the aircraft's wing structure. The two main tanksof 4,590 Kg capacity each were formed (one in each wing) by themain torsion box, and extended from the root rib outboard to aposition close to the wing tip. The wing centre section formedthe centre auxiliary tank, which had a capacity of 7,416 Kg.

Access to the interior of each main wing tank was provided bymeans of a total of 13 elliptically shaped removable access panelsvarying in size from approximately 18" by 10" inboardto 16" by 6" outboard, which were secured flush withthe lower skin surface and sealed against fuel seepage by an '0'ring gasket. The access panels were manufactured from a cast aluminiumalloy material and had stiffening webs integrally formed on theupper (internal) surface. The panels were nominally non-stressedcomponents so far as flight-loads on the wing were concerned;impact strength did not form a part of the design requirementsfor the wing lower skin, nor the access panel. The cast aluminiummaterial had an impact strength approximately one quarter thatof the lower wing skin, which formed the tank floor proper.

1.6.5 Air conditioning system

The aircraft had two air conditioning packs, each with a maximumdelivery rate of 78 lb/min, which were supplied by the main enginesor by the Auxiliary Power Unit (APU). The conditioned air wasdistributed throughout the cabin via a system of manifolds andducts leading to the overhead nozzles and zone supply louvres.Exhaust (stale) air left the cabin via floor level louvres locatedin the cabin side-wall panels, and made its way into the cavitiessurrounding the cargo hold liners, ie the interspaces betweenthe fuselage outer skin and the cargo hold side-lining, and thecargo hold roof-lining and the cabin floor (Appendix 6 Fig b).(The fibreglass wool insulation blankets, which fill the structuralcavities between the cabin liners and the outer skin, were reducedin thickness around the hold areas to facilitate the passage ofexhaust air). Approximately 56% of the total cabin exhaust airwas routed via the floor louvres aft of the wing into the aftcargo hold cavity, from where it was dumped overboard via themain outflow valve situated in the rear fuselage underbelly. Approximately36% was routed via floor level grills in the forward cabin, intothe forward hold cavity, and thence into the electronic equipmentbay where it was used to cool the equipment before being dumpedoverboard via the electronic equipment bay exhaust. The remainderof the exhaust air left the aircraft via various local vents andas a result of general leakage.

1.6.6 Cabin windows

Each cabin window comprised an assembly of three acrylic ("perspex")panels mounted into individual recessed forged aluminium frames(Appendix 6 Fig c). In order to improve their physical properties,the outer transparency panels, (the primary load-bearing panels),were stretched during manufacture whilst in a heated (soft) state,and allowed to cool and harden in the stretched condition. Thecentre panels, which were failsafe load-bearing panels designedto provide a back-up in case of a failure of the outer panel,were manufactured from cast acrylic. The inner transparencieswere thin panels designed primarily to protect the load-bearingpanels from damage.

The two load-bearing panels in each aperture were located mainlyby the recessed shape of the aperture housing, and were held intothe aperture by a series of retention clips arranged around theperiphery. The edges of the acrylic load-bearing panels were fittedwith rubber gaskets to provide an air seal. The inner transparencypanels were attached to, and effectively formed a part of, thedecorative window reveal panels.

Acrylic is a thermoplastic material which starts to soften attemperatures of approximately 100°C.

1.6.7 Fuselage construction

The fuselage was of conventional construction utilising aluminiumalloys for the main structural components and the external skin.

The fuselage cross-section was formed by a series of approximatelycircular ring frames spaced at regular intervals (typically 20inches apart) along the length of the fuselage. Longitudinal stiffeners(typically of a 'top-hat' section) were spaced at intervals ofapproximately 10 inches around the circumference of the frames,and the whole structure was clad in skin panels which were rivetedto the frames and longitudinal stiffeners. In the area of therear cargo hold, the fuselage skin thickness was 0.036 inches.

At mid height on the fuselage (ie at cabin floor level) the longitudinalstiffeners extended the full width of the ring frame, and wereknown as "crease beams" (Appendix 6 Fig b). A seriesof floor beams, also fabricated from light alloy, were attachedtransversely to the frames at this same level, and these wereconnected fore-and-aft by further floor beams running longitudinally.

The cabin floor comprised a number of fibreglass/nomex honeycombpanels, which were attached to the floor beams. In the web sectionsof the crease beams there were a series of large holes to allowthe passage of air conditioning exhaust air from the cabin sectionabove the floor through to the cavity surrounding the cargo holdbelow.

The space below cabin floor level in the centre of the fuselagewas occupied by the mainplane centre section carry-through structure,which also formed the centre fuel tank. The greater part of theremaining sub-floor space was occupied by the aft and forwardcargo holds and the landing gear bays, except at the extreme forwardand aft ends of the fuselage, which housed various system components.The cargo holds were accessed only via separate external cargodoors on the right side of the fuselage.

Within each cargo hold area, the internal space was lined by athin, wear resistant fibreglass laminate, known as the cargo holdliner. The cavity formed between the cargo hold liner and theouter fuselage skins and between the liner and the cabin floorpanels was used to provide an exit path for air conditioning exhaust-airleaving the cabin interior.

1.6.8 Internal configuration - Approval and evacuation certification:

The aircraft was fitted with 130 passenger seats, two double andone single cabin crew seats. One of the double crew seats wasforward of door L1 facing rearwards and the other double aft ofdoor L2 facing forwards. In the forward passenger cabin a pairof full height galley bulkheads were positioned just aft of thetwo doors, L1 and R1. In the aft end of the cabin a full heightstowage unit was located just forward of door R2 with a singlecrew seat mounted on the rear of it, facing aft. (Appendix 3 Figsa-b)

This configuration was in compliance with British Airways ConfigurationModification No 25C211, Drawing No 1-54378 certified by the BritishAirways authorised engineer as being in compliance with the appropriateregulations on the 20 November 1981.

This drawing specifies a seating pitch of:

	Rows 1-9	Rows 9-10	Rows 10-22
Pitch	30 ins	31 ins	29 ins

In addition, this drawing specified that the outboard seats atrow 10, ie 10A and 10F, should be of a type modified to preventthe seat-backs from hinging forward and row 9 seats should haveno recline, in order that access to both overwing exits shouldnot be impeded.The seat backs of row 9, in common with the majorityof seats, could be folded forwards to create more room for theupper body of any person moving between rows 9 and 10 to the overwingexits. The Boeing 737 Type Certificate allowed the 737/200 modelto be equipped with 130 passenger seats provided there was compliancewith Federal Airworthiness Regulations (FAR) 25.2(b),(c) and (d).The Emergency Evacuation requirements for this Public Transportaircraft were in accordance with FAR 25.803 (Appendix 7).

United Kingdom evacuation certification of this aircraft type,with 130 passenger seats, was carried out at Luton Airport onthe 26 November 1970 using a Britannia Airways Boeing 737-204model. The 130 passengers and 5 crew were evacuated from the leftexits (ie aft, overwing and forward) in 75 seconds.

1.6.9 Emergency equipment and exits

The aircraft was equipped with four main cabin doors ('Type 1')(para 1.17.6), two overwing emergency exits ('Type III') and twosliding-window emergency exits on the Flight Deck (Appendix 3Fig a).

Each main door incorporated a slide pack which when used in the'automatic' mode, ie with the slide 'girt-bar' pre-engaged intwin floor-mounted brackets, was designed to provide automaticinflation of the slide when the door was opened in an emergency.In addition, each slide included a 'manual' release handle whichcould be used to achieve inflation if it had not occurred automatically.

The overwing emergency exits were located at either side of row10 and were intended for ground evacuation of centre cabin passengers,or as the primary exits for use after a sea-ditching (Appendix3 Fig c). For the latter purpose, these exits were each equippedwith a webbing-type escape rope/lifeline, anchored to the upper/forwardcorner of the aperture, with a snap-hook on the other end forattachment to a lug located on the upper surface of each wingnear the trailing edge. These lifelines were some 17 feet in lengthand designed to provide evacuees with a means of stabilising themselveswhile on the wing upper surface prior to boarding the rafts. Fromthe anchor point a single thickness of line ran along the topof the exit to a storage tube at the upper aft edge of the aperture.This portion of the line was designed to be held in position byretaining clips. The remaining line was stored in the tube attachedto the structure with the exception of the snap hook which waslocated in a pouch at the upper aft corner of the exit. For groundevacuation, arrows painted on the upper surface of each wing wereintended to lead evacuees to the trailing edge and down the extendedflaps.

On pulling the overwing exit hatch release handle the hatch, weighing48 lbs, pivots inboard about its lower edge and requires liftingto remove it from the aperture to make the exit available.

The passenger flight safety card exercised a large amount of artisticlicence in representing the area local to the overwing exit.(Appendix3 Fig d) It indicated a large area in which to stand to removethe hatch and showed the hatch then being placed on the row 10seats, the armrests raised. Even if this was achievable, bearingin mind the weight of the hatch and the fact that armrests arenormally down, (always for take-off and landing), in this positionit represents a further obstacle to anyone trying to reach theexit from the aisle. Furthermore the person opening the hatchwas depicted in an all blue 'uniform' in the same way as werecabin crew in other sections of the safety card, possibly leadingpassengers to think that the hatch would be opened by a memberof the crew.

The Flight Deck had two sliding-window emergency exits for useby the pilots, with two associated webbing-type escape ropes storedin the overhead above the windows.

The cabin crew stations at the forward and aft passenger doors(ie left) were each equipped with an interphone and passengeraddress microphone. The forward cabin crew were also providedwith two 'Scott' smokehoods, located in a cupboard stowage facingtheir bench-seat. One 1.5 Kg capacity Bromochlorodifluoromethane(BCF) fire extinguisher bottle (discharge duration 15 seconds)was also located in a stowage locker facing this seat. The otherthree smokehoods, for use by the cabin crew, were stored in theoverhead 'bin' at row 18 (right). One 1.5 lbs capacity water fireextinguisher was stored in this area of the cabin within the rightoverhead at row 20. A further two, 1.5 Kg BCF extinguishers werelocated on the aft wall of the rear right bulkhead. Two megaphoneswere available for cabin crew use, one stored in the forward leftoverhead bin at row 2 and the other in the aft right overheadat row 18.

Ten portable oxygen bottles were stored in the cabin overheads;two (for crew use) were located at row 2 right, two units eitherside of the aisle at row 10 (for passengers) and four units withinthe overhead at rows 20-21 right, of which three were designatedfor crew use.

1.7 Meteorological information

The accident happened during daylight.

The weather recorded at Manchester Airport at 0550 hrs was:-

Surface Wind:	270°/5 kt
Visibility:	25 km
Cloud:	1 okta at 1,400 feet
Temperature:	+ 13°C
QNH*:	1014 millibars

*(Corrected mean sea level pressure setting)

The weather recorded at 0620 hrs was:-

Surface Wind:	260°/6 kt

Visibility:	1,000 metres in smoke
Cloud:	1 okta at 1,400 feet
Temperature:	+ 13°C
QNH:	1015 millibars

The Manchester Automatic Terminal Information Service (ATIS),information 'C' was received by the crew prior to starting engines.This gave the surface wind as 280°/6 kt, variable 240°-320°.When ATC cleared the aircraft for take-off, they passed a surfacewind of 250° at 7 kt. The runway was dry.

1.8 Aids to navigation

Not applicable.

1.9 Communications

1.9.1 ATC

The RTF callsign of this flight was Beatours 28 Mike and VeryHigh Frequency (VHF) communications were entirely normal.

Communications on the Ultra High Frequency (UHF) frequencies usedby the fire service and ATC, together with those on the telephonelinks, were normal.

1.9.2 Aircraft public address (PA)

The aircraft's PA system allowed announcements to the passengersto be made from the flight deck, the forward galley area, andthe rear galley area. The system had two gain (volume) levels,the lower for use before engine start, and the higher gain (by6 decibels) selected automatically by the operation of the leftengine oil pressure switch, for use after engine start and duringflight. The failure of the left engine therefore caused the systemgain to revert to the 'low' setting, significantly lowering thevolume at the time the purser instructed the passengers to remainseated and the commander ordered the evacuation A number of passengersdid not hear these announcements, however, whether this was dueto the lower volume or the effect of the noise level in the cabincould not be determined.

1.9.3 Interphone system

The aircraft's interphone system comprised a Service Interphone,allowing communication between the flight crew, cabin crew andground engineers, and a Flight Interphone to permit communicationbetween the flight crew and a ground crew member without interferencefrom the Service Interphone.

It was possible to communicate with the flight deck from the forwardand rear cabin crew stations using the Service Interphone, butits use was not encouraged during periods of high flight crewworkload, such as take-off or landing, and it was not used followingthe 'thud'.

1.10 Aerodrome information

1.10.1 Manchester International Airport (Appendix 2)

Manchester International Airport, located 7.5 nm south west ofManchester was operated by Manchester International Airport Authority.The airport had a single runway 06/24, 3,048 metres in lengthby 46 metres wide with hard shoulders extending to 23 metres eachside, giving a total paved width of 92 metres. The take-off runavailable was 3,048 metres with a take-off distance availableof 3,200 metres. The surface was concrete/asphalt.

The main terminal and manoeuvring areas were all on the northernside of the runway. The southern area was used almost exclusivelyfor light aircraft and general aviation activities.

The scale of rescue and fire fighting (RFF) protection at ManchesterInternational Airport met the requirements of CAP 168 for a Category8 Aerodrome. Operation of a Boeing 737 only requires protectionat Category 6 level at best.

1.10.2 Media requirements, media provision and discharge rates

Under clause 2 of the aerodrome licence, Manchester InternationalAirport was required to provide the following minimum amountsof fire fighting media appropriate to a category 8 airfield:-

Water for production of fluorochemical foam	= 18,200 litres
Fluorochemical foam concentrate	= 1.080 litres
Discharge rate water/foam	= 7,200 litres per minute

Complementary media requirement was:-

450 kgs of Dry Powder or 450 kgs Halon (BCF) or 900 kgs CarbonDioxide or a combination of the above. 50% of the complementarymedia could be substituted by water for production of fluorochemicalfoam. In that event a substitution rate of 1 kg for 1 litre ofwater applied.

The following amounts of media were available for immediate responseat the time of the accident:-

Water for production of fluorochemical foam	= 24,244 litres
Fluorochemical foam concentrate	= 2,850 litres
Maximum discharge rate water/foam	= 13,183 litres

1.10.3 Fire fighting and rescue equipment

On the day of the accident, Manchester Airport fire service hadthe following vehicles on immediate standby:-

Two rapid intervention vehicles (RIVs):

Each vehicle carried 50 kgs of Halon BCF, 817 litres of water,73 litres of Aqueous Film Forming Foam (AFFF) concentrate andhad a maximum (mixed) foam discharge rate of 908 litres/minute.These vehicles were based on modified Range Rover chassis andtheir purpose was to provide rapid access to the fire - to give'first aid' fire protection pending the arrival of the major foamtenders.

One 'Protector' major foam tender, carrying:-

100 kgs of Halon BCF, 9,080 litres of water, 1,067 litres of AFFFconcentrate and having a maximum foam discharge rate of 4,540litres/minute,

One "Jumbo" major foam tender (J1), carrying:-

13,620 litres of water, 1,634 litres of AFFF concentrate and havinga maximum foam discharge rate of 6,810 litres/minute.

Each of the major foam tenders carried sufficient foam concentratefor two full water tank loads, ie their water tanks could be replenishedonce before there was a need to re-charge with foam concentrate.

These appliances, together with a small ambulance, were on standbyin the airport fire station located just north of the intersectionbetween taxiways 2-North and 3, some 825 metres from the positionwhere the aircraft stopped. A second fully equipped Jumbo foamtender (J2) was undergoing re-painting in hangar 3, some 550 metresfrom the fire station. Additionally, a Land Rover fire vehicle,which at the time of the incident was providing fire cover atthe apron area, responded to the incident. This vehicle carried50 kgs of Halon BCF and 100 kgs of Monnex powder (100 kgs of Monnexis deemed equivalent to 200 kgs of Halon BCF), but it had no foamcapability. Even with the absence of J2, the fire cover availableat the time of the accident exceeded the licencing requirementsthen applicable at Manchester.

1.10.4 Airport hydrants

Manchester Airport was equipped with a series of water hydrantsspaced at intervals along the southern edge of the main runway,around the airfield western boundary, and at the fire station.Shortly after the accident, the water pressures at the hydrantsin the area of link Delta were measured and found to be between40 and 50 psi, giving flow rates of between 165 and 190 imperialgallons per minute.

At the time of the accident, the water hydrant system on the airfieldwas in the process of being modified by the installation of anadditional water main, which was being laid alongside the existingmain south of the runway to provide increased flow rates. Thiswork had been in progress for some considerable time prior tothe date of the accident. To facilitate the interconnection ofthe new and original pipework it had been necessary from timeto time to isolate sections of the system.

Control over maintenance work at the airport was enforced by asystem of work permits, issued solely on the authority of theHead of Engineering Services. Permits for work involving the isolationof hydrants carried several conditions, one of which was thatthe isolation was not to be carried out by the contractor's personnel.Furthermore, in the case of any work affecting the serviceabilityof hydrants, it was established practice for the Senior Fire Officerto be informed in advance and the information promulgated on thefire station notice board. At the time of the accident, no permithad been issued in respect of any work involving the serviceabilityof the hydrant system, nor had notification been given of anyproposed work.

Investigation of the circumstances surrounding the hydrant failurehas revealed that the system of work permits had not been adheredto; valves had been turned on and off by the contractor's personnelwithout any form of control and without the knowledge of the fireservice. On the morning of the accident, contractors arrivingfor work observed firemen attempting to obtain water from thehydrants. Shortly after this, the water supplies were restored.

1.10.5 Emergency services liaison

The emergency orders in force at the time of the accident providedfor the immediate notification of the Local Authority emergencyservices in the event of an aircraft accident. This notificationwas to be communicated by land line from the Airport Fire Servicewatch room.

For some considerable time prior to the accident it had been thepractice of the external emergency services to respond to theWest RVP, which is located near the airport fire station, wherethey met with a police escort vehicle. However, on the 25th July1985, a meeting was held between the Head of Airport Services,the Airport Fire Officer and a Senior Fire Officer from the GMC.At that meeting, it was agreed that for all future incidents theRVP for external emergency services would be changed to the NorthRVP. The Police were not informed of the meeting and did not attend;they were not informed about the changes in procedure, nor werethe changes promulgated. When the accident occurred, the externalemergency services were told to report to the (new) North RVP,but this detail was not passed to the police, who dispatched theirescort vehicle to the original West RVP. The fire service ambulance,departing from established procedure, acted as an escort vehiclebut it too went to the old meeting point at the West RVP.

The delay in attendance by the GMC fire service, caused directlyby the confusion over RVPs, was approximately 3 minutes, and occurredat a time when the effectiveness of the airport fire service wasbeing limited by a shortage of water.

1.11 Flight recorders

1.11.1 Flight data recorder (FDR)

The aircraft was equipped with a Davall 1198 re-cycling wire,accident protected, digital FDR, this had a duration of 25 hoursand was part of a Plessey PV1940 recording system. This systemalso incorporated a quick-access cassette which recorded essentiallythe same information as the accident protected recorder. A totalof 27 analogue parameters plus 73 discrete parameters (events)were recorded.

The FDR was mounted overhead in the rear passenger cabin, justforward of the rear pressure bulkhead. It was recovered intact,the exterior being smoke blackened. The mechanism showed no signof damage and no major problems were encountered during replay.

1.11.2 Cockpit voice recorder (CVR)

A Fairchild A100 CVR, an endless loop four track recorder witha duration of 30 minutes, was installed in the aircraft. The allocationof the four tracks was as follows:-

Track 1	P2 headset audio + 'live' microphone
Track 2 -	cockpit area microphone
Track 3 -	P3 headset audio + 'live' microphone
Track 4 -	P1 headset audio + 'live' microphone

The CVR was mounted in the aft end of the rear cargo hold. Itwas recovered slightly fire damaged and with some physical damageto the casing. The plastic based recording medium had not sufferedany damage whatsoever and after removal a satisfactory replaywas obtained.

1.11.3 Flight recorder analysis

There was an area of poor quality data during the ground roll,but this was partly recovered using manual bit shifting routines.Part of a second was, however, not recoverable. It is probablethat the data had been corrupted due to electrical transientscaused by the automatic bus bar switching which took place asa consequence of the engine failure.

A transcript of the CVR over the relevant period was producedand synchronised with the FDR data by comparing the recorded VHFkey switch position with the ATC calls on the CVR.

The airspeed measuring system was of a type which did not recordbelow 40 kt, and as such was not suitable for deriving the aircraft'sposition along the runway. This was derived by calculating thegroundspeed by means of an integration of the recorded longitudinalacceleration which had been corrected for datum error and pitchattitude changes. This was then used in conjunction with the recordedheading to calculate the aircraft's position, assuming that therehad been no sideslip. The fixed datum position used was the knownpoint at which the aircraft had come to rest.

It was known that the aircraft had executed a rolling take-offand from the calculations it would appear that the ground speedat power up was of the order of 5 kt. The airspeeds derived fromthe calculated groundspeeds and reported windspeed agreed wellwith the recorded airspeeds.The points along the runway at whichsignificant events occurred were thus deduced.

1.12 Wreckage and impact information

1.12.1 On site

1.12.1.1 Wreckage trail

The dome-shaped section of the left engine No 9 combustor can,sections of engine cowl, broken pieces of bypass duct, fragmentsof left wing tank access panel and other debris from the vicinityof the ruptured left engine combustor case were found on the runwaybetween link 'C' and runway 06 fast turnoff.

A trail of fuel was identified from characteristic damage to therunway paved surface, caused in part by the solvent action ofthe fuel alone and in some areas by a combination of solvent andheat damage. The outline of this trail, which could be identifiedon airborne photographs taken by a Royal Air Force reconnaissanceaircraft shortly after the accident, began in the same area ofrunway that the engine debris was found. Initially, the trailtook the form of a series of increasingly large patches of unburntfuel, which merged into a continuous but irregular trail approximately1.5m wide running parallel with, and approximately 5m to the leftof, the runway centre line. The width of the fuel trail remainedirregular, but progressively widened until it appeared to stabilisein the region of runway 24 fast turn-off, where it was approximately3.5m wide and was darker in colour with a sooty appearance, consistentwith the fuel having been burning at that stage. This burnt fueltrail continued around into link Delta and up to the positionwhere the aircraft came to rest, where, in the area around theleft engine, it merged into a larger area of fuel and fire-stainedtarmac.

It was not possible to directly determine the boundary of thepooled fuel fire because of the extent of general heating of thetarmac in the area of the wing puncture and the rear fuselage.However, a topographical survey carried out specifically to determinethe ground slopes in the area where the aircraft stopped identifieda general slope away from the area of the left engine into theregion forward and to the left of the fuselage. This coincidedwith a spur of tarmac damage clearly caused by fuel and/or firerunning diagonally forward from the area of the wing puncture(Appendix 8 fig g). The slope of the ground between the wing punctureand the rear fuselage was uphill, involving a rise of approximately70 mm.

The aircraft came to rest on a heading of 315° true.

1.12.1.2 Examination of engines

The left hand engine, Serial No P702868, had suffered an explosiverupture of the CCOC. The case had split along an axial line adjacentto No 9 combustor can and had then 'petalled' apart from approximatelythe 11 o'clock to 5 o'clock position (viewed from the front),failing the attachment bolts on the front flange and the flangeitself on the rear face. The upper section of the CCOC had blownupwards onto the underside of the engine pylon, striking the fire/overheatdetection system electrical loom. The lower section had blowndownwards and outwards. Witness marks on the exterior surfaceof the CCOC adjacent to the rupture showed that it had struckthe inner surface of the fan case as the rupture occurred. (Appendix5 Fig e)

The aluminium alloy fan case had shattered into several piecesin the region of the CCOC rupture. The remainder of the outboardhalf had suffered severely from the post-rupture fire.

The engine cowlings comprised two upper fixed sections and twolower hinged access doors. The outboard upper section had beenbroken into many fragments consistent with object(s) having passedthrough it. A section of the lower outboard door had blown offin a large, single piece, indicating that overpressure, ratherthan contact with other debris, was responsible for its detachment.In-fill panels on the engine pylon also showed evidence of overpressuredamage. The remainder of the engine, its cowlings and thrust reverser,(which remained deployed) had suffered severe fire damage, particularlyon the outboard face. Through the ruptured CCOC, it could be seenthat only some 50% of the No 9 combustor can remained in the combustionsection.

The aft portion of the can remained in the transition duct bulkheadin a crushed and burnt condition, and had rotated about 90°from its normal orientation. Hastelloy X metal spatter depositscould be seen on the adjacent cans 1 and 8, and more spatter waslater found behind the can in the transition duct and on the firststage nozzle guide vanes. The dome recovered from the runway showedthat separation had occurred around the 3rd/4th liner joint area- the aft portion of the can had then burnt and buckled in anirregular manner (Appendix 5 Fig f). A sizeable portion had brokenoff into the can and was found lodged against the nozzle guidevanes.

The dome portion, which embodied the majority of liner 3, hadsuffered comparatively little damage. Witness marks were foundwhich matched those on the holed underwing fuel tank access panel,and a sizeable metal scrape deposit on the air scoop was lateranalysed and found to be of the same material as the access panel,proving conclusively that the dome had struck the panel. Two smallindentation marks in the air scoop also showed that the can locationpin retention bolts had contacted the scoop as the dome assemblywas forced outwards, fracturing the pin with a single overloadbending force. Some galling of the fuel nozzle shroud, associatedwith similar marks in the mating hole in the dome was also found,indicating movement of the dome relative to the nozzle. The domeitself, particularly the exposed fracture surface of liner 3,was noticeably free of burning or overheat damage although therehad been some mechanical damage to the fracture surfaces. In additionto extensive cracking in the 3/4 liner joint area cans numbered1 and 8 had clearly suffered extensive damage due to their proximityto the badly disrupted No 9 can, with material missing. The othersix cans showed varying degrees of circumferential cracking inthis area.

The right hand engine, Serial No P 702841 was undamaged with thethrust reverser stowed.

1.12.1.3 Airframe mechanical damage

The centre of a fuel tank access panel on the lower surface ofthe wing immediately outboard of the left engine was broken-out,producing an approximately elliptic hole, 8" by 7",directly into the central region of the main fuel tank. The panelexhibited signs of having been struck forcibly on its lower (outer)surface.

The upper skin on the left wing was torn upwards, the correspondingsections of lower skin were severely bulged downwards and theribs inside the tank were buckled. All of the damage to the leftwing structure, with the exception of the broken access panel,was consistent with a rapid over-pressure of the tank cavity resultingfrom the ignition of fuel vapour within the tank.

The rest of the airframe was free of mechanical damage, but hadsuffered extensive fire damage.

1.12.1.4 Airframe fire damage - general

The aircraft was extensively damaged by fire. Most of the lightalloy components in the aft region of the left engine nacellewere melted or burnt away. The left wing lower aft surfaces, largesections of the trailing edge flaps inboard of the engine andthe lower surfaces of the flaps outboard of the engine were melted,and the remaining regions of the left inner wing and the mainlanding gear bay were superficially fire-damaged. The lower skinof the left tailplane was burnt through over a region extendingapproximately 1 metre inboard from the tip.

The rear fuselage was extensively burnt between the wing trailingedge and the rear doors; a large part of the left fuselage sidebetween frames 787 and 887 (approximately seat rows 17 to 21)was completely burnt away.(Appendix 8 Fig a) The wholeof the fuselage aft of the rear cargo door and the tail sectionhad collapsed onto the ground.

Most of the passenger cabin ceiling and crown skins were burntaway (Appendix 8 Figs a-b) and all of the overhead luggagebins were destroyed. The support beams which carried the cabinfloor above the rear cargo hold were burnt away in the centralaisle area and on the right side of the cabin (in the areas immediatelyforward of, and aft of, the rear cargo door), allowing most ofthe cabin floor above the hold to collapse down onto the baggage.Most of the cabin interior fittings and seats in this sectionof the cabin were destroyed completely or were very extensivelydamaged. The interior fittings in the centre and forward sectionsof the cabin were generally less severely affected by the fire.However, there was considerable local variability, particularlyin the severity of seat damage. Notably, seats 8C and 9C (leftaisle seats just forward of the overwing exits) were completelydestroyed, whereas the adjoining seats were relatively intact.(Appendix 8 Fig c)

1.12.2 Subsequent detailed examination

1.12.2.1 Engines

Following removal of the left engine it was transported to anoverhaul shop where it was stripped to its basic components. Thisshowed that, apart from damage to the combustion section it appearedto be generally in good condition, although it was noted thatsome turbine blade rubbing had occurred, apparently due to enginecase distortion after the CCOC rupture.

All components of the combustion section of the engine were subjectedto detailed examination both at the manufacturer's premises andthe Royal Aircraft Establishment, Farnborough under AAIB supervision.In addition to a bench test in the overhaul shop, the FCU wasdespatched back to its manufacturer for testing.

Only the dome portion of combustor can No 9 was subjected to detailedfractography, because the degree of burning and material losson the aft portion of the can precluded examination of the 3rd/4thliner joint area. In the following description, positions of thecan fracture surface are by reference to 'clock' positions, viewedfrom the front with 12 o'clock being the mounting lug.

From 10 o'clock to 2 o'clock, the fracture surface had sufferedconsiderable rubbing and, in the vicinity of the cross-over tubes,severe burning prevented identification of the nature of the originalfracture mechanism. (Appendix 5 Fig g) Most of the fracture surfacewhich had not suffered secondary damage was identified as beingof a fatigue nature - a significant proportion exhibiting fatiguefacets. Generally, the cracking appeared to originate on the innerwall of the can and the facets appeared to originate at a multiplicityof origins. These multiple origins led to the simultaneous growthof many cracks at different positions around the circumferenceof can No 9. Indeed, as noted in paragraph 1.6.2.2., this canhad exhibited two separate cracks, centred on the 11 o'clock and2 o'clock positions, prior to its last shop visit for repair.These had been repaired but cracks at similar radial positionsre-grew in service and were joined by a third major crack centredon the 6 o'clock position. On a microscopic scale, these majorcracks were facetted, formed by the joining of smaller cracksgrowing from separate origins. Patches of fatigue growth linkingthe major cracks were found, some exhibiting very clear fatiguestriations. The nature of this striated fatigue damage was differentfrom that observed in the facetted crack areas in that it appearedto propagate from but a small number of origins, indicating thatthe striated areas propagated after the major crack areas haddeveloped - ie the previously weld-repaired areas and a thirdarea at the 6 o'clock position had cracked first from multipleorigins and were subsequently joined together by a further fatiguemechanism, resulting from an increased mechanical influence, whichresulted in 360° separation of the can.

Although it has been established that the weld-repaired areasappeared to have been the first to re-crack in service, it wasnoted that the crack did not necessarily follow the original pre-repaircrack path. Whilst the re-cracking did exploit the repair in someareas, in others it carved a new path adjacent to the weld.

The quality of the weld repair was checked by microscopic examinationof the material structure. Voids, cracks and included matter weredetected in the weld repairs. Although these features indicateddeficiencies in the welding technique, it was felt that a betterindication of the strength of the weld would be the path of there-cracking which occurred. As noted above, it did not necessarilyfollow the original crack path and it was felt that other factors,such as the build-up in material thickness after welding and thelocal temperature distribution in service, would be just as importantin determining the re-cracking path as the quality of the weldper se.

The CCOC was examined metallurgically to confirm the nature ofthe rupture. It was obvious on a microscopic scale that a portionof the fracture surface in the region just aft of No 9 can domehad thinned to a 'knife edge' over a length of about 175 mm -the remainder exhibiting rapid tensile shear failure characteristics.

A plot of the material dimensions in the thinned area showed thatan elliptical-shaped bulge in the CCOC had occurred prior to therupture and the material had thinned to effectively zero thicknessand a 175mm slit had formed.

The engine manufacturer provided data gathered from previous CCOCfailure incidents in which the length of pre-existing longitudinalcracks in the CCOC had been determined. Although these incidentsresulted from primary fatigue cracks in the CCOC itself, it wasfelt that the situation was analogous to the loss of materialproperties resulting from softening/bulging. This data suggestedthat for the JT8D-15 engine, the nominal critical crack lengthwould be 117 mm, beyond which explosive rupture would be likelyto occur. It was therefore appreciated that CCOC overheating wouldnot necessarily lead to explosive rupture if it occurred overa relatively small, discrete area, in which case burn-throughor bulges might occur. In the case of the left engine of G-BGJL,the overheating had occurred over a length considerably exceedingthe critical length and had resulted in catastrophic failure.

A check on the hardness of the CCOC in the vicinity of the bulgedarea suggested that temperatures of up to 930°C had beenexperienced by the casing, at which temperatures the materialproperties would have been significantly impaired.

The fuel nozzles from engine P 702868 were tested against themanufacturer's specifications for both the flow rate and flowpattern, which could affect the local heat distribution and thusthe level of distress felt by the can. The conclusion of the testswas that they did not reveal any functional discrepancies comparedwith in-service standards.

The No 9 nozzle exhibited heavy wear of the outside diameter ofthe nozzle nut where it engages in the No 9 can, consistent withexcessive movement of the can relative to the nozzle having occurredafter the dome section had separated from the rest of the can.

The FCU was examined to check its serviceability and settings.Whilst the unit had suffered some fire damage, it was still possibleto bench test it and to extract various parameters relevant tothe accident. In particular, it was found that there was no evidenceto support a lack of 'idle speed repeatability' - ie failure tomaintain an idle speed setting. The condition of the unit wasgenerally as might be expected from a unit with about 15,000 hourssince last bench calibration. The idle trim screw was found aboutmid-way in its 22-turn range. It was concluded that the unit wascapable of running a JT8D-15 engine throughout its operationalrange.

FDR evidence indicated that both the right and left reverser systemsdeployed normally, but that only the right reverser retractedagain into the stowed position; the left reverser remained fullydeployed.

The left reverser mechanism had suffered general fire damage,resulting in partial seizure of the feedback mechanism and stiffnessof the lock mechanisms. The operating cable and interlock systemmounted in the wing above the pylon were also affected by thefire. The retraction mechanism operated satisfactorily when thehydraulic system was pressurised by means of a hand pump, andthe only evidence of abnormality was stiffness of the variouslinkages as a result of the fire.

Analysis of the flight recorder data from preceding flights showedthat the left engine oil pressure typically decayed to 35 psiat an N2 of 26% (the oil pressure switch which inhibits the thrustreverser actuating system is set to trip at a nominal 35 psi).Recorder data for the accident flight indicates that the leftengine oil pressure fell below this value 3 seconds after thereverser had deployed, but approximately 6.5 seconds before reversethrust was de-selected (assuming right and left reverse were de-selectedtogether), de-activating the operating system before reverse wascancelled.

1.12.2.2 Fire (Appendix 8 Figs a-b)

Fuselage

The whole of the rear fuselage aft of seat row 19 had collapsedonto the ground as a result of external fire attack on the fuselagelower skin and longerons between frames 867 and 907, and firedamage to the cabin floor structure which led to floor collapseover much of the area above the aft cargo hold. Aft of the wingtrailing edge, between seat row 14 and the rear entrance vestibule,the fuselage was partially destroyed by a combination of externaland internal fire. The greatest damage was concentrated on theleft side in the vicinity of the aft baggage hold.

Empennage

The left tailplane lower skin panels were burnt through over aregion extending from the tip inboard approximately 1m. The remaininglower skin panels over the outboard two thirds of the tailplanewere burnt free of paint and buckled by heat, and the honeycombpanels and lower elevator structure had been partially destroyed.Inboard of this region, the damage tapered-off rapidly, leavingthe innermost 50 cm almost undamaged and with little discolourationof the paint - comparable with the damage on the adjacent fuselageskin. The left tailplane upper surfaces exhibited little heatdamage and were free of heavy sooting except for a small regionapproximately 2m wide at mid-span, extending from the leadingedge back to approximately the half-chord position. The leadingedge over this same region was heavily streaked with an oily -soot deposit running in streamlines back over the leading edge,consistent with the impingement of partially burnt fuel dropletswhilst the aircraft was moving at speed. This contaminated sectionof the tailplane leading edge was approximately in line with theouter lip of the deployed inboard (upper) bucket on the left enginethrust reverser. The upper surface of the elevator horn balancewas heavily sooted and had suffered moderate heat damage. Theleft side of the fin and rudder were undamaged, with bright andclean painted surfaces.

The right side of the fin and rudder, together with the uppersurface of the right tailplane and adjacent fuselage, were sootyand had suffered moderately intense heating - sufficient to burnthe paint from the skin panels between frames and stringers. Thedamage on the fin and rudder progressively tapered off towardsthe tip, where it was limited to sooting and blistering of somehoneycomb panels. The upper surface of the right tailplane wassimilarly affected, with moderate heat damage tapering-off towardsthe tip, becoming negligible at about two thirds span.

The remainder of the tail section exhibited sooting, paint blisteringand/or discolouration in varying degrees but without any evidenceof intense heating.

Cabin interior (Appendix 3 Photos e-f)

The fire destroyed all of the overhead lockers except for a smallsection above seats 21B and 22B, which had remained in positionbut was badly charred. Remnants of overhead lockers were foundrandomly distributed throughout the cabin (there had been considerabledisturbance by rescue personnel). The ceiling panels were alldestroyed. The cabin side-liner panels were destroyed over mostof the cabin aft of seat row 14, but forward of that locationthe panels had survived mostly intact below seat squab level;above squab level the aluminium backing panels had generally survivedbut the decorative plastic coating had mostly melted and peeledaway in strips, or had been burnt off completely.

The carpet forward of seat row 14 was largely intact, except forsome areas of localised burning from above, which matched damageon the adjoining seats. Aft of seat row 14, the carpet was burntfrom below in the areas where the floor had collapsed, and fromabove where the floor panels had remained in position.

The seats on the right side of the rear cabin (seats 15 to 22D, E & F) were completely burnt away leaving only the steelsubframe components. The corresponding seats on the left side(rows 14 to 20) were badly damaged but were still in position.Further isolated areas of badly damaged seats were located aroundthe left overwing exit (rows 8 to 10), just forward of the floorcollapse area on the right side (rows 13 and 14), and at the forwardend of the cabin against the right sidewall (rows 1 to 5). Elsewhere,the seats were lightly or moderately damaged, but there was considerablevariability and much of the damage appeared random. In particular,seats 8C and 9C were completely destroyed whereas the adjacentseats were either undamaged, or were much less severely damaged.Generally, the seat damage above and below squab level was similar,but there were several small areas where the fire beneath theseats had been more severe than that above them. (Appendix 8 Figc).

The upper halves of the forward entrance vestibules were sootedand, above chest height, the plastic decorative surfaces had partiallyburnt away. In contrast, the lower halves were free of significantsoot deposits and there were no indications of heat damage. Therear vestibule was more severely damaged, but the fire's attackwas mainly evident above waist level and was more pronounced onthe right side of the aircraft, adjacent to the door aperture:there was relatively little heat damage close to the floor.

The upper halves of each toilet compartment and the flight deckwere heavily sooted and there were thick layers of oily soot onall horizontal surfaces, but each of these zones was free of heatdamage.

There was no significant fire damage aft of the rear entrancevestibule nor below cabin floor level forward of the rear cargohold.

The damage affecting the centre and forward sections of the cabinwas consistent with a fire burning internally within the passengercompartment, whereas the damage to the aft fuselage was consistentwith a combination of external and internal fire.

The fire damage to the cabin interior as a whole did not fallinto any single overall pattern, but it did reflect the generalseverity of damage to the adjacent structure, upon which was superimposedadditional damage produced by burning overhead debris fallingdown onto the seats. Pockets of severe, isolated damage were presentat several locations, but there was no direct evidence as to theircause.

Window panels

All three panels were missing from most of the window aperturesin the rear cabin; some panels had remained in position in thethree apertures immediately forward of the L2 door and the partiallyburnt remains of all three panels were still present in the apertureimmediately forward of the R2 door. In the centre and forwardsections of the cabin most window apertures had one or more panelspresent. All of the surviving outer window panels aft of the overwingexits displayed a cubic cracking pattern on their outer surfacesconsistent with heating of the panel from outside. Forward ofthe overwing exits, many of the outer panels displayed similardamage but with the cracking on the inner surfaces - consistentwith heating from inside the cabin.

Examination of the window panels indicated that the followingexternal fire penetration mechanism had occurred:-

a) outer panels - extreme local shrinkage of the outer (heated)surface producing a deep cubic cracking pattern of the affectedsurface together with overall shrinkage and thickening of thepanel, causing it to pull out of the retaining clips and fallout of the aperture.

b) centre panels - softening and bulging of the panel. The lossof the outer panel removed clamping pressure from the centre panel,allowing the centre panel to come out of its securing clips andfall out of the aperture.

c) The inner (anti-scratch) panels melted down and burnt.

The window apertures in which there were no panels remaining displayedwidely differing degrees of heat damage and sooting in the areasnormally protected by the silicone rubber window seals, givingan indication of the stage in the fire when the window panelsbecame detached. Generally, the sooting and heating reflectedthe degree of fire damage evident in the adjoining area of cabin.However, in the apertures adjacent to seats 17A and l8A (in theleft side burn-through zone) the paint was still present and relativelyfree of soot, although it had started to bubble due to heat - consistent with those panels and/or rubber seals having been inposition until quite late in the overall fire sequence.

Cabin doors and overwing exits

All main cabin doors were found latched fully open. Both overwingexits had been opened and the hatches thrown to the ground. (Therehad been significant unrecorded disturbance of all cabin accesspoints during the rescue.) Neither L1 nor R1 door had sufferedsignificant damage during the fire, but sooting on the doors andapertures indicated that each had been open for most of the periodof the fire. The fire damage on the doors and apertures at therear of the aircraft was consistent with the R2 door having beenopen throughout the fire, and the L2 door having been closed throughout.The sooting pattern around the overwing exit hatches and hatchapertures indicated that the right exit had been opened duringthe fire, but the left exit had remained closed throughout.

1.12.2.3 Fire detection and suppression systems

The FDR indicates that the left engine fire detector triggered9 seconds after the combustion case ruptured, but the overheatdetector did not trigger at all. Examination of the fire detectorsystem was limited to the left engine sub-system.

The fire and overheat detector control modules were undamagedby the fire and performed satisfactorily when bench checked inaccordance with the approved test procedures. The upper detectormodule overheat element was badly kinked and crushed during theengine rupture; all other detector elements were undamaged. Alldetector elements were electrically checked in the cold stateand under hot conditions using approved test equipment; all performedwithin specification.

The power supply cable feeding the left engine overheat detectorelements was severed in the area of damaged firewall above theruptured engine casing, disabling the whole of the left engineoverheat detector system. The remaining overheat detector wiringand the whole of the fire detector system wiring was intact.

Both main engine fire extinguisher bottles had discharged fully.Examination of the discharge heads indicated that both bottleshad been discharged into the left engine. Subsequently, the thenempty number 1 bottle had been "discharged" into theright engine.

The enclosure formed by the left engine cowls, upon which thesystem relies to contain the extinguishing agent, was lost asa result of the heavy damage sustained when the combustion caseburst.

The APU fire extinguisher bottle was completely discharged.

1.12.2.4 Fuel system

The fuel system was in its normal take-off configuration withall fuel pumps ON and the cross-feed OFF. At the time of examination,both Low Pressure (LP) shut-off valves were closed.

The right and centre tanks were completely undamaged. The lefttank was not damaged by the fire but had suffered extensive mechanicaldamage. The access panel on the lower surface immediately outboardof the ruptured engine combustion case had been broken out inits centre, producing an approximately 42 square inch hole directlyinto the tank interior (Appendix 9). Fragments of this accesspanel were recovered from the runway and one other fragment ofthe panel was recovered from inside the tank cavity. Reconstructionof the access panel fragments revealed witness marks and a patternof distortion which matched exactly the shape of the No 9 combustorcan dome and a fan case fragment.

Outboard of the engine, the skins forming the tank roof were tornupwards from the spars and the corresponding bottom skin, formingthe tank floor, was severely bulged downwards. The tank ribs andinternal structure were distorted in a manner compatible withchordwise tensile loading of the skins between the spars. Withthe exception of the damaged access panel, all damage to the leftmain fuel tank was consistent with a rapid overpressure of thetank cavity due to the ignition of fuel vapour in the outer sectionof the tank. The fracture surfaces at the upper skin/spar interfacewere relatively clean, whereas the adjoining skin surfaces weresignificantly sooted - indicating that the explosive overpressureoccurred after the fire had been burning for some time.

At the start of the accident sequence the aircraft fuel load isestimated to have been:-

each wing tank	(full)	4,590 kg
centre tank		3,420 kg
total		12,600 kg

The fuel remaining in each tank could not be measured directlybecause of the practical difficulty of emptying each tank separately.However, a tide mark of soot was found on the internal rib andspar surfaces inside the left tank at a height which correspondedto the level of the damaged access panel, enabling the post-accidentfuel contents of the left tank to be determined and hence thetotal fuel loss to be estimated.

The total quantity of fuel lost from the punctured left wing tankis estimated to have been 2,109 kg (689 US gals at specific gravity0.808), based on the position of soot 'tide-lines' on verticalsurfaces wihin the interior of the left wing tank and the tankinitial contents and taxi fuel consumption data.

The leak rate was estimated by the manufacturers, based upon theirknowledge of fuel flow rates through the various baffles and theinternal structure of the wing. This data suggested that the leakrate would initially be very high, in the order of 16 US galsper second, but this would decay rapidly as the tank compartmentimmediately above the puncture emptied. After about 40 seconds,the leak rate would have decayed to approximately 2 US gals persecond and would remain at approximately that level until approximately200 seconds. Beyond that stage,the rate would taper off and theflow would cease after a total time of approximately 250 seconds.(Appendix9)

As an independent check on the validity of the leak rate estimate,the theoretical leak rate was integrated with time and the resultingtotal compared with the leaked fuel estimate based on the residualfuel contents. These figures agreed within 5%.

1.12.2.5 Oxygen

The emergency oxygen distribution system mounted in the overheadunits was destroyed in the fire, but because the system was isolatedthere was no discharge of oxygen. Both passenger and crew reservoirswere indicating full and the discharge discs were intact.

1.12.2.6 Doors and emergency equipment

Door slides

Inspection of the R1 door confirmed that the hinged lid of theslide container had fouled against the aft/lower radius of theaperture. A witness mark was present adjacent to the aft/lowercorner of the lid which was consistent with contact between thelid and the door aperture.(Appendix 10 Photos a-c) The slide containerlid is designed to be held closed by a latch mechanism, attachedby a short length of cable to the 'girt-bar', which is manuallyengaged within two floor mounted brackets when the doors are 'selectedto automatic' by the cabin crew as part of their pre take-offprocedures. This latch will then automatically release the slide-boxlid due to cable tension if the door is opened for emergency evacuation.The latch mechanism should not unlock until the door has clearedthe aperture sufficiently to allow the slide to fall and deploywithout any risk of fouling.

The R1 door slide was still inflated after the accident, as wasthat from the L1 door. The R2 slide had deployed fully, but hadsubsequently been partially burnt in the ground fire, causingdeflation. The R2 girt-bar was still in position on the floorengagement brackets, with remnants of the slide 'apron' stillattached and the manual inflation handle still fixed to its 'velcro'retainer.

Overwing exits

A male passenger had become lodged within the right overwing exitwhere he had ultimately died and the area adjacent to this exitwas therefore examined in detail.

The seat next to this exit (ie seat 10F) was inspected in orderto identify any means by which the man may have been trapped.It was noted that the existing gaps between the six coil springs,which support the vinyl-plastic seat-base to the seat-frame oneither side, could trap only a small foot if the seat cushionbecame displaced from its "velcro" retention.(Appendix11) The photographs taken of this area immediately after the accidentshow this cushion to have been displaced but this mechanism couldnot have trapped this particular individual.

In addition, this seat (and seat 10A adjacent the left overwingexit) was of a type with a 'baulk' fitted to the seat-back hinge,designed to prevent the seat-back hinging forward and restrictingaccess to the overwing exit. However, inspection of the baulkon the 10F seat showed that it had failed as a result of pressureapplied from behind the seat-back. In addition, the position ofthe baulk was consistent with the seat-back having been displacedalmost fully forward, onto the seat cushion. The correspondingseat at 10A was inspected and the associated hinge-baulk was foundstill intact.

Two childs' lap-belts were found still attached to the seat-beltsassociated with seats 10C and 10D.

In addition some survivors who had used this exit referred toa "white canvas strap" or "webbing" acrossthe aperture. These descriptions were consistent with the ditching-strap/lifelinewhich is secured to the forward/upper corner of the overwing exitand is, in part, clipped along the upper width of the aperture.This strap had been consumed by the fire.

Seat pitches and aisle dimensions

Dimensional checks were carried out at the row 10 exit area andgave the following results:-

Access gap between front of row 10 seat cushions and back of row9 seats: 10.5 inches

Distance from front of seat 10F cushion to projected forward outsideedge of overwing aperture : 2 inches

Height of exit 'sill' above cabin floor: 14 inches.

Overwing exit aperture: 38.25 inches high x 20 inches wide.

Height of exit 'sill' above wing surface: 22-24 inches.

In addition, the cabin seat-pitch was measured:-

	Rows 1-9	Rows 9-10	Rows 10-22
Pitch	30 inches	31 inches	29 inches

Dimensional checks carried out with respect to cabin aisle widthand also the width between the twin forward bulkheads gave thefollowing results:-

Aisle width (measured at arm rest level): 15.5 -17.5 inches.

Forward cabin bulkhead gap width (constant width, floor to ceiling):-

22.5 inches.(Appendix 3 Fig b)

Cabin crew seats and equipment

The aft cabin-crew seats were inspected. The forward-facing twinbench seat located on the left side adjacent the L2 door was foundwith the seat folded up, enclosing both sets of lap straps, withthe associated buckles undone. The surfaces enclosed by the foldedseat had escaped the effects of fire, in contrast to the upperarea of the back-rest and associated shoulder straps, indicatingthat the seat had been unoccupied and folded-up before the heathad become intense. The cabin crew torch was still in its holderabove this seat and was badly fire-affected. The interphone andpassenger address microphone were still in their stored positionson the intercom panel located outboard of the seat-back. Althoughblackened by smoke, these units were not badly fire-damaged andthe associated coiled wiring was intact. The aft-facing singlecabin crew seat located on the right/aft bulkhead showed similarevidence of the seat having been in the folded-up position duringthe fire, with harness undone and protected by the seat.

The forward cabin crew twin bench seat (aft-facing) located adjacentto the L1 door was undamaged by heat with both harnesses intact,and buckles undone. However, the torch located above the seathad partially melted.

The right escape 'rope' had been deployed from the right sliding-windowon the flight deck.

Of the five cabin-crew 'Scott Aviation' smokehoods (15 minuteendurance type), the three units which had been stored in theaft right overhead 'bin' at row 18 were found partially burntand still in their respective cases. The two smokehoods for theforward cabin-crew were found undamaged and still in their bulkheadlocker which faces the forward cabin-crew seat, together withthe associated two pairs of asbestos gloves.

The forward 1.5 Kg BCF cabin fire extinguisher was in its storagelocker and the two similar extinguishers on the rear right bulkhead(aft side) were still in their wall-mountings; all were fullycharged. The single 1.5 lbs water-filled extinguisher from theaft/right overhead storage bin at row 20 had thermally ruptured.

The two megaphones, from the forward/left (row 2) overhead binand aft/right (row 18) bin had been destroyed by the cabin fire.

Of the ten portable oxygen bottles (of 120 litre capacity), ninewere found in the cabin. One of these had explosively ruptured,leaving the bottom 6 inches on the cabin floor in the region ofseat 1D. The remaining eight cylinders had vented their contents,due to excessive temperature and pressure.

1.13 Medical and pathological information:

The pathological examination of the 54 people who died on boardthe aircraft was carried out by three teams of pathologists, eachincluding one civilian pathologist and one aviation pathologistfrom the Institute of Pathology and Tropical Medicine (IPTM) atRAF Halton, Wendover. In addition, RAF odontologists assistedwith the identification of the bodies. A special examination ofthe toxicology and histology aspects of the fatalities was carriedout at the IPTM.(Appendix 12)

A marked deposition of carbon particles was found within the tracheaof all victims, with some congestion of the mucosa (mucus lining)in 17 cases ("marked congestion" in the case of onepassenger) with many instances of "excess mucus". Thelungs of all fatalities showed marked general congestion and oedema(fluid), with carbon particles in the air passages, consistentwith the inhalation of smoke. There was no evidence of organicdisease which could have caused the death of any of the victims.

Blood samples were analysed to determine carboxyhaemoglobin andcyanide levels. In addition, hydrocarbon absorption was measured,including benzene and toluene, these two being the most prevalentvolatiles found in all fatalities. Many other minor trace volatileswere found, including acetaldehyde.

Of the 54 occupants who expired on the aircraft, 43 (80%) hadcyanide levels in excess of 135 micrograms/100 ml which wouldhave led to incapacitation. Of these, 21 had levels above 270micrograms/100 ml, the fatal threshold. Forty passengers (74%)had levels of carboxyhaemoglobin in excess of 30% saturation whichwould also be expected to cause incapacitation. Of these, 13 passengershad levels in excess of 50%, which is generally accepted as thefatal threshold. Only 6 passengers (from seats 21A, 21E, 20E,17A or B, 17C or D, and 16C) had absorbed less than the incapacitatinglevels of carbon monoxide and hydrogen cyanide stated above, havingdied from direct thermal assault. The remaining 48 passengerswho died on board did so as a result of smoke/toxic gas inhalation.

The passenger who survived for 6 days in hospital died becauseof severe pulmonary (lung) damage and associated pneumonia. Hehad suffered approximately 24% surface burns.

1.14 Fire fighting

The fire station crash alarm was initiated by ATC immediatelythe fire was observed from the tower. However, many fire crewpersonnel heard the bang, saw the fire and started to respondbefore the alarm had sounded. RIV2 and RIV1 rapidly departed andheaded to where the aircraft could be seen entering link Delta,followed immediately by the Protector and J1 foam tenders. RIV2routed via taxiway 2-North, RIV1 and the major tenders via taxiway2. Other RFF personnel, on hearing the alarm, departed immediatelyto recover J2 from the hangar where it was undergoing re-painting.

The fire station ambulance, manned by RFF personnel, immediatelydeparted for the West RVP to await the arrival of the GMC andCheshire Fire Service appliances. The Airport Police also dispatchedan escort vehicle to the West RVP. However, the GMC Fire Servicehad been alerted by the land line and told to report to the NorthRVP, which was in accordance with recently changed procedures.

RIV2 arrived at the scene approximately 25 seconds after the aircrafthad stopped. It was positioned on the left side of the aircraft(Appendix 13 Figs a-d) and foam was applied initially onto theleft side of the fuselage and then onto the left engine. RIV1arrived shortly after RIV2, positioned off the nose slightly onthe left side, and discharged the whole of its foam along theleft side of the fuselage with the intention of protecting passengers,who by then were evacuating from the L1 chute, and cooling theleft side of the fuselage. RIV2, having apparently knocked downthe fire around the left engine, re-positioned to the rear onthe left side, discharged its remaining foam into the rear fuselage,which by that time had collapsed to the ground, and was then re-positionedclear of the aircraft.

The Protector foam tender arrived at the aircraft approximately30 to 40 seconds after the RIVs and positioned some distance offthe nose, well on the right side. It then started to deliver foaminto the area of the right overwing exit and the right rear fuselage,which appeared to be burning fiercely. Subsequently it was re-positionedtwice, each time to bring it closer to the apparent seat of thefire on the right rear fuselage, before its water ran out. J1arrived immediately behind the Protector, but was unable to positionin the normally anticipated position on the nose of the aircraftbecause of the presence of RIV1. It was therefore positioned some12 metres forward of the nose, slightly on the right side to therear of RIV1, and foam was delivered down the length of the fuselageon the right side. This drove the flames rearwards, maintainingthe forward and overwing exits clear of fire. Approximately 1minute after commencing foaming, J1 was re-positioned onto theleft side in order to attack more effectively the fire in thearea of the left engine and rear fuselage.

J2 (the foam tender retrieved from the paint shop) arrived atthe scene some 4 to 5 minutes after the aircraft stopped and positionedto the front of the aircraft in the area originally occupied byJ1. Upon arrival, the driver of J2 saw an apparently lifelessbody hanging out of the right overwing exit, and above this bodya hand was moving. The driver immediately left his cab, climbedup onto the wing and pulled out a boy, who although unconsciouswas still alive and subsequently recovered. After this casualityhad been handed down to officers on the ground, the fireman wasforced off the wing by the smoke. Acting on the orders of theofficer in charge, he then returned to J2 and applied foam alongthe top of the fuselage. Side lines were also deployed from J2at this stage to cool a running fuel fire which was burning inthe vicinity of the left engine. After some determined effort,this fire was eventually extinguished using two 50 kg units ofHalon (BCF).

Approximately 7 minutes into the incident, after it became clearthat no more passengers were likely to emerge unaided, a teamwith breathing apparatus made an entry via the R1 door. Conditionsinside the cabin at that time were very bad, with thick smokeand a serious fire in progress at the rear of the cabin. Shortlyafter entering, an explosion occurred which blew one of the firemenout of the door onto the tarmac. The officer in charge was bythat time becoming increasingly concerned about the reducing watersupplies, especially with regard to the potential loss of watersupplying sidelines deployed within the cabin, and directed thatthere would be no more attempts to gain entry until there wasa reliable supply of water. In the interim, sidelines were usedon the exterior only. At about this time a fire was seen to flashbriefly along the cabin.

About 8 minutes into the incident the GMC appliances, carryinga total of l,600 gallons (7,272 litres) of water, arrived at theNorth RVP but there was no police escort there to meet them. Some3 minutes later, the GMC appliances were still without an escortand a radio call was made to GMC fire control advising them ofthe situation. Shortly after this transmission, a police escortarrived and the convoy set off for the scene.

By approximately 11 minutes into the incident, the internal fireappeared to have spread forward throughout the cabin, where breachesin the roof could be seen. J1 was dispatched to replenish withwater from the hydrant system: the vehicle was positioned at threehydrants in succession, but no water could be obtained from anyof them. This resulted in a delay of about 10 minutes, after whichJ1 returned to the scene empty. It was then dispatched to thehydrant behind the fire station, where replenishment was successful.However, the hydrant discharge rate was such that this took between15 and 18 minutes and the vehicle returned to the scene too lateto play any further active roll. The Protector foam tender wasalso despatched to the fire station to replenish with water.

The GMC fire appliances arrived at the aircraft approximately13 minutes into the incident. Initially, the Station Officer (SO)in charge experienced some difficulty in identifying the officercommanding the airport fire service, resulting in some delay beforethe water requirements were identified and the transfer of the1600 gallons of water from the GMC appliances to J2 could begin.Using a sideline from the newly replenished J2 tender, a two manteam with breathing apparatus was then able to make an entry viathe R1 door using a short ladder, and, for the first time, werein a position to begin addressing the internal fire.

At approximately 21 minutes into the incident, a Divisional Officer(DO) from the GMC arrived and, in accordance with procedure, tookcommand of the emergency services. At +29 minutes, unaware ofthe earlier problems with the hydrants, he ordered a hose relayto be set up and this was done, using one of the RIVs to carryhose across to hydrant 130. On this occasion the hydrant suppliedwater. Shortly afterwards, the GMC DO and SO each donned breathingapparatus and entered the cabin via the R1 door. Conditions insideat this time were poor, with very limited visibility. Two bodieswere visible and the DO left the aircraft to transmit a messageadvising that there were fatalities. Upon re-entering the aircraft,the smoke had cleared somewhat and further casualties could beseen at the rear of the aircraft.

At approximately +33 minutes a male survivor was found near thefront of the aircraft. Regrettably this casualty, who was thelast person to be found alive, died some time later in hospital.

1.15 Survival aspects

From the statements of the survivors, it is evident that the effectsof the fire on the left side of the aircraft rapidly instilledfear and alarm in many passengers, particularly those in the aft/leftcabin - ie row 14 aft. These effects appear to have been markedheat radiation through the windows together with "cracking,melting and smoking" of the window transparency panels, whichmotivated some passengers from the aft cabin to enter the aisleand move forward before the purser's 'sit down' announcement onthe PA, and therefore before the evacuation call 14 seconds priorto the aircraft stopping.

The opening of the R2 door by one of the rear cabin crew, withslide deployment approximately 6 seconds before the aircraft stoppedmay have been a rapid reaction to the evacuation call or a directresponse to the worsening situation within the aft cabin. However,as the aircraft came to a halt this exit was rapidly engulfedin thick black smoke and no one escaped via this route.

As the aircraft stopped, the aft cabin was suddenly filled withthick black smoke which induced panic amongst passengers in thatarea, with a consequent rapid forward movement down the aisle.Many passengers stumbled and collapsed in the aisle, forcing othersto go over the seat-backs towards the centre cabin area, whichwas clear up until the time the right overwing exit was opened.A passenger from the front row of seats looked back as he waitedto exit the aircraft, and was aware of a mass of people tangledtogether and struggling in the centre section, apparently incapableof moving forward, he stated "people were howling and screaming".

Many survivors from the front six rows of seats described a rollof thick black smoke clinging to the ceiling and moving rapidlyforwards along the cabin. On reaching the forward bulkheads itcurled down, began moving aft, lowering and filling the cabin.Some of these passengers became engulfed in the smoke despitetheir close proximity to the forward exits. All described a singlebreath as burning and painful, immediately causing choking. Someused clothing or hands over their mouths in an attempt to filterthe smoke; others attempted to hold their breath. They experienceddrowsiness and disorientation, and were forced to feel their wayalong the seat rows towards the exits, whilst being jostled andpushed. Many, even in the forward cabin, resorted to going overthe seat backs in order to avoid the congested aisle. This wasreported by passengers in seats 7A, 6B, 5D, 3E, 3Fand 2F, in additionto statements from passengers who confirmed that they had goneforwards over the seats. Some stated that "the smoke generatedan immediate sense of panic".

At the start of evacuation from the L1 door, the stewardess statedthat passengers seemed to be jammed in the cabin aisle and entranceto the galley (ie between the twin forward bulkheads). She clearedthe jam by pulling one young passenger forwards and the flow thenstarted. Later she saw a young girl lying on the floor of theforward aisle. She pushed another youth back, pulled the girlforward by her collar and pushed her down the slide. As the passengerscame forward through the bulkhead aperture so the smoke builtup in the forward galley area. She recalled feeling a body slumpagainst her legs, bent down and, due to improved visibility nearthe floor, saw that it was another girl passenger. Her face wasblack with soot, eyes fixed and dilated with no signs of breathing.The stewardess considered giving her the kiss of life when a firemandown below shouted for her to throw the girl down to him. Withgreat difficulty she lifted her by the waist and threw her ontothe chute. After being forced down by the smoke onto her handsand knees, the stewardess felt around for other passengers backas far as the galley cabin entrance. She was considering gettingher smokehood when a fireman shouted at her to jump, concernedthat she would perish if she delayed. Having been unable to locateany further passengers, she went down the slide.

The Purser stated that, after getting the R1 door open at hissecond attempt and initiating evacuation from this exit, the smokebegan entering the galley area. He stood with his back to thegalley bulkhead with the door on his right, pushing passengerspast towards the chute. He stated that passengers were not carryingany "noticeable or unacceptable hand baggage". The densityof the smoke increased very rapidly, and became very acrid. Itbecame so bad that he could not see across the galley, and thencould not see his slide as the visibility went down to inches.Smoke was by this time pouring out of the door. He inhaled somesmoke and felt that if he inhaled any more, he would not survive.A number of people came out of the cabin and he followed themonto the slide.

The aisle aperture between the twin forward bulkheads in thisconfiguration was 22¤ inches wide, effectively restrictingpassengers approaching along the aisle and over the seat backsto a single-line exit flow in spite of both forward doors beingopen from approximately 1 minute 10 seconds after the aircraftstopped. Many passengers, in addition to the two females assistedby the stewardess, collapsed in this area but survived. Unfortunatelyone of these passengers, (from seat 8B) who was found some 33minutes after the aircraft stopped, died some 6 days later dueto lung damage and associated pneumonia. Four bodies were eventuallyrecovered from the area of the forward aisle.

The 18 passengers from the front 3 rows of seats appear to haveescaped from the forward exits before being affected by the smoke.In addition 3 passengers from row 13 and 2 passengers from row14 were also unaffected. Thus, of the 17 passengers who escapedfrom the L1 exit and 34 passengers who escaped from the R1 exit,some 23 (45%) escaped before the thick smoke had reached them.

The decision to open the right overwing exit was taken by passengersthemselves, motivated by the fact that the forward aisle was bythis stage blocked with passengers waiting to exit through theforward galley area, with others already making their way overthe seats. The female passenger in seat 10F adjacent to the rightoverwing hatch, upon being exhorted by passengers behind to openthe door, undid her seat belt and turned in her seat to face thehatch. She saw the 'Emergency Pull' instruction at the top ofthe hatch, but pulled at the armrest which was fixed to the lowerarea of the hatch. She was not familiar with the door openingprocedure and unaware if the door was hinged at the top, bottom,left or right, or if it would come straight off. Her female friendin seat 10E stood up and pulled at the release handle adjacentto the instruction. The hatch, which weighed 48 lbs, fell inboardacross the chest of the passenger in 10F, trapping her in herseat. She managed to get out from under the door and a male passengersitting behind her assisted by lifting the hatch over the backof row 10, depositing it on the vacant seat 11D. This exit wasseen to be open by about 45 seconds after the aircraft stopped.The two female passengers escaped onto the right wing and bothjumped down from the leading edge, the passenger from seat 10Etwisting her ankle. At that stage, there was no foam on that sideof the aircraft. A number of other passengers quickly followedthem out including the occupants of 10C and 10D carrying theirchildren.

The girl from seat 10E stated that there had not been enough roombetween the seats at row 10. A further passenger from 15D alsocommented on the lack of space at the overwing exit and more generallyabout "Far too little space to evacuate the plane in a panicsituation, 2-3 exits not enough".

Shortly after the right overwing exit was opened, it was obscuredby dense black smoke which came forward from the aft cabin. Thesmoke poured out of the overwing exit, which was on the down-windside of the fuselage. The smoke was consistently described asheavy, thick , black, acidic, toxic and very hot. As observedby the forward cabin passengers the effects of this smoke on therespiratory system was rapid and for some catastrophic. Withinone or two breaths of the dense atmosphere survivors recall burningacidic attack on their throats, immediate and severe breathingproblems, weakness in their knees, debilitation and in some instances,collapse. A male passenger from seat 15C recalled taking one breathwhich immediately produced "tremendous pain" in hislungs and a feeling that they had "solidified".

Very rapidly the area around the overwing exit became a mass ofbodies pushing forward to the exit. People all around were fallingand collapsing to the floor. Many passengers who ultimately gotout of the right overwing exit, nevertheless collapsed temporarilywithin, or adjacent to it. The exit was blocked with "people'sbodies lying half-in and half-out of the aircraft". A malepassenger, from 16C, died after becoming lodged in this rightoverwing exit. A young boy, from 12D, was pulled out over thisman's body by a fireman about 5¤ minutes after the aircraftstopped. It is notable that some passengers managed to escapeforward from the worst area of the rear cabin only to succumbwithin the central area. Several of the survivors who used theoverwing exit were impeded by becoming entangled in the ditchingstrap. However, one passenger recalled catching hold of it asshe collapsed, to recover consciousness with her head outsidethe exit.

Of the 24 passengers who escaped from the right overwing (notincluding the 2 young children and the young boy pulled clear)some 11 passengers (46%) went over the seats as opposed to usingthe congested aisle to get there. Only two of the 24 reportedseeing fire in the aft cabin. More observations of fire in theaft/centre cabin were reported by passengers before they evacuatedfrom the forward exits. A passenger from 8D recalled looking aroundafter the aircraft had stopped and seeing huge tongues of flameshooting into the cabin through the windows of the fuselage onthe left side. He stated that flames commenced at the first windowpast the central emergency hatch with six or seven windows behindthus affected. The flames were lapping up to the ceiling. Severalpeople who were in seats nearest these windows were seen engulfedin flames.

A passenger from seat 6A saw a sheet of flame inside the cabin.It seemed to be near the centre of the aircraft and separatedthe front half from the back. Another passenger from 6B, afterseeing foam being sprayed over the fire on the left side of theaircraft, tried to move into the aisle but it was jammed withpeople and it was difficult to move. On turning he saw flamesshooting in through the side windows and up through the floorarea. The flames were several feet in length and continual.

The fireman who, after rescuing the young boy, attempted to rescuethe man jammed in the overwing exit, reported feeling "dizzy"from the effects of the fumes and smoke. Comments on the effectsof the smoke outside the aircraft were made by many of those assisting,who complained of its effects on their throats and breathing.

A British Airways coach had collected the crew of a Tristar aircraftwith the intention of taking them to their flight office afterclearing Customs. When the driver saw the aircraft on fire heinformed his passengers that he was taking the coach to assistat the accident. Upon arrival (at approximately 4 minutes afterthe aircraft stopped) the cabin crew immediately went to the assistanceof the survivors, many of whom ran towards the coach. The firstevacuees were in a state of shock, but dry, whereas those followingthem were blackened with smoke and wet with foam. Several stewardessesassisted a woman who was lying approximately 100 yards forwardof the aircraft and appeared unconscious. She was being givencardiac massage by a fireman. After resuscitation with oxygen,this passenger began to recover and a deep wound was found onthe back of her head. She was taken to an ambulance. A young girlof approximately 17 years, was also found in the grass forwardand to the left of the aircraft. Her face was black, hair wet,and her eyes "frosted over" with a white deposit. Shehad no signs of burning on her clothes.

The crew members also assisted a young man of about 24 years,he was crouched on the grass and covered in soot. He was havingdifficulty in breathing and thick mucus was pouring from his noseand mouth. A stewardess hit him in the back, the practised methodof causing a cough reflex. As she did this, he started to coughand his breathing became easier.

The TriStar crew members met both surviving cabin crew and assistedthem away from the aircraft. The British Airways coach was joinedby another three coaches from the Manchester Airport Authority.

After some 40 survivors had been led aboard the British Airwayscoach, it left the scene at approximately 0725 hours for PierB, gate number 1 departure lounge where approximately 15 BritishAirways cabin crew had set up chairs, blankets etc to receivethe passengers. The young boy pulled from the overwing exit wasgiven some treatment here for the burns to his hands, using afirst aid box from an adjacent aircraft. Another passenger whowas having difficulty breathing was given oxygen to ease her respiration.It was, however, quickly decided that this area was not suitablefor the condition of the survivors who were in a state of shock,and they were then taken on by the British Airways coach to WythenshaweHospital at 0745 hours, where staff were ready to receive them.

The young boy, whose condition was deteriorating, was not takendirectly to the hospital, but was taken to the Fire Station ina catering van by a British Airways stewardess, where he was reunitedwith his father. The remaining survivors had been taken to thefire station crew room by the Manchester Airport coaches. Thesesurvivors were later taken to Wythenshawe Hospital. Many BritishAirways cabin crew staff stayed at Wythenshawe Hospital to consolethe survivors and also to take names and addresses for disseminationto relatives.

A cabin seating plan showing which passengers used each exit andthe seat location of those who died is at Appendix 14.

1.16 Test and research

1.16.1 Engines

A general feature of most, if not all combustor designs is thatuneven temperature distributions can occur, producing areas oflocally relatively high temperatures. The combustor cans fromthe left engine of G-BGJL and others from the same operator showedevidence of localised 'hot-spots' ie areas of the can liner materialexhibiting excessive overheat blistering and/or multiple cracking.Such local effects can also be produced by different causes, suchas a distorted fuel nozzle flow pattern, distortion of the dimensionsof the can or cooling airflow disturbance caused by repairs orfaulty design/manufacture.

In order to measure the temperature of these hot-spots and thegeneral temperature distribution and gradients around the can,a series of tests was undertaken using a JT8D-15 engine loanedby the operator and using the operators facilities. The enginewas assembled with part-run cans which had been painted internallyand externally with temperature sensitive paint. The engine wasthen run through a typical British Airtours cold day take-offand pull back sequence, returned to idle for a short time andshut down. The cans were removed and the paint examined. A suitablecan was then selected to be instrumented for a further test. Forthis test, seven thermocouples were attached onto the outsideof the can at various locations including on-and-around a hotspot in the 3rd/4th liner joint area identified from the heat-sensitivepaint. An eighth thermocouple was used to record combustor inletair temperature (T4). All the cans were re-coated with heat sensitivepaint and then re-assembled into the engine.

The procedure for the first run was repeated, using chart recordingof the thermocouple measurements but, in addition, the throttleswere advanced for a few seconds above the maximum rated power.This was to simulate a rated power take-off on a hot day, sincethe tests were performed in ambient temperatures of around 5°Cor less. It is estimated that the degree of 'throttle push' employedwas equivalent to:-

a) Exhaust Gas Temperature (T7) changes approximately equivalentto a l5°C increase in ambient temperatures.

b) T4 changes approximately equivalent to a 12°C increasein ambient temperatures.

NB These effects still fall short of simulating a 30°C ambientday take-off, as may commonly have been encountered on the ofroutes flown by G-BGJL.

Examination of the paint and thermocouple results after the secondtest showed eight cans with hot-spot temperatures of 825-950°Con the third liners and two cans with spots in excess of 1,025°C.The distribution of temperatures was generally similar on allnine cans and the instrumented can did not appear to be the hottest.The thermocouple traces showed that maximum material temperaturesoccurred at highest power rather than associated with any transientcondition, such as throttle retardation effect.

It was noted that the temperature of the hot spot rose dramaticallyas peak power was approached ie. at a greater rate than simpletheory would have predicted. It is hypothesised that a concentrationof combustible reactants in the wall cooling layers became richenough for combustion to begin next to the wall itself, elevatingthe liner temperature disproportionately.

The results of these tests were used to estimate the stress levelsgenerated by thermal cycles and a simplified mathematical modelused to calculate the stress/cycle relationship for HastelloyX material. The tests showed that temperature gradients of atleast l50°C and possibly 200°C over 2-3 mm can be anticipatedat peak power, and the calculation showed that thermal stressesin the order of 29,000 psi would therefore be generated in theliner material. Tests on sample Hastelloy X material at elevatedtemperatures showed that, at this stress level, the fatigue lifeof the material would vary between 100 cycles at 980°C to1,000,000 at 815°C. These results serve to emphasise thevery damaging effects of high temperatures and it can thereforebe argued that hot spots in the can will suffer rapid localisedcracking within, say, 1,000 flights from new or repair whilstthe cooler regions would have a vastly greater life. The fatiguelife of the can is thus essentially limited by the performanceof the cooler, longer-life regions, rather than the performanceof localised hot spots.

1.16.2 Search of existing data on Aircraft Fires

1.16.2.1 Emissions from burning aircraft cabin materials

Much attention has been paid to the emissions from the syntheticfoams used in cabin-seat cushions. Thermal decomposition of suchfoams in air produces a complex mixture of smoke and gases, whichnot only varies with the type of foam (eg polyurethane, polyetherurethaneetc) and whether it has added constituents (eg flame-retardants),but is also dependent upon combustion conditions - eg flamingor non-flaming (eg smouldering) conditions. However, the othercabin materials such as wall panels, windows/surrounds, overheadpassenger service unit panels, overhead baggage compartments,ceiling panels, sealing strips, curtains etc. also produce toxic,irritant gases and smoke when burnt.

Comprehensive data on the gases emitted from the combustion ofseat-foams and other cabin materials is contained in a FederalAviation Administration (FAA) report1 (Appendix 15a). These dataindicate that the well known problems associated with the foamsused in cabin seat-cushions represent only one part of the generalproblem concerning the products of combustion of aircraft cabinmaterials.

Polyvinylchloride (PVC) material from cabin panels produces almostas much carbon monoxide as does polyurethane foam, for the sameweight burnt, but also produces almost six times the concentrationof the acidic gas hydrogen chloride.

Polyurethane foam produces less hydrogen cyanide than modacrylicmaterial, which can be used for curtains, carpets etc. Relativelysmall weights of any such materials can produce substantial concentrationsof toxic/irritant gases and smoke when burnt within an aircraftcabin volume.

eg. The burning of only some 5.7 lbs of modacrylic curtain materialin a

cabin volume of about 6,000 cubic feet, will produce a critical

concentration of 200 parts per million (ppm) of hydrogen cyanide-

sufficient to induce rapid incapacitation and death.

Wool is often preferred to modalcrylics for curtains, carpetsetc (as was the case on G-BGJL), but also produces hydrogen cyanide,although in reduced quantities.

Fluorinated materials which are frequently applied in the formof decorative films to cabin wall panels (eg 'Tedlar' Polyvinylfluoridefinish on the wall panels of G-BGJL at Manchester) emit the intenselyirritant hydrogen fluoride acidic gas when burnt.

Fibreglass materials generally exhibit much lower toxic/irritantgas emissions, dependent upon the resin used - eg phenolic fibreglassis superior in this regard to epoxy fibreglass. Such materialscan still, however, emit large concentrations of particulate -ie 'smoke'.

The cabin materials fitted in G-BGJL are listed at Appendix 15b

1.16.2.2 Toxicological effects of combustion gases (Appendix 15Table c)

The effects of those gases which are generally recognised as theimportant toxic/irritant components of such combustion atmospheresare listed below:

Carbon Monoxide (CO):

Carbon monoxide is produced when any combustible cabin materialburns incompletely, or in reduced oxygen conditions. It is alwayspresent, often in high concentrations, in large uncontrolled fires.It is the agent that is generally accepted as being most responsiblefor deaths due to smoke inhalation. In large fires involving kerosenefuel, large concentrations of carbon monoxide can be expected.(egthe tests at Teesside, where carbon monoxide concentrations ofseveral thousand ppm were measured inside a Trident fuselage duringa large-scale test demonstrating water spray systems)

When carbon monoxide is inhaled, it is absorbed by the blood fromthe lungs and combines with haemoglobin to form carboxyhaemoglobin.This reaction inhibits the absorption and therefore the transportof oxygen to the body tissue. 10-20% carboxyhaemoglobin in theblood can be tolerated generally with only a slight headache,but concentrations of 30-40% may induce a severe headache, weakness,dizziness, dimmness of vision, nausea, vomiting and collapse.Concentrations above 50% can lead to collapse and death. Recoverycan be effected from lower concentrations, since the reactionis reversible with the administration of oxygen to the victim.

The effects of a given concentration of carboxyhaemoglobin areinfluenced by physical activity.

Hydrogen Cyanide (HCN)

This gas is produced from the combustion of wool, modacrylics,nylon and leather and stimulates breathing, thereby acceleratingthe rate of absorption. Cyanide affects the body by direct absorptioninto the tissues, affecting certain enzymes such as cytochromeoxidase which blocks the uptake of oxygen by cell tissue fromthe blood. A concentration of only approximately 200 ppm of hydrogencyanide in the atmosphere will induce rapid collapse and death.

Nitrogen Dioxide (NO2)

This gas often occurs with other nitrogen oxides, such as nitricoxide (NO), in fires and is often denoted as NOx, for this reason.Nitrogen oxides combine with moisture to form nitric and nitrousacids. These can be absorbed directly, or with the carbon particlesof smoke which have 'adsorbed' these acids. The acids attack thethroat, trachea and lung tissues and are highly irritant. Someof the acid may also be neutralised by an alkaline reaction withinthe tissues producing nitrate of sodium. Nitrate absorption causesarterial dilation, hypo-tension, headache, vertigo and the formationof methaemoglobin.

High concentrations cause pulmonary oedema which, even after asuccessful evacuation, may cause death some hours later.

Hydrogen Fluoride (HF)

Hydrogen fluoride, produced from fluorinated polymers such aspolyvinyl fluoride, combines with moisture to produce hydrofluoricacid, one of the most powerful acids. Pathologically, this acidis much more active than hydrochloric acid and causes major oedemawithin the respiratory tracts. It is also a protoplasmic poison.

Burns produced by hydrofluoric acid produce throbbing pain andprogressive destruction of tissues with decalcification and necrosisof bone. Combustion of fluorinated polymers may also produce saturatedand unsaturated fluorinated hydrocarbons of low molecular weight,which are also extremely toxic.

Hydrogen Chloride (HCl)

Combustion of PVC and many fire-retardant materials produces hydrogenchloride. Hydrogen chloride combines with water to form hydrochloricacid which has a highly irritant effect on the throat and respiratorytracts, causing destructive damage to the mucous membranes andpulmonary oedema. It is an intense irritant to the eyes, throatand respiratory tracts, causing destructive damage to the mucousmembranes and pulmonary oedema.

Sulphur Dioxide (SO_2)

This gas is produced on combustion of both natural and syntheticrubbers and other compounds containing sulphur. It combines withmoisture to produce sulphurous acid which is highly irritant totissue, including the eyes. It attacks the mucous membranes ofthe respiratory tract, causing uncontrollable coughing. Very highconcentrations can induce respiratory paralysis.

Ammonia (NH_3)

This gas is produced upon combustion of polyurethane, polyamides,polyacrylonitrile, silk and wood. It is a highly irritant causticand has a violent affect upon the respiratory tract and eyes.It inhibits respiration and in high concentrations may cause cardiac-arrestvia the respiratory reflexes. It produces bronchial constrictionand pulmonary oedema.

Acrolein (CH_2 CH CHO)

Acrolein is one of the most irritant of the aldehydes producedby the combustion of cabin materials. It is also produced in smallamounts from burning kerosene and from the combustion of naturalmaterials such as wood and cotton. It is an intense eye irritantand in concentrations as low as 5.5 ppm has been shown by Deichmannand Gerarde2 to cause irritation of the upper respiratory tract.At higher concentrations, pulmonary oedema occurs, with deathafter a few minutes at only l0 ppm.

Aromatic hydrocarbons (eg Benzene, Toluene, Styrene etc)

A whole range of aromatic compounds are produced by the thermaldegradation of synthetic (and natural) materials. They producevarying degrees of narcosis. Several of these aromatics such asbenzene (from PVC) are not only absorbed due to inhalation, butcan also be absorbed directly through the skin. Concentrationsof l00 ppm are considered injurious to health. Toluene is lesstoxic than benzene but, conversely, represents a greater dangerin chronic exposure.

Styrene is considered safe at concentrations less than l00 ppm,but above this is highly irritant to the mucous membranes, causingsymptoms of toxicity with impairment of the neurological functions.In concentrations of approximately 800 ppm, it causes 'styrenedisease', characterised by nausea, vomiting and total weakness.

Aliphatic hydrocarbons

Thermal degradation of all organic materials produces a varietyof aliphatic compounds. Some of these compounds with the lowermolecular weights can produce narcosis. Unsaturated hydrocarbonsgenerally have a greater toxic effect than saturated compounds.Acids, alcohols and aldehydes may be present with their respectivetoxic effects.

Acetaldehyde

This is produced from the thermal degradation of a wide rangeof synthetic (and natural) materials. It is an irritant gas whichcan induce central nervous system suppression, producing headaches,stupor and eventually coma and death. Even amongst those who recover,pulmonary oedema usually develops within 2 hours of exposure.

1.16.2.3 Full scale fire tests

Whilst there has been research carried out over the years intothe atmospheres associated with aircraft fires, and much valuablework has been done particularly by the FAA Technical Centre atAtlantic City, the tests in general have been rather limited interms of the fire-model used. There is a lack of information concerningthe atmospheres generated in differing types of fire, coveringa wide cross-section of situations. This has led to the 'read-across'of such results from rather specific test scenarios to generalaircraft fire accidents.

The FAA Technical Centre has, for many years, carried out fullsize fire tests on a Lockheed C133 fuselage, extensively thermallyinsulated to withstand repeated fire tests. The test set-up wasintended to simulate a pooled-fuel ground fire attack on the cabininterior via a door aperture (76" x 42") representinga breach in the fuselage. An 8 ft x 10 ft 'tray' of kerosene wasignited immediately outside the aperture and the resultant thermalradiation of 1.5 BTU/sq ft/second initiates an internal fire amongstthe cabin furnishings. A second single door was used to exhaustthe combustion products from the cabin.

This test series3 has demonstrated one phenomenon repeatedly -ie that of 'flashover' (Appendix 16 a). Flashover occured at about2› minutes after the tray-fire had been initiated. At thispoint the cabin temperatures soared to approximately 1,700/1,800°Fat ceiling level near the fire aperture plane. In addition theoxygen level, which remained at the normal 21% prior to flashover,reduced to approximately 12% after 3 minutes 10 seconds (measuredat a datum 40 feet from the fire aperture towards the 'exhaust'door).(Appendix 16 Figb-c)

Three points are notable from these results:

1. Before flashover, only hydrogen chloride and hydrogen fluorideare shown as being emitted in significant concentrations, risingto some 830 ppm and 840 ppm respectively.

2. The carbon monoxide concentration appears negligible (approximately100 ppm) before flashover.

3. Very little hydrogen cyanide is produced, even after flashover,with a maximum of around 20 ppm.

This latter finding is somewhat surprising, since real survivableaircraft accidents with fire-related fatalities have shown significantcyanide absorption by the victims.

The limiting incapacitation time based on calculations from thistype of data and applicable to three heights within the cabin- ie at the 5ft 6 inch, 3 ft 6 inch and 1ft 6inch levels , giverespectively a time to theoretical incapacitation of 2 minutes39 seconds, 3 minutes 13 seconds and 3 minutes 22 seconds (Appendix16 Fig d). It is notable that for these tests the thermal partof the total incapacitation threat, even after flashover, wasvery small when compared to that due to the effects of hydrogenchloride, hydrogen fluoride, carbon monoxide and hydrogen cyanide.

Thus, even given this extreme situation of flashover within 2›minutes of the cabin interior being exposed to the heat flux froma large pooled-fuel fire, it would appear that incapacitationmay be delayed beyond flashover in parts of the cabin away fromthe fire, until some 2 minutes 39 - 3 minutes 22 seconds. Furthermore,experience from real aircraft fires indicates that this situationis not always encountered - ie flashover is either significantlydelayed or may not occur generally at all in the cabin.

In this context it is notable that the authors of this work, havestated:-

"uncontrolled post-crash fires in an intact fuselage willproduce a flashover condition, which will be followed by a lossin survivability throughout the cabin."

In addition it is the case, from pathological examination, thatthe majority (c.80%) of fire fatalities occur not due to directand excessive thermal assault, but due to smoke/gas incapacitation4.

Tests have also been carried out at the FAA Technical Centre onthe effectiveness of seat cushion 'fire-blocking' coverings. Polyurethanefoam cushions covered with materials such as 'Vonar' have beentested against unprotected foam cushions, both in simulated groundfire situations and also internal cabin fires with air-conditioningair-flow, to simulate in-flight fires. These tests indicated anincrease in the time to incapacitation of about 60 seconds asa result of reduced cabin temperatures (Appendix 16 Fig e). Itshould be noted, however, that fire-blocking layers merely delaythe onset of combustion of these cushions in a full-scale groundfire situation.

One aspect of the 'in-flight' tests is of interest. Flashoverdid not occur during the time that 'air-conditioning' air-flowwas being used, but when it was shut-off at approximately 3¤minutes, flashover occurred very quickly thereafter, within 30seconds. It is also notable that well before this time, and indeedfrom the start of the fire, the concentrations of hydrogen fluorideand hydrogen chloride became critical, in spite of the air-flowoperating. However, during this period the oxygen concentrationremained at 21%.

The final fire test of the C133 series was carried out on the30 July 1987 and produced some interesting new data. In this testsome 105 seats were installed in the cabin. All seats were ofthe new 'fire-blocked' type. The fire, which in earlier testswas extinguished after some 5 minutes, was allowed to continuefor some 15 minutes. The hydrogen cyanide sampling was locatedat a higher level in the cabin than in all previous tests - ieat a height of 5¤ feet above the floor. For the first time,some 200 ppm of hydrogen cyanide was detected in the time beforeflashover occurred (latter took place 4 minutes from the initiationof the fire). In addition, some 700 ppm of hydrogen bromide wasalso detected before flashover. This emission was attributed tothe epoxy-fibreglass material of the wall, overhead stowage 'bins'and ceiling panels. Hydrogen fluoride and hydrogen chloride werealso detected before flashover, as in previous tests.

1.16.2.4 The materials fire hardening strategy

It is notable that the current regulatory standard for cabin materialscertification, FAR 25.853, was adopted in May 1972 and specifiesthat all large usage material must be self-extinguishing in avertical orientation when subjected to a 'Bunsen-burner' flame.Whilst such a test may be useful for demonstrating protectionagainst a small flame in a cabin, it clearly does not indicatethe results of exposure to a large external (eg pooled-fuel) fire.

As a result of their awareness of the clear deficiency of thiscertification test and the effects of toxic gas and smoke on survivability,the FAA proposed two important changes in 1974/75:-

Advance Notice of Proposed Rule-Making (ANPRM) No 74-38 was issuedon 30 December 1974. This notice invited 'public' participationin developing standards governing the toxic gas emission characteristicsof compartment interior materials when subjected to fire.

Also, Notice of Proposed Rule-Making (NPRM) No 75-3 was issuedon 12 February 1975. This notice invited comments on proposedamendments to FAR parts 25 and 121 concerning the introductionof limitations on smoke emission characteristics of compartmentinterior materials when subjected to fire.

The industry responded, citing inadequate test methodology andquestionable safety benefit. The FAA withdrew both proposals.

The FAA then set up the SAFER (Special Aviation Fire and ExplosionReduction) Committee in June 1978 to: "Examine the factorsaffecting the ability of the aircraft cabin occupant to survivein the post-crash environment and the range of solutions available."

After its investigations into cabin materials technology, thiscommittee issued recommendations concerning further research anddevelopment of materials, investigation of the problems of smokeand toxic gas emissions and the evaluation/implementation of a"radiant-heat" test method for cabin materials certification.

The previously described C133 fire-test programme originated fromsuch recommendations. The flashover phenomenon, which was apparentduring these tests, sustained the flammability approach to materialscertification, but it appears to have done so at the expense ofany serious consideration of smoke and toxic/irritant gas emissions.The associated justification for this was that:-

"(1) There is a correlation between flammability characteristicsand toxic emissions.

(2) The severe hazard from toxic emissions occurs as a resultof flashover in fires involving interior materials. The levelof toxic gases measured before flashover or when flashover didnot occur, were below levels estimated to prevent occupant survival."

Both of these conclusions are severely undermined by the lastC133 fire test on 30 July 1987, when some 200 ppm of hydrogencyanide was detected in the time before flashover.

As a result of that approach, the Ohio State University (OSU)radiant heat test apparatus, modified to measure heat release,was adopted. This test used a radiant heat flux of 3.5 watts/sqcm.

The current regulatory response to this problem has thus beento continue to approach it solely through material flammabilitycriteria, excluding any certification requirements for smoke ortoxic/irritant gas emissions.

In this context, a discussion document issued by the FAA in July1986 requesting further comments on their 'Improved FlammabilityStandards for Materials Used in Interiors of Transport CategoryAirplane Cabins' is of interest. In response to requests fromtwo commenters from the materials industry for assurance thatno rule-making with respect to smoke and toxicity was anticipatedin the foreseeable future, the FAA replied ; "Based on theinformation currently available, the FAA has no plans to establishstandards for either smoke or toxicity; however this does notpreclude taking such action in the future if, as noted above,further research shows such standards are warranted and humantolerance levels can be adequately defined." The FAA thusamended FAR parts 25 and 121 to include the OSU test, on 20 August1986.

Airworthiness Notice No 61, 'Improved Flammability Test Standardsfor Cabin Interior Materials' issued by the CAA on 16 March 1987and applicable from 20 August 1988 is in compliance with thisapproach, and does not include any criteria for smoke and gasemissions.

This regulatory approach has already led to the use of flame-retardantmaterials developed by the chlorination of earlier materials.However, when burnt in a real fire, many such materials were foundto generate even more smoke and gas (eg hydrogen chloride) thanpreviously.

Research work5 completed as early as 1973 into smoke emissionfrom aircraft interior materials indicated that:-

"To date the major concern of those engaged in the developmentof fire-retardant materials has been the reduction of the ignitiontendency and flame propagation. Thus, it has been possible tomeet code and regulatory requirements regarding flame-spread butin the opinion of the author the total hazard resulting from incompletecombustion has been increased".

This report also included the standard disclaimer used by theAmerican Society for Testing Materials:-

"No direct co-relation between these tests and service performanceshould be given or implied".

Whilst the regulatory authorities have not yet introduced requirementsfor materials certification to take account of smoke and toxic/irritantgas emissions, many aircraft manufacturers already stipulate associatedlimitations for their materials. For example, in 1977 Boeing establishedgoals/guidelines (the so-called "Withington" guidelines)covering smoke emission (more stringent than the limits in NPRM75-3), toxic gas emission (hydrogen cyanide, carbon monoxide,hydrogen chloride, hydrogen fluoride, sulphur dioxide + hydrogensulphide, nitrogen oxides), and flame spread index (ASTM E162).In 1978 Airbus Industrie released ATS 1000.001 covering smokeemission (using the limits in NPRM 75-3) and toxic gas emission(using the limits in Boeing's Withington guidelines). ATS 1000.001has subsequently also been used by Fokker and British Aerospace.McDonnell Douglas has similar criteria on smoke and toxic gasemission.

Whilst this type of testing represents a considerable improvementin materials certification, the radiant heat flux used to combustthe material sample is still low (2.5 watts/sq cm) compared withthe radiant heat from a real pooled fuel fire which can rise to14-20 watts/sq cm.6

1.16.2.5 Visibility and escape path low level lighting

In addition to the toxic effects of gases, such as hydrogen cyanideand carbon monoxide etc, the 'acid' gases such as hydrogen chloride,hydrogen fluoride, sulphur dioxide etc. attack the eyes, causingintense irritation and lachrimation (discharge of tears). Considerableresearch has been carried out into the effects on vision of smokeemissions from burning cabin materials7, revealing that:-

"The predominant factor affecting visibility is not the obscurationof vision by particles of smoke, but the irritating effects ofcombustion gases, predominantly hydrogen chloride and sulphurdioxide. These gases in combination with the moisture in the eyes,tend to cause great discomfort and irritation".

"The dominating factor on human critical visibility is stronglyrelated to the irritating effects of combustion gases generatedfrom flaming materials in a crash-fire situation".

Further research work carried out in Japan8 also highlighted themarked effects of irritating gases on vision:-

"In thick irritant smoke, the subjects could not keep theireyes open for a long time, and tears ran so heavily that theycould not see the words on the signs".

"In irritant smoke, the subjects could no longer walk straightand began to 'zig-zag' or walk along a wall".

Walking speed slowed down in smoke by more than 50% and was furtherreduced in irritant smoke.

Notwithstanding such research evidence, the regulatory authoritieshad for some time been progressing towards a requirement for lowlevel lighting within aircraft cabins with the intention thatevacuating passengers would be able to follow the lights to escapemore quickly in conditions of thick smoke and reduced visibility.

1.16.2.6 Passenger smokehoods:

As a result of several accidents in the United States, and particularlythe short landing/fire accident to a Boeing 727 aircraft at SaltLakes City on the 11 November 1965 where 43 passengers died,35 of whom had carboxyhaemoglobin levels of 13-82% (Av = 36.9%),the FAA Civil Aero Medical Institute (CAMI) at Oklahoma initiatedresearch into passenger smoke protection.

A simple hood was developed made from 'Kapton' polymide, a high-temperatureresistant translucent material which could protect the head againsttemperatures of 800°C. This simple device had no air supply,filter or carbon dioxide absorbent and merely provided a reservoirof air within the hood sufficient for some 1¤-2 minutes breathingunder heat/exercise conditions.

The first model, which featured a 'draw-string' neck seal, wasquickly superseded by a hood with a much improved elasticated'septal' neck seal. This hood was known as the Schjeldahl 'S'hood and subsequent variants were partly metalised to reflectradiant heat. In the following 4 years, considerable testing wascarried out on these hoods9 and included:-

neck seal leakage evaluation (including exposure to carbon monoxideand smoke);

breathing capacity and carbon dioxide build-up under exerciseconditions;

visibility measurements;

acoustic measurements;

effects of variations in safety briefings on use of hoods by naivesubjects;

evacuation tests using naive subjects in dense non-toxic smokeconditions.

In assessing the evacuation tests this report concluded that theuse of hoods had no significant effect on evacuation rates, themain factor affecting evacuation rates being the presence of smoke.

In 1967, aircraft belonging to the FAA were equipped with Schjeldahlsmokehoods for their occupants.

On February 27/28th 1968, more extensive evacuation tests werecarried out at the Aeronautical Centre, Oklahoma. An FAA Boeing720 aircraft was fitted with a passenger seating capacity of 124with 4 stewardesses supplied by Braniff. A total of six evacuationtests were carried out, both with and without smoke. The associatedreport concluded:-

"There are indications that the use of smokehoods duringan emergency evacuation of a typical air carrier jet aircraftcauses a small increase (approximately 8%) in the overall timerequired for naive passengers to evacuate".

The results of this test and the other research were judged satisfactoryby the FAA and on the 11th January 1969 NPRM 69-2 was publishedin the Federal Register, with the intention of amending FAR part121 to require that protective smokehoods be carried for all occupantson aircraft operating under these regulations:-

"These hoods would be available for use by their occupantsto facilitate airplane evacuation when fire or smoke is presentafter a crash-landing or other emergency".

Whilst there was much support for this proposed change, some sectionsof the aviation community were unconvinced. On the 11th August1970, NPRM 69-2 was withdrawn by the FAA, with the principal reasongiven that the hood might cause a delay in evacuation.

In late 1971 a comprehensive report on smokehoods was reviewedby the US National Research Council. They rejected the viewpointthat carbon dioxide accumulation in the hood and the accompanyinghyperventilation would cause passengers to remove the hood, butsuggested the addition of a carbon dioxide absorber and oxygensupply to the hood to extend usage. The feasibility of using asmall chemical oxygen source was investigated.

In June 1980, the FAA Technical Centre at Atlantic City requestedCAMI to re-examine passenger smokehood protection, stating:

"Survival and escape of passengers in a transport cabin firemay be impaired or prevented by smoke and toxic gasses. Advancementsin protective breathing devices and limited progress in the minimizationof cabin fire hazards prompted the SAFER (Special Aviation Fireand Explosion Reduction) Committee Technical Group on CompartmentInterior Materials to recommend a re-assessment of protectivebreathing devices for usage by passengers aboard Part 25 Aircraft".

This led CAMI to evaluate, in the period 1981-1985, the possibilityof using a 'rebreather bag' attachment to the standard passengeroxygen-mask ('yellow-cup'). This system had a number of deficienciesin supporting respiration and failed to protect the eyes or addressthe evacuation case.

In 1983, as a result of their investigation into the in-flightfire and emergency landing accident to an Air Canada DC9 at Cincinnation the 2 June, in which 23 of the 41 passengers died before theycould evacuate the cabin (and survivors breathed through handtowels), the National Transportation Safety Board (NTSB) issuedSafety Recommendation A-83-76 on the 31 October 1983. This recommendedthat the FAA:-

"Expedite the research at the Civil Aero Medical Institutenecessary to develop the technology, equipment standards, andprocedures to provide passengers with respiratory protection fromtoxic atmospheres during in-flight emergencies aboard transportcategory airplanes".

It is also noteworthy that in July 1982 a very comprehensive report,sponsored by the FAA, was issued on the problems of aircraft fire10.This report included a very detailed cost/benefit analysis ofa wide variety of different approaches to combat fire on aircraft.It concluded that smokehoods were by far the most cost-beneficialapproach for survivability and would achieve the highest survivabilityfactor, with the lowest cost per death prevented. (Appendix 17)

1.16.3 AAIB passenger smokehood test programme

During a visit to CAMI by AAIB investigators on the 17/18th March1986, it was confirmed that the 'rebreather-bag' approach wasunlikely to prove satisfactory for passenger smoke protection.It was also established that CAMI had not, at that stage, carriedout any assessment of modern breathable-gas or filter type hoods.

It was therefore confirmed that the AAIB would continue to fundand direct a research/test programme to explore the potentialof breathable gas and filter hoods. Work on this programme hadbegun in January 1986.

1.16.3.1 Breathable gas smokehoods

The tests on the breathable gas hoods were carried out in twostages. Initially, four different types of passenger hood andone French cabin crew hood were tested at the RAF Institute ofAviation Medicine, Farnborough, to establish the breathing capacity/duration,carbon dioxide build-up and temperature rise within the hoodsat various work rates, using human subjects. Additional testswere also carried out at the Chemical Defence Establishment, PortonDown, to establish the ability of the neck seals to prevent theexternal atmosphere entering the masks.

Using test protocol l (Appendix 18 a), it was found that noneof the 5 hoods achieved a fully satisfactory standard, with threeof the hoods requiring an increased oxygen capacity and at leastone other hood needing improved carbon dioxoide absorption. Theseresults were not altogether surprising since each of the hoodstested had been developed prior to the CAA draft specification,which was used as the basis for these tests.

In the spring of l987, 2 of the latest standard of passenger typehoods were tested, together with a cabin crew hood of the sametype used in the earlier tests to provide comparative data. Thesetests were carried out in the laboratories of the Scientific Divisionof British Coal at Edinburgh, using an 'Auer' lung simulator.(Appendix 18 b)

Three test protocols were devised for these tests (Appendix 18a), designed to cover broadly the performance envelopes requiredfor the emergency evacuation case; a 15 minute test to allow comparisonwith the cabin crew hood (rated for 15 minutes duration); andtesting to the CAA Draft 'Type 1' test performance requirement.

In the first two protocols, both passenger hoods substantiallyout performed the cabin crew hood which weighed 3 lbs, comparedto the 1 lb weight of each passenger hood.

The first passenger smokehood surpassed the CAA Draft Specification20 minutes endurance with ease, achieving 28 minutes (with thefinal 10 minutes at the highest workload of 100 watts/minute)before the inhaled carbon dioxide concentration exceeded the 5%limit. Indeed when the CAA required 15 minute sedentary periodwas extended to 25 minutes in a later test this type of hood achievedan endurance of 31 minutes before the inhaled carbon dioxide concentrationexceeded 5%.

The second passenger hood achieved the 20 minutes endurance requiredby the CAA draft Type 1 specification, although it exceeded slightlythe carbon dioxide level (7.75%). (Appendix 18 c)

The tests at Porton Down indicated that elasticated septal neckseals alone were capable of providing adequate sealing againstthe external atmosphere. It was considered that the addition ofan ori-nasal mask would further enhance sealing effectiveness.

1.16.3.2 Filter smokehoods

The problem of testing filter hoods was the more difficult. Indeed,the initial question confronted was whether filter-protectioncould be regarded as a viable approach to survival in aircraftfires, since there was a widespread belief that there is insufficientoxygen in fire atmospheres. However, the young boy and man survivedthe fire at Manchester, others have survived for protracted timesin other aircraft ground fires and there have been many instancesof passengers surviving in-flight fire/smoke situations - eg theCanadian DC9 at Cincinatti in June 1983 (para. 1.17.7), wheremost survivors breathed through wet hand-towels issued by a stewardess.

In addition, the large amount of data from the C133 Fire TestProgramme at the FAA Technical Centre, Atlantic City, indicatedthat the available oxygen concentration in the cabin did not reduceappreciably until temperatures exceeded human tolerance levels.Similar evidence was apparent from the earlier NAFEC cabin firetests carried out in 1965. Thus, whilst this vital question isstill open to the consideration of further data, based on thisassessment carried out early in 1986 there appeared reasonablegrounds to proceed with a scientific evaluation of filter-protectionin order that the other important questions of particulate-inducedblockage, toxic/irritant gas protection etc, could be addressed.

The next question concerned how a meaningful test could be devised,since aircraft fires are infinitely variable. The key to thisquestion, which began to emerge as the research data was examined,appeared to be that although fires are variable, the prime reasonsfor incapacitation, which appeared generally accepted, were thoseassociated with hydrogen cyanide and carbon monoxide toxic gasabsorption and the related problems of attack by irritant gasessuch as hydrogen chloride, hydrogen fluoride, nitrogen oxides,sulphur dioxide and acrolein.

With regard to carbon monoxide, there is a body of opinion thatthis particular gas is slow to reach incapacitating concentrationsin fires and that much of the pathological evidence of high carboxyhaemoglobinlevels in fire-fatalities derives from post-incapacitation absorption,before respiration ultimately ceases. It is contended that hydrogencyanide, which can cause rapid incapacitation at very low concentrationsof approximately 200 ppm, is the more potent toxic gas. This wasan important consideration, since although carbon monoxide canbe countered by catalysts such as Hopcalite*, this requirementincreases the weight and depth of any filter.

Since however, the aim of the AAIB tests was to evaluate the bestprotection that filters could provide, a firm decision was madethat any filters to be tested within the AAIB smokehood test programmewould be required to combat carbon monoxide.

Following a search of available data the following Challenge Atmosphereand acceptable filter breakthrough levels were arrived at:-

Gas	Challenge concentration	Filter Break-through (After 5 minutes)
Carbon Monoxide	10,000 ppm (1%)	400 ml (max cumulative total)
Hydrogen Cyanide	400 ppm	20 ppm

Hydrogen Chloride	1000 ppm	10 ppm
Nitric Oxides	200 ppm	10 ppm
Sulphur Dioxide	100 ppm	10 ppm
Acrolein	20 ppm	1 ppm
*Hydrogen Fluoride	500 ppm	10 ppm

* Separate single gas challenge requirement.

The above definition of the challenge atmosphere was includedin Passenger Smokehood Acceptance Criteria, issued by the AAIBon 5th March 1986 to interested manufacturers within the UK andabroad, which included requirements for the following parameters:-

filter performance, including carbon dioxide limitations (5%);

inhaled gas temperature limitations (45°C, wet);

flame and molten drop resistance;

robustness;

weight (1 lb);

compactness;

donning time target (8 seconds) for both breathable gas and filter-typehoods.

Challenge atmosphere generation and analysis

A major question was whether such an atmosphere could be modelled,particularly since the aim was to attempt generation by burninga wide cross-section of cabin materials and kerosene in orderto derive a representative complex atmosphere.

This task was given to the Rubber and Plastics Research Association(RAPRA) at Shawbury on the 19 February 1986. By the end of May,they had achieved significant success with generation of the atmospherein a large 34 cubic metre chamber, lined with polypropylene. ByJune of 1986 the atmosphere could be generated on an acceptablyrepeatable basis, using a derived weight and 'mix' of cabin materials.An effective degree of control for such gases as carbon monoxide,carbon dioxide, oxygen, hydrogen cyanide, nitrous oxides, andsulphur dioxide was achieved, although hydrogen chloride levelswere still variable.

The range of cabin materials used to generate the atmosphere wereas follows:

Material	Source
Wool	Curtains, carpets, seat-covers
Polyurethane Foam	Seat cushions
GRP (Polyester)	Ceiling panels
Epoxy Honeycomb	Overhead bins
PVC (rigid and plasticized)	Carpet strips, seat backs/mouldings, life-

	jacket holders
PVC/Polyester	Seat cushion support
Polyester Fibre	Lap belts
Polycarbonate	Window surround
Nylon	Mouldings - eg hinges
Acrylonitrile-Butadiene-Styrene (ABS)	Seat leg mouldings
Chlorosulphonate Polyethylene	Cable insulation
Polyethylene Foam	Seat padding
Polysulphide	Sealants
Kerosene	Aircraft fuel

Note: Fluorinated compounds (such as the 'Tedlar'/Polyvinylfluoridefilm used to cover aluminium alloy side panels on the Boeing 737)were not included within the above list of materials due to currenthealth concerns regarding the combustion of fluorinated compounds.Separate tests were conducted later at the Scientific Divisionof British Coal at Edinburgh using hydrogen fluoride gas atmospheres.

The equipment used to analyse the challenge combustion atmospherepermitted continuous monitoring of carbon monoxide, carbon dioxide,residual oxygen, nitrogen oxides, chamber temperature, and time-weightedaverages of hydrogen cyanide, hydrogen chloride, sulphur dioxide,acrolein and particulate.

A full Gas Chromatography Mass Spectrographic (GCMS) analysisof the complex organic compounds in each of the atmospheres wasalso carried out.

In addition to the required levels of the challenge atmosphere,RAPRA were asked to monitor for other gases, including ammonia,hydrogen sulphide and phosgene. This testing indicated the presenceof up to 850 ppm of ammonia within these atmospheres, acroleinlevels up to 40 ppm and in addition particulate densities up to5 milligrammes/litre.

The only gas which was difficult to generate to the required levelsvia natural combustion of the materials was nitrogen dioxide andbecause of this, cylinders of this gas were used to boost theatmosphere to the required levels artificially. In retrospect,some boosting of the hydrogen chloride levels would also havebeen advantageous, although supplementary tests were carried outwhere high hydrogen chloride levels had not been achieved in earliertest-runs.

Lung simulation and filter breakthrough analysis

The second major task was to devise truly representative lungsimulation (with carbon dioxide and humidity insertion, to simulatehuman respiration) associated with a dummy head in the test-chamber.For this part of the exercise the AAIB obtained the committedassistance of the Scientific Division of British Coal at Edinburgh.

An extensively modified 'Auer' lung simulator was used so thathuman breathing could be fully simulated. In addition, a systemwas devised so that the inspired gases entrained through a filterduring each inhalation could be sampled, so that accurate analysiswas achieved. The lung was set to inhale 30 litres/minute at abreathing frequency of 20 cycles/minute, with the exhalate fullysaturated with water vapour at 37oC and containing 4.5% carbondioxide.

Carbon monoxide, carbon dioxide, oxygen, nitrogen oxides, inhaledgas temperature and filter resistance were monitored continuously,whereas hydrogen cyanide, hydrogen chloride, sulphur dioxide,acrolein etc were absorbed in impinger-solutions so that theirassociated average concentrations could be measured over the testduration of 5 minutes.

In addition, a GCMS analysis was carried out on the filtered atmosphere.

Filter tests

Testing began at the end of July, 1986. Although the intendedapproach was to test in the region of 40°C and 100°C,this was in fact quickly modified. High temperature runs weredirected towards a 5 minute test averaging approximately 100°C.Medium temperature runs were initiated later in the natural temperaturedecay and averaged approximately 65°C for 5 minutes. Runswere also carried out to check carbon monoxide penetration atlow challenge levels around 0.25%, where carbon monoxide 'slippage'(filter penetration) can occur, and were achieved using a partial'purging' of the smoke chamber, the temperature averaging approximately65°C during these runs.

Filter performance tests were conducted against the ChallengeAtmosphere to establish:

gas and particulate filtering efficiency;

limitation of inhaled carbon dioxide concentration;

breathing resistance characteristics against time;

limitation of inhaled gas temperature;

% moisture in the inhaled gas.

These tests were primarily directed towards a 5 minute test duration,but many tests were extended beyond this time scale, up to 30minutes endurance.

A total of 5 weeks intensive testing of six different filter typeswas carried out, before the facility was closed down on the 16October 1986. Seventy test-runs had been completed, using a totalof approximately › ton of materials.

In addition, at the laboratory of the Scientific Division of BritishCoal at Edinburgh, testing was carried out to check the performanceof filters against hydrogen fluoride atmospheres to assess the'sorption' capacity, followed by testing against 1% carbon monoxideto check for any deterioration in carbon monoxide catalyst efficiencyresulting from hydrogen fluoride exposure. Tests were also conductedagainst an hydrogen fluoride/carbon monoxide mixture, followedby carbon monoxide exposure.

Results summary:

The filter test programme demonstrated that filters based on the'Hopcalite' catalyst can provide the necessary protection againstcarbon monoxide, hydrogen cyanide, hydrogen chloride, hydrogenfluoride, nitrogen oxides, sulphur dioxide, ammonia, acrolein,benzene, toluene, styrene, acrylonitrile and other toxic/irritantgases, including the associated particulate, provided there issufficient oxygen in the fire atmosphere to sustain life and thatthe concentration of carbon dioxide is not such as to induce severedebilitation. The C133 test results indicated that, prior to flashover,oxygen levels were maintained at the normal level of 21% by volumeand the carbon dioxide concentration was negligible.

The inhalation resistance of filters increased, as expected, withtime of exposure to such atmospheres. However, except for a numberof high temperature fires (approximately 140°C) the inhalationresistances measured would be reasonably acceptable to most healthypeople in an escape situation, for periods of 5-10 minutes.

While certain designs of filter can maintain the inhaled gas temperaturejust within acceptable limits even when exposed to atmospheresat 100°C, it was demonstrated that the inclusion of a simplemetal heat exchanger behind the filter can satisfactorily reduceinhaled gas temperatures.(Appendix 18 d)

1.16.3.3 Summary of additional tests carried out at RAPRA on filterand breathable gas hoods

1 Smokehood light transmission measurements before and after exposureto the challenge atmosphere, with further light transmission measurementsafter a simple 'wiping' of the hood transparency.

2. Monitoring of any detrimental effects on the hood materialsas a result of exposure to the challenge atmosphere.

3. Flame tests on all hoods using the British Standards InstituteFlame Test Rig with a modified protocol.

4. Molten drip tests on all hoods.

It was found that smokehoods lost some 40-50% of their light transmissioncapability by the end of their exposure to the challenge atmosphere,as a result of smoke particulate deposition on their transparencies.With the exception of one hood, all had their light transmissioncharacteristics restored to within 10% of their 'as-received'values after simple 'finger-wiping'. The one exception was a hoodmade from pure 'Kapton' material which was affected by the challengeatmosphere, creating a 'tacky' surface on the exterior. This couldnot be restored by wiping, and left the hood with a reductionin light transmission of some 30-35%. PFA*-coated Kapton was notaffected in this way and performed satisfactorily. No other detrimentaleffects were found due to exposure to the atmospheres.

Flame testing demonstrated that hood materials are available whichcan successfully resist an impingeing flame of 915-920°Cmaximum temperature for some 6 seconds. In addition smokehoodmaterials can satisfactorily resist the effects of flaming dropletsof nylon.

A full report on the AAIB Passenger Smokehood trials is availableas a separate publication.

1.16.4 Internal water spray systems

The potential for water to extinguish many types of fire has longbeen appreciated. However, although fire authorities have knownfor some time that the way in which water is applied is of importanceit is commonly believed that relatively large volumes of waterare required and that its use on certain fires, involving fueloils for example, is undesirable if not counter productive.

Water typically extinguishes a fire by absorbing the heat generatedand depriving the fire of oxygen. The heat absorption rate islargely governed by the surface area of water exposed to the fireenvironment and therefore the larger the surface area of the waterthe greater the effect. The exposed area is increased by reducingthe droplet size in a spray application but below a certain massthe droplets lack sufficient momentum to penetrate the turbulentgases to reach the seat of the fire. There is, therefore, an optimumdroplet size to meet the compromise between maximum exposed surfacearea and minimum droplet mass.

Consideration of the use of water spray systems in aircraft isnot new and was the subject of an evaluation by the FAA10 in theearly 1980's. Such systems appeared at that time to have significantpotential but the cost of installation and the weight of onboardwater necessary to effectively supply the spray nozzles were issueswhich, it was felt, required further reseach and development toreduce the operational penalties.

For some years before the accident to G-BGJL water spray nozzleshad been developed for use on manifold systems distributed aboutlarge earth moving vehicles, which had proved prone to fire anddifficult to evacuate. An installation had then been developedfor road transport passenger vehicles and thought given to developingthe system for aircraft passenger cabin protection. The Manchesteraccident accelerated this development and a number of trials11were conducted with systems installed in a VC 10 passenger cabinfurnished with limited seat rows and cabin materials. Two separatebut complimentary philosophies have been demonstrated:-

1) an 'onboard' system, primarily intended to protect the cabinand passengers until the first fire appliance arrives, comprisinga single line of misting nozzles down the centre line of the cabinroof. These were to be fed from an onboard water supply at a totalflow rate of approximately 13 gallons/minute into a cabin 15 ftdiameter by 60 ft long. This water could be drawn from the aircraft'sdomestic system or from a dedicated supply - about 30-40 gallonsbeing required in a Boeing 737 sized aircraft to give 2-3 minutesapplication. It was intended that the system would only operatewith the aircraft on the ground and be activated as soon as therewas risk of fire starting in, or penetrating the fuselage.

2) a 'tender' system having an array of sprays inside the cabinand other critical zones to be supplied with water from a fireappliance alongside the aircraft. (In the case of an airfieldaccident the first fire appliance should arrive in not more than3 minutes and could then start pumping water into the system,at 150 gallons/minute in the case of a Boeing 737 sized aircraft.)

Tests were carried out using fires initiated directly within thepassenger cabin, using trays of kerosene producing fire transferto rows of seats, and fires initiated with trays of kerosene outsideof a door sized aperture igniting seat rows adjacent to the doorby radiant heat transfer.

The 'onboard' system at a flow rate of 13 gallons/minute preventedthe external fuel fire transferring into the cabin and preventeda large fuel fire within the cabin from developing to involvesignificantly the seats.

The 'tender' system extinguished the cabin fires in approximately3 seconds, dramatically dropping the cabin temperature and improvingvisibility by 'washing' much of the particulate out of the atmosphere.

Further trials are planned to demonstrate the systems within afully furnished aircraft. Although the tests carried out to datehave not explored the issues of installation, reliabilty and systemintegration, they have nevertheless demonstrated that the concepthas great potential both to limit fire development before thefirst fire appliance arrives, and then to allow firefighting personnelto tackle internal cabin fire directly - something which airfieldfire services are currently denied during the period of passengerevacuation.

In further, separate, developments in this area, nozzle designsused within the petro-chemical industry have been adapted to producevery small droplets, with attendant increase in surface area,which are transported to the seat of the fire on their own columnof moving air. This nozzle has, to date, only been tested on hose-endapplications but has shown great potential when used to extinguishpans of burning crude oil. In controlled tests this nozzle significantlyout-performed more conventional fire hose nozzles on a 'standardbuilding fire'. A major advantage, in addition to the extinguishingpotential is the relatively low pressures of water required toachieve a 'throw' comparable with conventional hoses, resultingin greatly reduced hose-end reaction forces. It is hoped thatfuture tests will explore the application of this nozzle and deliverysystem to cabin spray distribution systems.

1.17 Additional information

1.17.1 Pratt and Whitney JT8D relevant history

The JT8D first entered service in 1964, since when it has becomethe most widely used jet engine in the world. It has undergonemany developments to increase its performance, resulting in arange of engines with differing rated thrusts. Information providedby the manufacturer shows that the JT8D-15 engine, as fitted toG-BGJL, exhibits the highest combustor can metal temperaturesof the entire engine model range.

There had been twelve reported cases of CCOC explosive ruptureprior to the G-BGJL accident of which seven were attributed toa primary defect in the CCOC itself. Two cases were attributedto problems with the fuel nozzle and/or support, while the remainingthree cases resulted from combustor can problems. These engineswere fitted to Boeing 727 aircraft and involved two JT8D-15 andone JT8D-9 model. In at least two of these cases, parts of thecan responsible for the rupture had been expelled, causing someminor airframe damage, but there was no resultant fire.

In addition to those instances when explosive rupture of the CCOCactually occurred, it must be recognised that 'burn-throughs'of the CCOC (ie penetration by the combustion flame but not resultingin explosive casing rupture) represent a different outcome froma similar initiating failure mechanism and should be includedfor consideration. There were 16 recorded cases of burn-throughof the CCOC prior to the accident to G-BGJL, of which 4 were attributedto combustor can failure, 5 were due to can shift (locating pinfailure) and the remainder due to fuel nozzle or fuel system failure.

1.17.1.1 Pratt and Whitney letters and telexes to operators relatingto combustor can/CCOC failures

Regarding the three cases of CCOC explosive rupture due to canfailure which occurred in 1979, 1984 and 1985, Pratt and Whitneyadvised all JT8D operators of the 1979 incident in a letter, dated31 January 1980. This letter described the circumstances of theincident to a JT8D-9A:-

"In July 1979, the combustion case of a JT8D-9A engine rupturedduring climb out after take-off. The case rupture initiated atthe 8 o'clock position and the resultant blowout pressure causedthe edges to peel back in both the clockwise and counterclockwisedirections resulting in a hole which extended circumferentiallyfrom 5 o'clock to 11 o'clock. The fan case and engine nacellewere also ruptured along this same plane. A 1 inch by 2 inch holewas found in the aircraft vertical fin, evidently caused by debrisliberated from the case rupture. The No 7 combustion chamber wasexpelled through the hole in the combustion case. Although thechamber was not recovered, our investigation into this incidenthas led us to conclude the incident was initiated by the completefracture of one of the chamber seam welds joining two liner sections.Resultant misalignment of the chamber segments caused combustionwithin the chamber to impinge on the combustion case wall, softeningthe case to the point of rupture." (ie a very similar mechanismto that known to have occurred on G-BGJL, albeit where the 360°fracture occurred in the No 3 liner material, not in the seamweld itself).

The letter further documents numerous cases of 360° can crackingreported to Pratt and Whitney:-

"2-3 Liner Seam Weld Cracking: This condition was first observedafter introduction of reduced smoke combustion chambers and ispeculiar to that configuration. It has occurred in all JT8D models.There have been 9 reported instances of 360° cracks in the2-3 liner seam weld with part times ranging from 1,810 hrs to7,510 hrs. Twenty additional instances of 360° cracking havealso been reported. Part times for these cases could not be determined.Because of the 'piloting' effect of the air scoop and crossovertubes, 360° cracking in 2-3 liner seam weld is usually seenonly at engine dissassembly. However, if allowed to continue inservice for a sufficient period of time in the 360° crackedcondition, vibration and gas loads could cause the chamber toseperate, sag and allow fuel spray deflection."

"3-4, 4-5 and 5-6 Liner Seam Weld Cracking: Circumferentialcracks in these liner seam welds have been reported in reducedsmoke liners in all JT8D engine models. These cracks typicallyvary from 1 inch to 6 inches in length and are normally detectedduring hot section inspections. This condition has been repairedin the shop by fusion welding the cracked areas or by replacingthe entire liner. Recently, however, we have received severalreports documenting 360° cracking of the 4-5 or 5-6 linerseam welds. Although part times were not available, times sincelast shop visit ranged from 3,200 hrs to 7,000 hrs. Chamber separationin these seam welds is potentially more serious than in the 2-3liner area because these liners do not have the benefit of thepiloting features of the air scoop and crossover tubes. Once thecrack has progressed 360°, combustion chamber sag withina short period of time is possible. One of these incidents causedsoftening and bulging of the outer combustion chamber case dueto resultant fuel spray deflection."

"Liner separation in some cases, is evidenced by slow spool-upfrom light off to idle or by slow acceleration above idle."

The letter then described a "development programme to betterunderstand the liner cracking and to identify improved repairand management procedures" recently initiated by Pratt andWhitney. The programme was to include the following elements:-

(a) Investigation of improved techniques for detection of cracksin the shop (maintenance workshop).

(b) Investigation of high time combustion chambers for possibledegradation of material properties such as hardness and fatiguelife.

(c) Evaluation of fusion weld overlay to strengthen the 3-4, 4-5and 5-6 liner seam welds.

(d) Evaluation of the effectiveness of SHT of the combustion chamberliner assembly for restoration of fatigue life.

(e) Determination of the number of cycles to crack initiationand for 360° progression.

(f) Evaluation of alternate methods for production welding ofcombustion chamber liners for improved weld life.

(g) Re-examination of Engine Manual limits and procedures forcombustion chamber repairs.

The target date for the completion of the above programme wasJuly 1980, at which time Pratt and Whitney expected to provideadditional information directed towards controlling liner seamweld cracking. The letter concluded; "Pending completionof the programme, we recommend that the following currently availableshop maintenance procedures be utilised to reduce the potentialfor combustion chamber liner seperation due to circumferentialseam weld cracks."

A Solution heat treat the combustion chamber liner assembliesprior to weld repair. Refer to the Engine Manual, Section 72-42-1,Repair for the SHT procedure. SHT is beneficial in fatigue liferestoration of the Hastelloy X material, and has the additionaladvantage of cleaning the part prior to welding if done in aninert atmosphere.

B Pay particular attention to detection of circumferential seamweld cracks. Completely rout out cracks prior to weld repair toensure weld integrity.

C Replace bulged and oxidised liners and replace liners whichhave been extensively weld repaired.

D Incorporate a 2-3 liner fusion weld overlay per Engine Manual,Section 72-42-1, Inspection.

A further letter was despatched to operators dated 5 December1980. This letter stated that the cause of the circumferentialcracking was identified as thermal fatigue and that the 360°circumferential progression generally occurred in weld-repairedliners which have "lower fatigue strength than non-weld-repairedliners". The letter further stated that tests had shown thevalue of fusion weld overlay and SHT on fatigue life and thatrig tests were being undertaken on weld-repaired cans in orderto develop an improved technique. Four recommendations were made:-

(a) To conduct a periodic inspection of combustion cans for seamweld cracks.

(Recognising the difference in operating patterns, maintenanceprocedures and part times Pratt and Whitney could only recommendthat each individual operator establish his own inspection frequency,but quoted one operator who had successfully overcome a can separationproblem by inspecting his combustion section at 6,000 hours timesince last workshop visit.)

(b) To undertake SHT prior to welding repairs.

(c) To rout out cracks prior to weld repair.

(d) To replace bulged and oxidised liners and liners which havebeen extensively weld repaired.

A further letter dated 13 May 1983, addressed primarily to overhaulagencies, recalled the circumstances of the 1979 CCOC rupturefollowing a can separation and introduced the process known asbraze reinforcement repair, which was claimed to provide a "two-times"improvement in can seam-weld fatigue life. (After the accidentto G-BGJL, this process was withdrawn by Pratt and Whitney inNovember 1985 as being counter-productive.)

Finally, a telegraphic 'All Operators Wire' dated 7 February 1985was despatched from Pratt and Whitney "to inform (operators)of two recent incidents involving the Combustion Chamber OuterCase". The first incident described a JT8D-15 engine whichexperienced a CCOC rupture during the take-off roll. The take-offwas abandoned without further problems. The telex went on to describehow the No 7 can was considered to have cracked sufficiently toallow combustion gases to impinge on the inner face of the CCOCand recommended "strict adherence to engine manual repairsand close monitoring of engine response especially during transientconditions". Specifically, "reports of slow startingor acceleration should be suspected as a potential cause of severelydistressed or misaligned combustion chambers". The secondincident described a primary failure of the CCOC on a JT8D-9Aengine.

1.17.1.2 Pratt and Whitney operators conferences

Pratt and Whitney JT8D Operators Conferences, held in 1980 and1985 addressed the can cracking problem and the notes preparedfor these generally reflected the situation described in the lettersissued in those years. It was noted that the 1980 conference depictedthe type of cracking which could lead to 360° can separationin the area of the No 2 through No 9 liner seam welds. The cracksobserved on the No 9 can of G-BGJL were not in the seam weld butadjacent to it.

The 1985 conference also gave much information on cracking inthe seam weld location and said "most reports of problemsrelated to chambers concern high time parts which have been weldrepaired many times and probably never metallurgically refurbished".

1.17.1.3 Pratt and Whitney Service Bulletins

In November 1980, Pratt and Whitney issued Service Bulletin 5192which introduced a re-designed combustion can for the JT8D-11,-15, -17 and -17R engines. This new can incorporated several improvements(including fusion weld overlay reinforcement of the 2/3 linerseam weld). It also addressed igniter guide wear and bucklingof the number 11 liner. The Bulletin stated that these modificationswould provide a can with "improved durability" althoughit wasaimed primarily at the problem of seam weld cracking ofthe 2/3 liner joint which, because it occurs under the air-scoop,requires radiographic inspection to detect. British Airways JT8D-15engines were all delivered with this modification incorporatedduring engine build.

A further Service Bulletin, No 5461 was issued in April 1983 andwas applicable to all JT8D-15/I5A engines fitted with SB 5192standard combustor cans. This SB introduced a modification tothese cans whereby a ceramic coating could be applied to the interiorto provide an insulation barrier and reduce metal temperaturesby 50°F-100°F. The compliance category was 8 - "Accomplishbased upon experience with prior configuration". Althoughit appears the modification was not widely adopted, it was notedthat it did provide the information that "burning and crackinghas been observed in some combustion chambers at the 2nd to 5thliners after 3,000 to 5,000 hours of operation". Pratt andWhitney do not apply this modification to new cans leaving theirfactory.

1.17.2 Engine maintenance requirements

1.17.2.1 General engine maintenance and repair

There is no laid-down time specified by Pratt and Whitney forstrip inspection and overhaul of the engine as a whole. Whilsthard-lifed items on the engine may require engine strip to replacethem (at which time, of course, the particular module would beinspected/overhauled as necessary) the operator is expected toarrange a maintenance programme with the relevant AirworthinessAuthority.

The "Pratt and Whitney Maintenance Planning Guidelines"booklet was produced to assist operators utilising any of theprincipal maintenance processes (hard-time engine overhaul, modularoverhaul, condition monitoring and on-condition maintenance) andprovided suggested initial inspection intervals for each, dependanton the particular operator's experience.

Following negotiations with the CAA, British Airways embarkedon an engine sampling programme in which engines were removedand strip-inspected at various times to monitor deterioration- the aim being to establish fixed overhaul lives for the majorparts of the engine. Commencing at 5,000 hours Time Since New(TSN) various engines were sample inspected, following which itwas agreed that each engine would run between 10,000 - 12,000hours TSN before an LMI was carried out - this would include afull combustion section overhaul. A Heavy Maintenance Inspection(HMI) was to be performed at 16,000 hours since last HMI or TSN.The LMI would be repeated at 10,000 hours since last HMI.

It can be seen, therefore, that the combustion section of engineP702868 would have been overhauled for the second time at 16,000hours on this maintenance schedule, although British Airways targetwas to establish a 20,000 hours/13,000 cycles HMI interval, subjectto a satisfactory 16,000 hour sample. The HMI would also includea combustion section overhaul.

The Pratt and Whitney Maintenance Planning Guidelines providedthe following recommendations when inspecting the combustor cans:-

"Visually inspect and x-ray combustion chambers. Repair combustionchamber distress to Engine Manual specifications, as required,paying particular attention to liner cracking, hole pattern/walldistortion, worn locater lugs and worn crossover tubes."

This appeared in the British Airways Approved "Light andHeavy Maintenance Inspection Schedule" as:-

"Fully inspect combustion chambers in accordance with OverhaulManual (including x-ray of No 3 Liner seam weld)"

-note this refers to the 2/3 liner weld under the air-scoop andwas not to address a known problem with the 3/4 liner joint.

1.17.2.2 Information contained in the engine technical manuals

In the Pratt and Whitney Engine Manual, inspection and fusionweld repair of combustion cans are covered in sections headed:-

"Inspection 01"

"Inspection 02"

"Repair 06"

Extracts from the Engine Manual relevant to the G-BGJL accidentare given below:-

Inspection 01 1B General

"(1) Cracks in combustion chamber surfaces are usually ofa stress relieving nature and, as such, are not serious in thatthe rate of growth decreases as the crack lengthens."

Inspection 01 Subtask 72-41-22-044

"(1) Any circumferential and axial crack, except in No 1liner and nozzle stator, not exceeding 0.030 inch wide may beweld repaired."

Inspection 01 Subtask 72-41-14-046

"(g) Severe local distortion and/or oxidation of liners isnot acceptable and is not weld repairable. See figure 807. Replaceliner if condition exists. (Appendix 5 h)

Inspection 02 Subtask 72-41-26-000

"(1) (e) Examine developed film for circumferential crackingin area of 3rd liner cooling holes. For crack limits see paragraph(2). For crack repair see Task 72-41-14-30-046 (Repair -06)".

Inspection 02 Subtask 72-41-26-000, paragraph (2)

"(2) Any circumferential or axial crack not exceeding 0.030inch wide may be weld repaired. See Fig 803. Cracks in excessof this limit will necessitate replacement of liner assembly.For combustion chambers with cracks more than 2.500 inches inlength stress-relief is recommended after welding. See Task 72-41-14-30-046(Repair 06)".

Repair 06 Task 72-41-14-30-046-001: Liner Crack Repair (FusionWeld Method). Subtask 72-41-14-37-005

"(2) Before welding solution heat treat @ 1,875° - 1,925°F".

Subtask 72-41-14-37-022-002

"(6) For combustion chambers with cracks in excess of 2.500inches in length, stress relief is recommended but optional basedon operator's experience".

It should be noted that the term 'Overhaul Manual' is used inthis report, as distinct from 'Engine Manual' as used by Prattand Whitney, to reflect the fact that the two are not necessarilythe same. Under the terms of the approval granted to British Airways/BritishAirways Engine Overhaul Ltd (BEOL) by the CAA, they may vary thecontent of their manual with respect to the manufacturer's document.

Such variations are submitted to, and approved by, the CAA. Thisoccurred with the requirement to SHT the material prior to welding.BEOL had difficulties with implementing the process and it wasdeleted from their Overhaul Manual for some years before beingre-instated in early 1985.

1.17.2.3 Trouble-shooting and trim runs

Information on day-to-day engine fault diagnosis is containedin the trouble-shooting sections of the Pratt and Whitney MaintenanceManual. At the request of British Airways, the section was alsoreprinted in the Boeing Maintenance Manual. The section covering'slow acceleration' as it existed at the time of the accidentis reprinted below:-

J. Slow Acceleration

Possible Cause	Test Procedure	Corrective Action
(1) Defective Fuel Control Schedule	Check Ps4 sense line for leaks	Retorque or replace line as necessary; if no leaks, replace fuel control
(2) Bleed Valves Off-Schedule	Check bleed valve operation per Adjustment/Test	
(3) Combustion Chambers Shifted Rearward	Perform hot section inspection (Chapter/Section 72-40, Removal/Installation)	Replace chambers as necessary (chambers incorporating SB 4190-and/or 4421 feature greater wear resistance in mounting lug area)

(4) Defective Start Bleed Control Valve	Check bleed valve operation (see Adjustment/Test)

It should be noted that cause (3) is not directly related to theproblem of combustion can cracking, but refers to an earlier problemexperienced with wear/failure of the can mounting pin. All BritishAirways engines were equipped with cans featuring SB 5192 withgreater wear resistance in the mounting lug area.

No mention of combustor can defects was made in the 'Thrust LeverMisalignment' (throttle stagger) section of the Boeing MaintenanceManual and there was no trouble shooting guidance given for lowground idle symptoms, nor was any mention made of possible inter-relationshipsbetween some of the symptoms.

The Boeing Maintenance Manual describes the procedure to be adoptedfor performing a Part-Power Trim Run. It is essentially to groundrun the engine with a test-set of reference instruments connectedand to record the various engine parameters for checking againstdata tables in the manual. Adjustments are then made to the fuelcontrol unit as required so that the engine performance correspondswith these data tables.

The first step is to check N2 idle speed and adjust as necesary(it is recommended that the ground idle be adjusted to the upperlimit of the tolerance band). A part-power trim stop is engagedon the engine and the pilot's throttle levers advanced until thethrust lever on the FCU contacts the stop. This provides botha datum against which to judge the engine's performance, and alsothe means to check for incorrect rigging of the throttle levercables (one possible cause of throttle stagger).

Since adjustment of the 'Idle' trim screw has some effect on theengine at higher settings, a second adjustment, refered to asthe 'Mil' trim screw is used to adjust the fuel flow at the part-powersetting. Having checked the parameters against the manual figures,the engine is returned to idle for 5 minutes, when the idle N2is checked again.

The manual procedure then continues:-

"Idle adjustment of as much as 0.5% N2 (8 clicks) is permittedafter final setting of part-power trim without a recheck of part-powertrim provided final adjustment is made in the increase RPM direction".

Both Boeing and Pratt and Whitney have stated that they do notsanction adjustment of the fuel control unit outside of a partpower trim run.

British Airways routinely performed trim runs when installinga replacement engine or FCU. They did them on some occasions whenlow ground idle, slow acceleration or throttle stagger were reportedby flight crews. It is known that some airlines regarded routinetrim runs as unnecessary if the replacement engine or FCU hadbeen calibrated on the test bench and would rely on the firstflight to verify performance. Equally so, minor idle speed adjustmentswould also be carried out without a trim run. Questioned by anoperator at the 1984 Hamilton-Standard Operators Conference ontheir opinion regarding the latter practice, Pratt and Whitneyaccepted that it was widely done. They added that the part-powertrim procedure was largely intended to correct throttle staggersnags and that, where the airline is satisfied with the initialengine output following a trim run and satisfactory experience,they could see no objection to minor adjustments being made aslong as they are logged and monitored. Pratt and Whitney demonstrated,however, that their customer training courses, which were attendedby a large number of British Airways technicians and engineers,emphasised the importance of correct engine trim in accordancewith the manual.

1.17.2.4 Post accident regulatory action

The basic mechanism and sequence of failure of the No 9 can wasappreciated at an early stage after the accident. Accordingly,the CAA, in consultation with Pratt and Whitney, the FAA, BritishAirways and other UK and foreign operators of the JT8D, issuedan emergency Airworthiness Directive (AD) No 011-08-85 on 27 August1985. This called for an isotope (radiographic) inspection ofJT8D engines, or disassembly, to permit visual examination ofthe combustion section to detect and measure the extent of combustorcan cracking.

The AD has undergone several subsequent revisions to both theapproved inspection methods and the initial and repeat inspectionintervals in response to operator feedback. A broadly similarFAA AD has also been issued along with an Alert Service Bulletinfrom Pratt and Whitney, No 5639.

These mandatory documents were drawn-up from a considerable massof data and information by the Airworthiness Authorities and itis to be hoped that they will prevent a similar accident occurringto a JT8D engine. It is also understood that the CAA have re-examinedsimilar British engine designs to see whether the same problemcould arise.

1.17.3 Malfunctions during take-off

The operator's Operations Manual - Flying, in use at the timeof the accident, contained the following instructions and adviceon the actions to be taken in the event of a malfunction beforeV1.

"Reject the take-off for engine failure, fire, take-off configurationwarning or if the Captain calls Stop. Upon recognition of failureor warning, either pilot may call "Stop". The handlingpilot should maintain directional control and apply MAXIMUM wheelbraking consistent with the airplane's position on the runway(overriding Autobrake on Series 2 Aircraft). The non-handlingpilot should immediately disconnect autothrottle, select idlethrust, lift the reverse thrust levers (to activate the automaticspeed brake facility) and apply GA (Go Around) reverse thrust.He should then check/select the speed brakes fully up. Whilstthe handling pilot brings the airplane to a stop (taxiing clearof the runway if conditions permit), the non-handling pilot mustmonitor the engine instruments and observe the GA thrust limitations.If a fire exists, consideration should be given to turning theaircraft into wind before bringing it to a complete stop. Oncethe airplane has stopped, the first officer should carry out anyemergency procedure as instructed by the Captain. (This appliesregardless of who was handling the airplane prior to the "Stop"call).

If the first officer was handling the controls at the time "Stop"was called, the Captain may elect to take control once the vitalactions are complete and the airplane is decelerating. In thisevent, the Captain should call "I have control" andthe first officer should take the reverse thrust levers, monitoring/adjustingthe power as required".

(This section has subsequently been amended so that the handlingpilot brings the aircraft to a stop on the runway and the revisedevacuation drill is commenced when the aircraft has slowed toa taxi speed in anticipation of a possible evacuation. The captain'soption of taking control from the first officer after the vitalactions are completed is retained.)

The Abnormal Procedures section of the Flight Crew Orders advisedthat:-

"When bringing the aircraft to a stop following an enginefire, consideration should be given to wind direction".

The Boeing recommended rejected take-off procedure differed fromthe operator's in use at the time of the accident in that it calledfor the pilot to stop the aircraft on the runway and evaluatethe problem, before deciding whether conditions permitted taxiingclear of the runway.

1.17.4 Passenger evacuation checklists

The Passenger Evacuation (Land) checklist contained in the OperationsManual and the Quick Reference Handbook in use at the time wasbased on the aircraft manufacturer's suggested format with detaileddifferences, and was designed specifically to cover all areasof ground operation from start up and push back, as well as take-offand landing incidents. The non-memory evacuation drill consistedof 15 items, of which item 14 (item 13 on Boeing drill) was theinitiation of the evacuation. The crew reported that they foundsuch a lengthy drill inappropriate to this emergency.

As a result of this accident a simplified memory evacuation checklisthas been produced and adopted.

1.17.5 Cabin crew composition, dispositon, training and duties

1.17.5.1 Composition of cabin crew complement

The requirement for cabin attendants is contained in Article 17paragraph 7 of the Air Navigation Order (ANO). Sub paragraph (a)refers. (Cabin attendants referred to in the ANO are synonymouswith cabin crew.)

"When an aircraft registered in the United Kingdom carries20 or more passengers on a flight for the purposes of public transport,the crew of the aircraft shall include cabin attendants carriedfor the purposes of performing in the interest of safety of passengersduties to be assigned by the operator or the person in commandof the aircraft but who shall not act as members of the flightcrew".

Sub paragraph (7) (c) of Article 17 relates to aircraft with aseating capacity of not more than 200 passengers and the numberof cabin attendants required.

"In the case of an aircraft with a total seating capacityof not more than 200, the number of cabin attendants carried onsuch a flight as is mentioned in sub-paragraph (a) of this Article,shall be not less than 1 cabin attendant for every 50, or fractionof 50, passengers carried".

1.17.5.2 Disposition of cabin crew

The Boeing 737 Air Cabin Crew Safety Equipment and Procedure Manualrecovered from the aircraft contained a diagram which illustratedthe cabin crew seating positions. The Senior Cabin Crew Member(SCCM) occupies the forward inboard, No 1, crew seat. The forwardoutboard seat is designated No 4, and the rear inboard and outboardseats Nos 2 and 3 respectively.(Appendix 3 Fig a) The cabin creware often referred to using the number of the station they wereallocated for the flight. The next most senior or experiencedmember of the cabin crew was usually given the choice of whichcrew station they would like to occupy. For a variety of reasons,the number 4 position in the forward cabin appears to have beena popular choice. All cabin crew are trained in emergency proceduresto the approved standard for each cabin crew station. Other operatorshave indicated that the SCCM, and the next most senior or experiencedcrew member would be positioned at either end of the cabin fortake-off and landing.

The door opening responsibilities assumed that the minimum complementof two cabin crew would be carried, and they were responsiblefor opening the left main doors initially. When four cabin crewwere carried, it involved the individuals crossing over to getto their individual doors.

An amendment issued in December 1985 resolved the anomaly, andNos 1 and 2 open the right main doors, and Nos 3 and 4 the leftmain doors.

1.17.5.3 Cabin crew training

The issue of an Air Operators Certificate by the CAA to an operatorengaged in public transport activities requires that the operatorarranges a suitable course of training for newly employed cabincrew. A very large proportion of such a course will consist mainlyof Safety Equipment and Procedures (SEP). The individual is thenrequired to undergo a refresher check at suitable intervals, normallyonce a year.

The cabin crew on G-BGJL had all undergone a course of lecturesand practical demonstrations upon their initial entry to the company.The certificates of competency for the purser and the No 4 stewardess,who were occupying the forward end of the aircraft, were renewedby undergoing a 2 day refresher course and both certificates werevalid for Boeing 737 and Tristar aircraft. The certificates ofcompetency raised for the Nos 2 and 3 stewardesses, who were occupyingthe rear cabin, were issued after they had both completed thesame initial entry course on 1 March 1985. These were also validfor Boeing 737 and Tristar aircraft. The Nos 2 and 3 stewardessesunderwent assessment flights under the supervision of a purseron 21 August, and 8 July 1985 respectively. The assessments inboth cases were "above-standard to excellent", the SEPknowledge being graded as "above-standard".

The smokehoods contained in the cabin were originally envisagedas being for use in dealing with cabin fires; three were positionedin the racks above row 18, and two stowed in the forward vestibule.Cabin crew were trained in their use, but not in removal fromtheir container. During tests carried out after the accident,the fastest removal and donning of a smokehood was 40 secondsby a steward, and 1 minute 40 seconds by a stewardess.

1.17.5.4 Safety Equipment Manual - Cabin Crew Procedures:-

The British Airways Air Cabin Crew Manual 'Safety Equipment andProcedures' for the Boeing 737 included direction in numerousareas associated with the initiation and control of an emergencyevacuation.

Part 1 of this SEP Manual, under 'Aircraft Hazards', stated:-

"Cabin crew should always bear in mind that an aircraft emergencycan occur without the flight crew being immediately aware of thesituation, eg auxiliary power unit fire, refuelling truck fire,cabin fire, engine fire, smoke in the cabin, noise and vibration.In any emergency situation, cabin crew should start an emergencyprocedure only after an order from the captain. However, in caseswhich are clearly catastrophic, individual crew members shouldbe prepared to act immediately on their own initiative.

Any cabin crew receiving an emergency instruction from the flightdeck shall repeat back the instruction".

In Part 3, the Manual further stated:-

"The captain or, in his absence, the next most senior crewmember, will order an evacuation indicating, if conditions sorequire, the exits that should be used. Only in cases which areclearly catastrophic should individual crew members be preparedto act immediately on their own initiative".

On page 6 of part 7 under 'Emergency Opening of Doors' the manualstated:-

"In the event of an emergency evacuation the doors are operatedin the following manner:

1 Check girt-bar engaged (not ditching).

2 Check for outside hazards.

3 Operate door handle in normal manner.

4 Push door outwards to eject slide which will inflate automatically.

To deploy escape slide the door must be opened in one continuousmovement without hesitation, to its fullest extent. A greaterforce is required to open the doors in these circumstances - soswing out and push hard. Automatic deployment of the slide occursduring door opening.

5 If a slide fails to inflate pull the manual inflation handlecompletely clear of the slide pack.

When the slide is ejected from its container the manual inflationhandle marked 'Pull' will become visible".

Part 10 dealt with 'Cabin Smoke/Fire'. This section describedthe cabin crew procedures relating to fire within the cabin, toiletsor galleys. It included the instruction:-

"Smokehood - if dense smoke is being generated, fit a smokehoodbefore entering the fire area. Portable oxygen bottles must notbe used as breathing apparatus when fire fighting."

This manual did not include any instruction to cabin crew concerningthe use of their smokehoods in a ground fire evacuation.

1.17.6 Minimum exits

The aircraft was equipped with exits in accordance with FAR Part25 which, in section 25.807 'Passenger Emergency Exits' specified,for a passenger seating capacity of 130, that the aircraft shouldhave two 'Type l' and one 'Type lll' emergency exits on each sideof the fuselage.

A 'Type l' exit is defined as having "a rectangular openingof not less than 24 inches wide x 48 inches high, with cornerradii not greater than one-third the width of the exit. Type lexits must be floor level exits."

A 'Type lll' exit "must have a rectangular opening of notless than 20 inches wide x 36 inches high, with corner radii notgreater than one-third the width of the exit, located over thewing, with a step-up inside the airplane of not more than 20 inchesand a step-down outside the airplane of not more than 27 inches".

Section 25.809 (c) states "the means of opening emergencyexits must be simple and obvious and may not require exceptionaleffort".

FAR Part 25 does not specify any minimum access widths to overwingexits. British Civil Airworthiness Requirements, Chapter D 4-3'Compartment Design and Safety Provisions' states in paragraph4.2.5 'Access', "Easy means of access to the exits shallbe provided to facilitate use at all times, including darkness;exceptional agility shall not be required of persons using theexits. To this end the following shall be complied with:-

(a) Passage ways between individual compartments of the passengerarea and passage ways leading from each aisle to each Type 1 andType ll emergency exit shall be provided and shall be unobstructedand not less than 20 inches (508 mm) wide.

(b) The main passenger aisle at any point between the seats willnot be less than, for aeroplanes having a maximum seating capacityof more than 19 persons, 15 inches (381 mm) wide up to a heightabove the floor of 25 inches (635 mm) and 20 inches (508 mm) wideabove that height".

There is no specified minimum access width to Type lll overwingexits, which are covered by the following:-

(d) Access shall be provided from the main aisle to all Type llland Type lV exits and such exits shall not be obstructed by seats,berths or other protrusions to an extent which would reduce theeffectiveness of the exit, and

(i) For aeroplanes that have a passenger seating of 20 or morethe projected opening of the exit provided shall not be obstructedby seats, berths or other protrusions (including seat backs inany position) for a distance from the exit not less than the widthof the narrowest passenger seat installed in the aeroplane".

1.17.7 Appraisal of other survivable aircraft fire accidents

An assessment of previous, fire-related, major aircraft accidentswas carried out in order to compare findings with this accidentand also to examine associated evidence from in-flight cabin-firesituations.

1.17.7.1 Respiratory effects on passengers

a) AN FAA report12 refers to the effects of smoke on the evacuationof the United Airlines DC-8 at Stapleton Field, Denver on the11 July 1961 stating the following:-

"During evacuation, the principal environmental hazard wassmoke. When the aft galley door (ie aft/right) was opened, a 'chimney-effect'developed, drawing outside 'kerosene' smoke into the right window(ie overwing) exits, down through the aft section of the cabinand out of the open door. For this reason, the concentration ofsmoke was heaviest in the aft cabin.

Although occasional tongues of flame were blown in through theright window exits, destructive invasion of the cabin by fireoccurred only after 98 passengers had escaped and 16 others hadbeen incapacitated by smoke.

Just prior to opening of the galley door, the passengers had promptlyleft their seats and began to queue-up in the aisle. From allaccounts, this was done in an orderly and relatively calm manner;little shoving or shouting occurred and many persons took timeto collect their personal belongings. As this line was forming,dense black smoke began filtering into the cabin, making breathingdifficult and obscuring vision. Judging from their statements,many passengers - who up to then had reacted calmly - became frightenedfor the first time."

"Most witnesses estimated that the evacuation was completedwithin 3-5 minutes after the aircraft came to a halt".

b) The same report refers to the accident to the United AirlinesBoeing 727 which landed short of runway 34L at Salt Lake CityAirport on 11 November 1965, initiating a localised fuel-fed firewithin the aft/underside of the fuselage as the aircraft sliddown the runway after both main undercarriage legs had sheared:-

"Apparently, one of the early effects of the dense, acridsmoke that rapidly filled the cabin was to cut short any attemptsto vocalise and many passengers stated that after a breath ortwo they could no longer breathe or utter any sound. One man,a registered pharmacist and the only survivor reporting with anymedical knowledge, described the sudden effect of smoke upon himselfas causing a "massive bronchospasm".

Other passengers recalled that after a few initial shouts andcries the cabin suddenly became quiet with the only sounds comingfrom the flames and the muffled efforts of passengers strugglingtowards the exits. This silence seemed especially eerie, somerecalled, because they had always previously imagined such scenesof human panic to be accompanied by screaming".

c) On the 11 July 1973, a Varig Boeing 707 Registration PP-VJZwas at FL 80 some 22 nm from Orly Airport, Paris after a flightfrom Rio De Janeiro with some 17 crew and 117 passengers, whenthe cabin crew reported smoke issuing from the area of the aftleft toilet. After alerting ATC the pilot reported, whilst stillsome 10 nm from Orly, that the passengers were being asphyxiatedby thick smoke in the cabin and that smoke could be smelt on theflight-deck. By the time the aircraft had descended to 2,000 fton approach, the flight-deck crew had donned their oxygen masks,but the visibility was so reduced by the smoke density on theflight-deck that they could not see their instruments. A forced-landingwas carried out 5 kilometers short of the runway. No significantfuselage damage was sustained and there was no evidence of externalfire.

Only ten escaped, all crew members. No external fire was evidentat this time other than smoke issuing from the right side of thefin root.

By the time the fire crew arrived, 6 minutes after the forced-landing,the fire had burnt through the aft upper fuselage. Four unconsciouspassengers were removed by the firemen, but only one survived.Subsequent pathological examination found that all passengershad died due to asphyxiation. The flight engineer died due toimpact injuries. Seventy-eight per cent of the 122 fatalitieshad levels in excess of 66% carboxyhaemoglobin, 9% had 50-60%and some 13% had less than 5%.

d) On the 19 August 1980 a Saudi Arabian Airlines Lockheed L1011aircraft, registration HZ-AHK, had departed Riyadh Airport fora continuation flight to Jeddah with 14 crew and 287 passengers.Seven minutes after take-off the crew were alerted, by an audiowarning and visually by smoke entering the aft cabin, that theyhad a fire in the aft cargo compartment.

Seven minutes later, the flight engineer informed the commanderthat the passengers were in a state of panic at the rear of thecabin. Some 4 minutes later the flight engineer reported to thecommander that fire was penetrating the cabin and a cabin crewmember reported "that passengers were fighting in the aisles",indicative of the extreme effects of such atmospheres.

e) The NTSB produced a report13 on the accident which occurredto an Air Canada DC-9-32, registration C-FTLU, on 2 June 1983which suffered a fire behind an aft toilet partition whilst en-routefrom Dallas to Montreal. The aircraft was diverted into GreaterCincinnati International Airport. The aircraft landed 17 minutesafter the smoke was first noticed issuing from the toilet. Ofthe 5 crew and 41 passengers, 23 failed to evacuate. This reportstated:-

"During descent, the cabin filled with black, acrid smokefrom the ceiling down to about knee level. Passenger and flightattendant testimony and statements indicated that all of the survivingpassengers had covered their faces with either wet towels distributedby the flight attendants or articles of clothing. They all attemptedto breathe as shallowly as possible, and all reported that thesmoke hurt their noses, throats, and chests and caused their "eyesto water". By the time the airplane landed, they could notsee their hands in front of their faces whilst seated or standing.One passenger was experiencing severe distress trying to breathe.He was brought forward and seated on the forward flight attendants'jump-seat', and the flight attendant in charge administered oxygento him from the portable bottle."

"The smoke in the cabin was reportedly so thick that mostof the passengers had to get to the exits by using the seat backsto feel their way along the aisle. None of the passengers noticedif the emergency lights were illuminated. Several passengers saidthat when they either bent forward or got on their hands and knees,they were able to breathe and see a little better, but it wasnot much of an improvement. One of the passengers who used anoverwing emergency window exit said that she was able to locateit when she saw a very dim glow of light coming through the aperture.Another stated that she was able to locate the overwing emergencyexit window when she felt a slight draught on the back of herknees".

Of the 23 passengers who failed to evacuate it was reported that10 were found still in their seats. Toxicological examinationfound levels of 20-63% carboxyhaemoglobin and 80 - 512 micrograms/100ml of cyanide in the victims.

1.17.7.2 Hair-ignition

The aft stewardess on the aircraft in the Salt Lake City accidenthad been seated at her station in the aft 'jump-seat', 3 seat-rowsaft of the area where the fire suddenly penetrated the cabin -ieunder seat 18E, as the aircraft slid down the runway. She stated:-

"When the plane came to a stop all lights went out. The backof the plane was filled with smoke and fire. I got out of my seat.It took a few extra seconds to get my shoulder straps off. I openedthe aft pressure door. Immediately two men ran through the dooronto the stairs. At this time my hair caught fire. I put it outwith my hand and my hat fell off."

This stewardess and the two men sheltered in the ventral areaof the tail section until rescued 25 minutes later by firemen.During this time the stewardess breathed through her jacket. Theywere assisted by some air entering the partially open stairwellexternal door.

This evidence on hair-ignition appears similar to observationsfrom the male survivor from seat 8D at Manchester who has referredto a lady passenger in the aisle whose hair suddenly ignited.

1.17.7.3 Effects of reducing/shutting-off air conditioning air-flow

The effect of reduced air-flow through the cabin during an in-flightemergency smoke situation are apparent from the following extractfrom the NTSB DC-9 Report12:-

"Once the passengers had been repositioned (ie forward ofrow 13) and the cabin air vents opened and directed aft, the smokeappeared to lessen, but shortly thereafter the smoke began toincrease rapidly. Several passengers stated that the cessationof air-flow from the vents coincided with the increase in thesmoke. Other passengers stated that it occurred at the beginningof the descent or sometime shortly after the airplane began descending".

The evidence relating to the events following the landing of theLockheed L1011 at Riyadh are also of interest in this context.

The aircraft landed on runway 01 at 1836.24 hrs - ie 21¤minutes after the first indication of a fire/smoke problem associatedwith the 'C3' aft cargo compartment. It was turned off the runwayand eventually stopped at 1839.03 hrs. No external evidence offire was seen by the following fire vehicles at this time.

At 1839.06 hrs, SV163 informed ATC that they were going to shutthe engines down and evacuate. At 1840.33 hrs, after SV163 wastold that their "tail was on fire", they replied "affirmative,we are trying to evacuate now". This was the last RT transmissionfrom the crew.

The engines shut down at 1842.18 hrs - ie some 3 minutes 15 secondsafter the aircraft had stopped (5 minutes 54 seconds after touchdownor approximately 27¤ minutes after the fire was detected).

External witnesses stated that just after the engines shut down,a large puff of white and black smoke was discharged from theunderside of the aircraft, just forward of the wings. Also within1 minute, smoke issued from the top of the fuselage just forwardof the number 2 (centre) engine followed by flames. The reportconcluded that a flash-fire had occurred in the cabin shortlyafter the engines had been shut down and the associated air conditioningair-flow ceased. All 301 occupants perished due to fire and smokeinhalation effects but there is insufficient pathological datato identify the exact cause of death.

1.17.8 Aerosol cans

In recent years the aerosol industry has moved away from the useof the non-flammable gas freon as a propellent in aerosol cans,and has adopted hydrocarbons instead, notably butane, which iswidely used as a fuel for camping gas stoves and lamps. Certainproducts, such as 'dry air fresheners', contain almost pure butanewith only a very small amount of an aromatic agent. Many otherproducts such as hair sprays, which are perhaps the most likelyto be carried in hand baggage, use butane as the propellent.

Research into the hazards posed by aerosols has shown that suchcans invariably rupture (as a result of gas overpressure) if thetemperature of the can and its contents exceeds approximately70°C, releasing the gas in a minor explosion. The extremeturbulence associated with this explosive release of the butanepropellent promotes very efficient mixing of the gas with theair. If this turbulent, rapidly expanding gas mixture ignites,which would inevitably occur in a cabin fire environment, theflame front will propagate extremely rapidly, producing a verysharp fronted, but relatively sustained pressure rise. (Duringa test detonation of an aerosol can located in an aircraft forwardtoilet, the overpressure was sufficient to blow out the toiletdoor, allowing the compartment pressure to vent into the cabin.Despite the cabin itself being vented by open rear doors and overwingexits, the resulting overpressure in the main cabin blew the flightdeck door out of its aperture and forward several feet into theflight deck, where it jammed between floor and ceiling.)

A total of 27 aerosol cans were recovered from the cabin debris.Fifteen of these had ruptured as a result of temperature overpressure,and of these 3 showed signs of having been propelled at high speedinto the aircraft structure or furnishings.

2. ANALYSIS

2.1 Introduction

Many of the factors which affected this accident should have biasedevents towards a favourable outcome. The cabin was initially intact,the aircraft remained mobile and controllable and no one had beeninjured during the abandoned take-off. The volume of fuel involved,although capable of producing an extremely serious fire, was relativelysmall compared with the volume typically carried at take-off,the accident occurred on a well equipped major airport with firecover considerably in excess of that required for the size ofaircraft and the fire service was in attendance within 30 secondsof the aircraft stopping. However, 55 lives were lost.

The investigation has identified the cause of the engine failure.The sequence of events which followed, relating to the developmentof the fire and the evacuation, were extremely complex, involvingnumerous interlocking factors, many of which critically affectedsurvival.

Although much evidence was destroyed in the fire and other evidence,especially that from survivors and rescue personnel required carefulinterpretation, particularly concerning their assessment of timescale,it has been possible to construct a reasonably consistent pictureof the fire in all its aspects. Statements from the survivorswere highly descriptive and provided a rare insight into the evacuationproblems encountered. For the most part, conclusions derived froman analysis of the wreckage accorded well with those arrived atvia witness testimony and from other sources.

2.2 General circumstances

The explosive failure of the CCOC and the damage to the adjoiningtank access panel were clearly related events. Witness marks onthe access panel fragments exactly matched the shape of the domedhead of the separated No 9 combustor can and the fan case fragment,and a smear of panel material was identified on the dome indicatingbeyond all doubt that it was this which struck and shattered thepanel. It is clearly evident that the dome was ejected throughthe disrupted engine casing as a result of the extremely rapidescape of high pressure combustion air through the ruptured CCOC.The release of fuel from the damaged wing tank directly into combustiongases from the ruptured combustion chamber, and its inevitableignition, changed the nature of the event from a purely enginerelated incident into a catastrophic accident.

2.3 Crew performance

2.3.1 Flight deck crew.

The flight deck crew were properly licenced, trained, experiencedand rested to undertake the flight. They were aware of the technicallog entries for the left engine and had monitored its performanceduring start-up, taxi, and the initial part of the take-off run.Throughout this period the engine appeared normal and, by thetime the event occurred, it had been dismissed from their minds.The commander's assessment of the 'thud' as a tyre burst or fuselagebird strike was therefore quite reasonable; he responded to thecues which were available to him, which at that time consistedsolely of the noise, a 'thud'. His response was rapid and decisiveordering "stop" in less than 1 second and he and theco-pilot speedily implemented the abandoned take-off drill. Althoughit might be argued that the falling left engine parameters shouldhave provided additional cues which might have altered their perceptionof the event, any such indications would have been masked by thefalling parameters on both engines accompanying the abandon take-off.During reverse thrust application, there would have been someindications of thrust imbalance, but the level of reverse thrustused was minimal and applied for a very short time, during whichneither crew member would have had cause to monitor the instrumentsclosely.

In the light of his assessment that the problem might have beena tyre burst, and the fact that a timely initiation of the abandonedtake-off had left plenty of runway available, the commander directedthe co-pilot not to employ unnecessarily harsh braking, so asto avoid possible wheel damage. The co-pilot responded by modulatingthe braking effort.

For the first 9 seconds after the 'thud', events proceded as expected,reinforcing in the commander's mind his assessment of the problem,and he had every expectation that they would be able to completethe abandoned take-off and turn off without difficulty. When hehad satisfied himself that the immediate problems associated withthe abandoned take-off were contained, with the aircraft deceleratingthrough 85 kt ground speed, he transmitted his abandon call toATC. As he began this transmission the number 1 engine fire warningoccurred and he modified his call adding,"it looks as thoughwe've got a fire on number 1." This fire warning was somewhatfortuitous, the system having been designed to respond to firescontained within, not external to, the engine cowlings, largepieces of which seperated as the engine failure occurred.

This was the first indication to the flight deck crew that theproblem could be other than a tyre burst or bird strike. It isevident that this new and conflicting information could not easilyhave been reconciled with either, except perhaps as a result ofsecondary damage, and the crew's ability to analyse its impactwas clearly limited by their already high workload. As a result,they proceded with the existing abandoned take-off plan whilstthey considered how to deal with the new information. While thefire bell was still ringing on the flight deck, as the aircraftdecelerated through 50 kt ground speed ATC transmitted, "rightthere's a lot of fire, they're on their way now." The commanderresponded quickly seeking guidance from the tower controller onthe need for passenger evacuation.

During this period, the actual handling of the aircraft was beingcarried out by the co-pilot following the original abandoned take-offplan, whilst the commander was dealing with the significant managementtask. However, with a nosewheel steering tiller on the commander'sside only, it was necessary for him to take control of the aircraftat some stage if he intended to turn off. It is quite apparentthat by the time the briefing and other tasks were completed andhe was in a position to re-assess the actual abandon take-offprocess, the commander was already committed to turning off.

All these events took place rapidly; the replay of the CVR provideda striking indication of the commander's workload during thatperiod of almost continuous communication, not only with the towerbut with briefing the cabin crew and responding to their confirmationrequest. (Appendix 1)

The key element in understanding why the crew did not continuea maximum braked abandon take-off, which would have resulted inan earlier stop, was the lack of any flight deck indication whenthe engine failed that an aircraft or engine malfunction had occurred,in particular the absence of a fire warning. Thus the decisionto abandon the take-off and the subsequent chain of actions waslargely determined by the initiating event; the apparent tyreburst or bird strike.

Had maximum braking been applied after recognition of the firewarning, or at least after the ATC transmission about "alot of fire", a number of seconds might have been saved.However, any change in the outcome due to this alone remains entirelyspeculative. Nevertheless, it is clear, that as the aircraft wasturning, the need to stop at the earliest opportunity introducedby the fire was recognised, because the aircraft was brought toa halt still partially on the runway.

With the benefit of hindsight, the decision to turn to the rightoff the runway can be seen to have had a severely adverse effecton the fire. The operator's Operations Manual-Flying, referringto engine malfunctions during take-off, advised taxiing clearof the runway if conditions permitted and added that, if a fireexisted, consideration should be given to turning into wind beforestopping. However, as already explained, the way that the limitedinformation became available to the crew, who were already engagedin a high speed abandoned take-off with concomitant very highworkload, left no capacity for analysing the true nature of theemergency. Furthermore the wind, which earlier had been variablein direction and on take off was quoted as 250°/7 kt, wouldhave been of little, if any, operational significance as far asaircraft handling was concerned. There is no doubt that this crew,and indeed the aviation community at large, were quite unawareof the critical influence of light winds on a fire, and they didas most other crews would have done faced with a similar predicament.The crew would have been conditioned to clear the single runwayto the right at the usual turn off at Manchester, where only lightaircraft were permitted to use the area to their left.

The commander wanted to alert the cabin crew to the need for apassenger evacuation as soon as the aircraft had stopped, so hebroadcast over the PA "Evacuate on the starboard side please",14 seconds before, and in anticipation of, the aircraft stopping.This call was acted upon by the purser, who obtained confirmationfrom the commander 8 seconds before the aircraft stopped and thenmade a number of evacuation calls himself over the PA.

It should be noted that if an evacuation instruction is made beforethe aircraft stops it could precipitate an evacuation, with cabindoors being opened, before the aircraft comes to a halt. At speedthis could result in slides being damaged and , in any event couldlead to inappropriate doors being opened. Unless there are overidingreasons to the contrary doors should not be opened until the aircrafthas stopped.

The fire drill was carried out for the left engine immediatelythe aircraft stopped and the right engine shut down, because evacuationwas to take place on that side. The crew then started on the non-memory'Passenger Evacuation (Land) Drill' which proved unrealisticallylong for such an emergency, calling for 'passenger evacuation'as item fourteen.

The drill carried an introductory note which read:-

"Shutdown engines as soon as possible to reduce possibilityof slide damage or personnel injury. Do not delay evacuation ifany possibility of smoke or fire exists".

Clearly in this case it was necessary to shutdown the remainingengine and smoke/fire did exist, leaving the crew without an appropriateeffective drill. Some items were actioned but the crew decidedto evacuate via the right side sliding window as burning fuelflowed forward on the left of the aircraft. The operator's procedurerequired the flight deck crew to leave the aircraft promptly andsupervise the evacuation from outside. The operator consideredit undesireable to use the flight deck crew as integral membersof the internal passenger evacuation team, as on some occasionsthey may be unavailable, having been incapacitated. However, theaircraft manufacturer's recommended procedure is for the flightdeck crew to enter the passenger cabin after completing the cockpitdrills and render all possible assistance to the evacuation frominside. Indeed this is the practice adopted, apparently successfully,during the evacuation certification tests.

The flight deck crew responded to the 'thud' in a prompt mannerin accordance with their experience and training. Their intialassessment of the problem and their subsequent actions were entirelyreasonable based on the cues available to them. The decision toturn off was a critical factor in the destructive power of thefire. However, in the context of the knowledge, training and operatingpractices current at the time of the accident, it is consideredthat this decision should not be criticised.

It is vital that in future operators and ATC services recognisethat all abandoned take-offs and emergency landings should endwith a full stop on the runway. Only then can a full evaluationof the situation be undertaken by the crew with the assistanceof ATC and the airfield fire service as necessary. ATC will haveto be prepared to accept any resulting disturbance to aircraftmovements, particularly at single runway airfields. Similarlyall operators must recognise the potential of even light windsto enhance the destructive power of a fire, and modify their proceduresand training to ensure that aircraft are not stopped with a fireupwind of the fuselage, if at all practicable.

2.3.2 Cabin crew

Those areasof the cabin interior which had escaped direct damage by the fire were covered with a thick coating of viscous soot. (Appendix 3photos e-f)

1.4 Other damage

There was some fire damage and fuel spillage on the runway andtaxiway link Delta.

1.5 Personnel information

1.5.1

Commander	Male aged 39 years
Licence:	Airline Transport Pilot's Licence valid until 9 March 1986
Last medical examination:	Class 1 Medical Certificate valid until 30 September 1985 with no limitations
Part 1 Pilot-in command ratings:	PA 23, 30 and 39 Trident HS121, HS 748 Boeing 737 Series Certificate of Test: valid until 16 December 1985
Instrument rating:	Valid until 7 December 1985
Route check:	Valid until 29 November 1985
Emergency equipment and procedures check:	Valid until 18 January 1986
Flying experience:	Total all types: 8,441 hours Total Boeing 737: 1,276 hours Total last 28 days: 54 hours 25 minutes
Other ratings and approval:	Authorised by the Civil Aviation Authority (CAA) as a Type Rating Examiner, in respect of Boeing 737 aircraft. Also CAA approved as an Instrument Rating Examiner.
Duty time:	On the day before the accident the commander

was on duty for 4 hours 30 minutes, positioning by surface transport. Prior to this he had had the previous 2 days free of duty. Rest period before reporting for duty on 22 August 1985 was 15 hours 45 minutes.

1.5.2

Co-pilot:		Male aged 52 years
Licence:		Airline Transport Pilo
Last medical examination:		Class 1 Medical Certi 30 September 1985, for distant vision and exercising the privile
Part 1 Pilot-in-Command		PA 18, 22, 25, 28 and ratings: Boeing 737-
Certificate of Test:		Valid until 30 Novemb
Instrument Rating:		Valid until 25 March
Emergency equipment and procedures check:		Valid until 5 March 19
Flying experience:	Total all types:	
	Total Boeing 737:	
	Total last 28 days:	
Duty time:	The co-pilot had, on the day before the accident, flown a total of 5 hours 50 minutes within a flying duty period of 7 hours 09 minutes. The previous 2 days were free of duty, and his rest period before reporting for duty on 22 August 1985 was 17 hours 06 minutes.	

1.5.3 Cabin crew:

1.5.3.1

Purser:	Male aged 39 years

combustion section generated high supersonicairflows which led to the fracture of the dome locating pin andthe expulsion of the forward portion of the can. The bypass ductfailed due to a combination of being struck by the edges of thesplit CCOC and overpressure or impact from the escaping No 9 candome.

It was not possible to identify the time interval between thefull development of the 360° crack and the rupture of theCCOC. It is even possible that deflection of the dome startedbefore the crack had run the full 360°. The wear on the fuelnozzle nut, however, showed that failure of the CCOC was not coincidentwith deflection of the dome. The rotation of the separated aftportion of the combustor can also must have occurred over a periodof time, sufficient to have permitted fretting marks to be lefton the can dome.

2.4.2 Failure of the No 9 Can

Metallurgical examination of the fracture surfaces indicated thatthe primary mechanism producing the 360° failure in the 3/4liner area was thermal fatigue. There were also indications ofa mechanical fatigue mode occurring, particularly around the 6o'clock position, which would be expected as the can lost structuralstrength due to the thermal fatigue cracking.

Thermal fatigue cracking of combustor cans is a relatively commonplacephenomenon and was acknowledged as such in the Pratt and WhitneyEngine Manual which also reassured operators that cracks were"usually of a stress relieving nature and, as such, are notserious in that the rate of growth decreases as the crack lengthens".Analysis of the temperature distribution around the 3/4 linerjoint of the post-modification 5l92 can also concluded that acertain amount of early cracking could be expected, particularlyin areas subject to 'hot-spots'. There are many variables whichcan affect the maximum temperature of such hot spots which, whilstpresent on a significant number of the cans tested, did not necessarilyresult in visible cracking in all cases. Theoretical analysisof stresses induced by some of the steepest thermal gradientsserved to emphasise the critical nature of the effects of temperatureon the fatigue life of the material, in which a relatively smallincrease in temperature dramatically reduces the fatigue life.

The above analysis illustrates how a wide spread of fatigue damageoccurring after various times-in-service could be expected, withthose cans experiencing relatively small increases in operatingtemperatures showing disproportionately longer cracks. Inspectionof the radiographic records of British Airways first-run cansprior to repair reflects this wide scatter but it is interestingto note that the length of cracking in the 3/4 liner area of canNo 9 from engine P702868 was at the limit of British Airways firstrun experience, indicating that some factor, or combination offactors, was causing greater distress in this can than the others.

It was also noted from detailed examination of the radiographsof the can set (para 1.6.2.2) that can No 1 had a distinctivearea of multiple 'branchy' cracking in the 3rd liner area - someof the cracks having joined together and liberated a small triangularpiece, measuring roughly 2.5 mm along each side. The length ofthe circumferential cracking was, however, only some 35 mm.

Visual examination of similar crack patterns in cans from otheroperators showed that such an area of branchy cracking usuallydisplayed slight bulging and an 'orange-peel' texture of the metal,indicating severe oxidation caused by a hot-spot.

The radiographs of can No 9 did not show evidence of such widespreadcracking or material loss although one area, close to the maletransfer port, did exhibit a short crack parallel to the maincircumferential crack in liner 3. Whilst the small crack wouldhave been apparent to the BEOL inspector/welder it is not possibleto judge the visual appearance of this area and therefore to statecategorically that it presented itself as an obvious area of thermaldistress.

It must be concluded that it was the length of cracking in canNo 9 which was the most obvious evidence of its poor fatigue performancewhen it was inspected prior to overhaul. It is also self-evidentthat the subsequent repair failed to impart sufficient life recoveryto enable it to remain in service until its next scheduled inspection.

2.4.3 British Airtours ' Maintenance and Repair Procedures

British Airways Engineering Dept. controlled British Airtoursengine maintenance and repair, BEOL implementing the overhaulpolicy. As noted in Paragraph 1.17.2.1 the engine manufacturerdid not specify any fixed times for strip inspection and overhaulof the engine as a whole. They advised that operators should negotiatewith their airworthiness authority using the method of sampleinspection to substantiate the optimum inspection intervals, oreven to operate the engine 'on-condition'. Guidelines were, however,presented as a basis for such negotiations.

The eventual system of LMI/HMI adopted by British Airways hadthe approval of the CAA whose representative witnessed the inspectionof the sample engines and was therefore satisfied that, in particular,the combustor cans of the sample engines were able to continuein service for the specified intervals.

British Airways have stated that they considered all components,including combustor cans, overhauled in accordance with the approvedmanuals should have achieved lives/performance similar to thatfor new items (ie combustor cans should have achieved a servicelife approved on the basis of the performance of new cans).

British Airways/Airtours were, by worldwide standards, a relativelynew operator of the JT8D engine. They had, however, many yearsof experience on the Pratt & Whitney JT3D engine, which alsoemployed combustor cans manufactured from Hastelloy X material.Although the JT3D cans are considerably larger in size, the repairlimits and procedures for circumferential cracks were substantiallythe same, and they could thus be considered experienced in theinspection and repair of such components.

Since, after the first run (ie period from new to first overhaul),none of their cracked cans had been repaired by any method otherthan direct fusion weld it appears that they did not considerany to be outside the limits contained in the Overhaul Manual.

The Pratt and Whitney Engine Manual placed no restriction on thelength of circumferential crack which could be weld repaired,specifying instead a .030 inch width limit coupled with the provisothat "severe local distortion and/or oxidation of linersis not acceptable". As noted in paragraph 2.4.2 it wouldappear that in the case of can No 1, at least, an area of oxidationand distortion had been direct weld repaired. On can No 9 however,this effect appeared not to be so marked and the crack width measuredfrom the radiograph appeared to be within the .030 inch limit.

Whether or not the presence of this hot spot, measuring roughly10-15 mm in diameter in liner 3 of can No 9, fell within the Prattand Whitney description of "severe local distortion and/oroxidation" remains unclear, although the evidence of canNo 1 indicated that BEOL were prepared to repair more severe damagethan this by multiple pass welding to restore material to thedamaged areas. The inspector who examined the can set upon removalfrom engine P702946 recorded "considerable burning and crackingof the 3rd liner" in five of them, but it is evident thatthe damage was thought to be repairable by direct fusion weld.Ultimately, assessment of such condition could be considered subjective,since the word "severe" implies that some local oxidationand distortion is acceptable for weld repair. Indeed, it appearsthat very few cans would ever be direct weld-repairable if nolocal oxidation and distortion were allowed, since hot spots ofvarying severity were present on a large number of cans inspectedat random.

As noted in paragraph 2.4.2., can No 9 exhibited an abnormallylong circumferential crack in the 3/4 liner area but no lengthlimit for weld repair had existed in the Inspection sections ofthe Engine Manual since some time before British Airways/Airtourshad become operators of the JT8D engine. It became apparent thata 3 inch crack length limit had been included in the Engine Manualuntil 1977, when it was deleted by Pratt and Whitney, followingrequests from a number of operators. Pratt and Whitney were unableto recall why the length limit had been included originally buthave stated that, "an engineering review had indicated thatcracks up to and including a full 360° could be safely weldrepaired using the proper Engine Manual procedures", as justificationfor its removal. British Airways stated they were unaware of thepre-existence of a limit, deletion of which occurred some threeyears before they commenced JT8D operations. It was also discoveredthat many operators were unilaterally imposing repair limits morestringent than those in the Engine Manual. A post-accident surveyof 13 operators and overhaul agencies who performed weld repairof circumferential cracks found that only British Airways andone other had no limit on the length of circumferential crackingpermissible for weld repair. The rest had imposed or retainedcrack length limits at or around 3 inches. Some other operatorshad a policy of no direct weld repair of circumferential cracks,opting instead for automatic patch or liner replacement techniques.

This would indicate that many operators were adopting what themanufacturer calls "Burner Management" programmes, thatis they had found from experience that reliable and economic operationwas achieved through selective application of the basic repairlimits and procedures. It should be noted that, prior to the accidentto G-BGJL, British Airways had not had a chance to inspect theircombustor cans after second run and therefore to judge how effectivetheir repair procedures were.

The process of "Burner Management" also apparently extendedto deletion of some of the Engine Manual repair requirements andrecommendations. BEOL had performed neither SHT or Post Weld StressRelief (PWSR) on the can set fitted to G-BGJL. Since SHT was arequirement in the Manual, BEOL needed to raise a Manual RevisionAuthority (MRA) and hence gain approval from the CAA to deletethis process. Although attempts were made initially to accommodateSHT in the can repair procedures, difficulties were encounteredwith its implementation and BEOL engineering took the decisionto delete it. Accordingly, an MRA was raised and approved by theCAA. The full process was, however, re-instated in 1985, priorto the accident to G-BGJL. PWSR remained an optional but recommendedprocedure and did not require such approval.

The survey of 13 operators/overhaul agencies previously referredto also found that 4 had been performing SHT for more than 2 years,2 had been doing SHT for about 2 years (ie since about the timethe G-BGJL can set was undergoing repair) and 5 had been doingSHT for less than 2 years. Two operators were still not doingSHT at the date of the survey (October 1985) and both were majorUS airlines. Only 2 were performing PWSR.

2.4.4 The effectiveness of Direct Fusion Weld Repair of circumferentialcracks

This method has always been a feature of JT8D and JT3D EngineManual repair schemes. It must therefore follow that it has beenemployed with success by many (but not necessarily all) operators.It was extremely difficult to compare the experience of otheroperators directly with that of Britih Airways in this rergardbecause of the very limited ammount of data available. Data suppliedby British Airways based on their post-accident fleet inspectionfor can re-cracking indicates strongly that they were achievinglittle recovery of can fatigue life by direct fusion weld repair.

It is difficult to reconcile this difference in experience since,leaving aside the arguments concerning compliance or non-compliancewith the repair limits and procedures in the case of can No 9,the general trend was that it was not proving satisfactory forthe British Airways fleet as a whole if it was to be assumed thatthe cans would achieve second run performance lives similar tonew cans.

Pratt and Whitney had, on several occasions through all-operatorcommunications and conferences warned that weld-repaired cansdid not have the same fatigue life as new cans or those repairedby material replacement techniques. This is confirmed both byexamination of the can No 9 fracture and by consideration of thenature of this type of thermal fatigue. The fatigue initiationoccurs at microscopic sites around the circumference of the canwhich in time link together to form one or more major (visible)cracks. Since direct fusion weld repair can only address visiblecracks, the embryonic sites remain untreated.In order to tacklethis problem, SHT was recommended by the manufacturer on the groundsthat it would retard the growth of such embryonic cracks. Sincethe major effect of SHT as specified in the Engine Manual wouldbe to restore ductility to the age - hardened material of a usedcan, it was argued that this would have a beneficial effect oncrack growth rate. An additional benefit would be that the 'weldability'of the material would be enhanced, with reduced post-weld crackingoccurring and, when performed in a reducing atmosphere, some removalof oxidation occurred. These latter benefits are certainly validand beneficial to the welding process, although the former claimthat SHT has a significant effect on fatigue crack growth rateis disputed. A Pratt and Whitney report dated 12 May 1986 concludedthat "Solution heat treatment of AMS 5536 (Hastelloy X) at1900°F-2050°F can restore original material propertiesand be used to extend the useful service life of JT8D combustors,sometimes by as much as one-third". However, an independentprogramme of analysis and testing of specimens also conductedafter the accident to G-BGJL concluded that SHT using the then-currentlyspecified temperatures would have no beneficial effects on fatiguecrack propagation rates. This same programme also concluded thatPost-Weld Stress relief seemed "unnecessary in view of thehigh running temperature of the cans" ie a similar effectwould be achieved during the first period of service of the cans.

In view of the modest life recovery now claimed by the manufacturerfor SHT and the evidence that even this is optimistic, it mustbe concluded that its omission by BEOL from the repair procedureprobably did not significantly affect the outcome. The same isheld to be true for PWSR.

It is possible that the combination of the omission of these processestogether with the (presumed) repair of the hot-spot may have shortenedthe life of can No 9 to some extent. However, it is difficultto envisage how, even without these factors, this can at leastcould have been safe to return to service with a direct fusionweld repair to the abnormally large crack in liner 3. It shouldbe noted that it only achieved some 46% of the target 10,000 hoursTime Between Overhaul.

Since it is beyond dispute that the residual life of a weld-repairedcan is an unknown quantity it follows that a separate re-samplingprogramme should have been advocated for cans after repair. Itis possible to draw the conclusion from the subsequently revealeddifferences between operators' repair policies (burner managementprogrammes) that they had achieved the required results throughindividual service experience of poor can condition. British Airwayswould have had an opportunity to re-examine their repair policyhad they seen the fleet-wide results after second run and certainlyif the No 9 can had resulted in the more benign failure mode ofa burn-through or even been detected as a 360° failure -either of which it could easily have been. It was tragic misfortunethat they should learn that they had a can cracking problem insuch a way.

2.4.5 British Airways reaction to previously reported incidentsof combustor can failure

Seen in the context of 300 million flying hours on the JT8D engine,the three recorded CCOC ruptures due to can failure prior to G-BGJLcould almost be regarded as random failures. However, the numberof CCOC penetrations without rupture and bulges or overheatingof the casing indicated that a significant problem existed.

The engine manufacturer was clearly concerned about these incidentsbut felt that the problem lay in improperly repaired and/or hightime parts and hence did not warrant Service Bulletin or AirworthinessDirective action. It must also be said that, presumably, neitherdid the regulatory authorities. The All-Operator Letters and Wiresissued were advisory communications between manufacturer and operators.They did, however, contain information which, in hindsight, mighthave prevented the accident to G-BGJL, viz:-

(a) Slow engine acceleration could be symptomatic of a disruptedcan.

(b) Direct fusion weld-repaired liners are more vulnerable tofatigue cracking than those cans which had been repaired by part-replacement.

(c) Operators were recommended to perform isotope inspectionsof their combustion sections according to their experience.

British Airways, in receipt of this information had to decide,therefore, what action they would take as a result. An airlinethe size of British Airways would deal with many such advisorycommunications through their engineering department and decidewhether the information needed to be passed to the maintenanceor workshop staff, together with any additional analysis whichcould assist. A line maintenance technician, for example, wouldexpect to receive more information on fault diagnosis that thesimplistic statement contained in (a) above.

British Airways Engineering cited various reasons why they didnot consider that they were likely to suffer from combustor canfailures:-

(1) Their engines were relatively new and were fitted with thelatest standard "improved durability" can.

(2) They had a hard-time LMI/HMI inspection programme which wasmore conservative than some other operators. They were aware ofat least one major US operator who had run his new JT8D enginesto 16,000 hours and beyond without a scheduled inspection of thecombustor cans.

(3) Prior to delivery of their first JT8D engine, a survey ofsix major US and European operators regarding their maintenancepractices had not revealed any general dissatisfaction with theperformance of the cans, nor any indication that operators hadspecial 'Burner Management' policies.

(4) References in Pratt and Whitney communications to limiting"extensive weld repairs" were taken to refer to canswhich continued to be weld repaired over multiple engine run lives.

(5) The Pratt and Whitney communications frequently referred tohigh time parts. They did not consider any of their cans at thetime of the accident to be 'high time'.

It has become evident from the complete absence of dialogue betweenBritish Airways and Pratt and Whitney on the subject of combustorcan potential failures that, on one hand, the manufacturer believedthat his messages were being understood and acted upon and onthe other, that the airline interpreted these messages as largelyinapplicable to them at that time. Whilst the Pratt and Whitneyliterature and discussions gave the impression that can failureswere largely a high-time problem, British Airways did not seekdefinitions of 'high-time' and 'extensive weld repairs' or confirmationthat modification 5192 standard cans were less prone to seriouscracking problems. Although it is difficult to speculate on preciselywhat reply they would have received at the time, it would havebeen prudent to have sought clarification on some of the moregeneralised statements.

The opinion held by British Airways that they were achieving,and would continue to achieve, satisfactory combustor can performancealso affected their response to possible symptoms of can distresssuch as might be reported by the flight crew.

2.4.6 British Airways reaction to pilot reports in the technicallog of G-BGJL

The phenomenon of slow engine acceleration on British AirwaysBoeing 737 fleet had been a source of some irritation to the airlinealmost since delivery of the first aircraft. An analysis of thepilot reports in the technical log for the first 7 months of 1985,across the fleet of 43 aircraft, showed some 60 reports of slowacceleration and 85 reports of throttle stagger. The rectificationaction had been, variously, to perform trim runs, drain/clearthe PS4 line, check rigging, change the FCU, adjust the FCU idle,etc. At no time was a disrupted can suspected or found. Althoughretrospective analysis of the technical logs revealed a largenumber of reports, it was noted that the random frequency of thereports was such that it did not trigger the repetitive defectalerting procedure adopted by British Airways. This procedurewas designed to identify problems which recurred within a shortperiod of time. The nature of the slow acceleration/throttle staggerreports was such that they occurred over an extended period oftime and did not appear to cause significant delays. They cameto be regarded as an irritating but non-critical fact-of-lifein JT8D operation and were dealt with at line maintenance level.The knowledge that some other operators were also suffering 'wandering'ground idle and consequent variable acceleration times servedto re-inforce this impression. It should be noted that the linemaintenance technicians were not aware of the content of the Prattand Whitney letters because British Airways Engineering had electednot to advise the maintenance staff of their contents. For thereasons stated in the previous section, they did not considerthat British Airways had, or were likely to suffer from, a cancracking problem.

An investigation conducted by Pratt and Whitney after the accidentto G-BGJL did not reveal any hardware problems peculiar to BritishAirways which could account for the persistent nature of pilotreports of slow acceleration and/or throttle stagger. It was concludedthat the large number of such reports were primarily caused by:-

(a) A lack of familiarity by the flight and maintenance crewswith the particular operating characteristics of the JT8D engine.

(b) Failure by British Airways engineers to properly stabilisethe engines during ground trim runs.

With respect to (a) above, the JT8D engine FCU has a droop governerlimiter, ie there is no fixed idle speed. The engine will adoptan idle speed appropriate to a set fuel flow but which can varywidely with ambient temperatures and pressures and engine bleedand accessory loads. There is thus the possibility that some pilotreports of slow acceleration and/or low idle were due to unfamiliaritywith the operating characteristics of the JT8D engine.

It should be noted at this point that a significantly reducedidle speed is likely to result in disproportionately increasedacceleration times from idle. This is because the accelerationschedule is depressed at low speeds, which the FCU can interpretas still being within the start cycle range. Once the engine hasaccelerated beyond this range, a more rapid rate is scheduled.An engine with 'gas path distress', such as a badly disruptedcan, would lose combustion efficiency with a corresponding reductionin idle RPMs and slow acceleration. However, none of the Prattand

Whitney letters nor published data spoke of low idle speedsor throttle stagger as a symptom of a disrupted combustor canand the 'Troubleshooting' section of the Boeing Maintenance Manualdid not refer to the possible inter-relationship of some of thesymptoms. There was no troubleshooting guidance at all for lowground idle defects, yet it is clear that British Airways believedthe low ground idle figure reported by the pilot on 21 Augustto be responsible for the slow acceleration and reacted accordingly.

It is regrettable that British Airways had not raised the wholequestion of the persistent fleetwide pilot reports for slow acceleration,low idle, and throttle stagger with the manufacturer prior tothe accident to G-BGJL. Even though a Pratt and Whitney engineerwas resident at the British Airways main engineering base, thisproblem was never relayed back to the engine manufacturer's designor operations staff. Information subsequently forthcoming fromBoeing and Pratt and Whitney and closer monitoring by BritishAirways has helped to considerably reduce the number of pilotreports. These discussions have also shown that some maintenancecrews were not analysing the reasons why certain rectificationactions were being performed. Although it would appear that drainingthe PS4 water drain trap was a commonly accepted action to takewith slow acceleration pilot reports, there is no technical reasonwhy it should have been effective. However, at the 1984 HamiltonStandard Operators Conference one operator indicated that theyhad achieved success using this approach.

The same criticism could be levelled at the one turn adjustmentof the ground idle screw. The frequency with which this was doneby British Airways line technicians outside of a part-power trimrun is not clear, but it remains the stated position of both Boeingand Pratt and Whitney that adjustment of the ground idle and/orMIL trim screws should only be done in the context of a part powertrim (see paragraph 1.17.2.3). It must, however, be acknowledgedthat at least two major and respected operators of the JT8D haveadvocated procedures for collecting trim information in flight(ie without a ground trim run).

The rationale behind the one turn adjustment of the ground idlescrew is also puzzling, since the pilot's report indicated a dropof about 8% idle N2 and the one turn adjustment would theoreticallyrecover only some 2%. Hence it would seem to be an ill-consideredattempt at rectification. Equally so, the actual adjustment wasperformed prior to starting the engine, thereby denying the techniciansthe opportunity of confirming the figures reported by the pilotand led them to think that their theoretically ineffective troubleshootinghad resolved the problem.

In making such criticism of the troubleshooting, however, it isnecessary to examine the other options open to the line techniciansfaced with three separate, but apparently inter-related symptoms.It is now clear that they believed that the problems lay in thelow idle RPM and intended to address this - for which no troubleshootingwas provided in the Maintenance Manual. A retrospective analysisof the effectiveness of troubleshooting for combinations of oneor more of these symptoms across the British Airways Boeing 737fleet, indicates that the most common and effective rectificationprocedure was a trim run. It should be remembered that the basicpurpose of a part-power trim run is to check and adjust as necessarythe engine power output and idle speeds. If the idle speed isfound to be low, the procedure is to adjust it until it fallswithin limits. For low idle and slow acceleration defects it isessentially a technique of adjustment rather than a diagnosticprocess.

The factor which rendered troubleshooting difficult in the daysleading up to the accident was that the symptoms appeared anddisappeared apparently at random. In establishing that the rectificationcarried out on the 21 August was insufficient to account for thedramatic recovery in idle speed, acceleration and throttle stagger,attention has been focussed on the one-turn adjustment of theidle screw. As discussed in the following section, the amountof idle speed recovery was approximately 13% - quite disproportionateto the amount of idle speed adjustment made. It is thus true tosay that the Manchester technicians were not simply grossly over-fuellingthe engine to compensate for the low idle figure. Considerationof the engine characteristics by engineers from Pratt and Whitneyand the Royal Aerospace Establishment has, however led to thesuggestion that, if the problems on 21st August were being generatedby a distressed No 9 can, then a mechanism could be envisagedwhereby a small step change in idle fuel flow could result ina large change in idle RPM. It is hypothesised that if distressin the can was causing the symptoms (and circumstantially it wouldappear to be the case) the major reason would be that the canwas failing to 'light' (ie sustain combustion). It is possible,therefore, that a relatively small step adjustment in engine trimcould change the characteristics sufficiently to cause the canto light and recover most of the lost combustion efficiency. Itis also true that the can might re-light on its own accord - thiscould have been occurring with the report of slow accelerationand throttle stagger of the 20 August. It is impossible to stateexactly how long the can had run in a badly disrupted state butit is felt that it was unlikely to have run for more than a fewflights with a 360° separation and consequent severe damage.

In summary, it must be emphasised that much of the above is notonly speculative but has also been arrived at following lengthyconsideration of the engine design and characteristics by professionalengineers and specialists. A line maintenance technician shouldnot be expected to have to apply such detailed reasoning to histroubleshooting nor, probably, would he have the time in practice.Whatever the inadequacies of the troubleshooting employed at Manchesterit is difficult to state that implicit following of the existingMaintenance Manual guidelines, and in particular performance ofa part-power trim run, would have revealed the defect in can No9.

Finally, since the accident, the manufacturer has recomended toBritish Airways that the engine be accelerated from idle to 70%N2 five times followed by a 5 minute stabilisation period eachtime they perform a part-power trim check of the idle speed. Themaintenance manual originally only called for a 5 minute idlestabilisation period following start up.

2.4.7 Information on engine performance extracted from the flightdata and quick-access recorders

Important evidence was obtained from the FDR and Quick AccessRecorder (QAR). The latter could have been used by the airlineto analyse and trend certain engine data on a routine basis, butBritish Airways were not doing so prior to the G-BGJL accident.There was no mandatory requirement for them to use the data fortrending. In fact, the pre-delivery operator survey, conductedby British Airways, seemed to indicate a general lack of enthusiasmfor the system by those canvassed. The recorder specified by BritishAirways for the batch of Boeing 737 aircraft which included G-BGJLlacked two important recorded parameters, LP shaft speed and EGT,which limited its usefulness. Using the engine manufacturer'smethod for analysing the data available from G-BGJL, the airlinewould not have been alerted to take further investigative action.However, a plot of corrected engine fuel flow versus N2 for theidle condition (Appendix 5 Fig i) was made to see whether thiscould identify a defect in the engine. This would not normallybe done by the airline.

As already mentioned, a possible effect of severe combustor candisruption would be a drop in overall combustion effeciency whichwould be most prominent at the idle condition. The degree of thisdrop is difficult to predict accurately but would probably amountto about one ninth of the overall efficiency per can affected,assuming the can was so badly disrupted that it failed to lightcompletely. Hence it can be seen that simple cracks in the cancould not be detected by monitoring the overall engine performance,although severe but localised damage to the flame transfer portscould cause erratic lighting performance. The effect on the enginewould most likely manifest itself as a drop in idle speed witha consequent effect on the acceleration times, which would dominate,rather than as a minimal direct effect on acceleration performance.Such a drop in idle speed would not be accompanied by a drop infuel flow.

Referring to Appendix 5 Fig i, a steady fall in the left Engineidle N2 can be seen occurring from sectors flown on 21 Augustuntil the ground run. Only point (6) fails to show a correspondingdecrease in fuel flow. The post-idle adjustment ground run point(4) then shows a jump of nearly 13% idle N2 at which time thetwo engines are within 1% of each other. Points (3) and (2) showa further decay but point (1), the accident take-off, shows asudden recovery to about 2% differential between the two engines.

The amount of recovery following the idle adjustment is quitedisproportionate to the actual adjustment made. Equally so, mostpoints apart from point (6), lie fairly close to the referenceline and do not exhibit constant fuel flow with decrease in N2,which might be expected if a loss of combustor efficiency wasthe cause of the idle N2 drop.

The fuel flow parameter, particularly at low flow conditions isopen to considerable inaccuracy, and must therefore be treatedwith caution. It is equally true to say, however, that this analysisdoes not provide any evidence that the No 9 combustor canwas causing disturbance of engine parameters or that such a defectwould have been revealed by a part-power trim run. The fluctuatingnature of the N2 parameter appears only circumstantially to beassociated with such gas path distress, and the degree of theRPM drop on 21st August is greater than theory would predict forloss of one ninth of the combustion system efficiency. If it isargued that the fluctuations were due to can distress, then itcould have been random movement of the can and/or 'lighting' ofthe flame which was causing the erratic behaviour. Testing ofthe engine indicating instrumentation did not reveal any defectwhich could have affected the readings.

In stating that ECM would not have detected the incipient failureof can No 9, it should not be inferred from this that it is nota valuable and worthwhile tool to assist with reliable and economicengine operation. With correct and rapid trend analysis it iscapable of detecting deterioration within the engine and its accessoriesbefore more serious problems result and, indeed, examples of candistress being predicted by ECM trends have been demonstrated.It would, however be incorrect to say that even full ECM programmeswill safely predict incipient can problems such that direct engineeringimprovements and additional inspection programmes are unnecessary.This accident has demonstrated that the erratic and fluctuatingperformance of a disrupted can makes fault diagnosis extremelydifficult, even though hindsight can sometimes explain and rationalisethe behaviour.

2.5 Wing tank penetration

Although only the compressor and turbine sections of an engineare conventionally regarded as high energy zones, with attendantpotential for uncontained failure, the energy imparted to thecombustor can dome in this instance was sufficient to shatterthe wing tank access panel. However, the indications are thatif the dome had struck the adjoining wing skin rather than theaccess panel, which has an impact strength approximately one quarterthat of the lower skin, penetration of the tank would not haveoccurred. The wing skin and access panel were not designed toany impact criteria and nor where they required to be.

In the light of this accident it is considered advisable that,in future, the access panels used in wing fuel tanks, in particularthose vulnerable to impact by engine or wheel/tyre debris, shouldhave impact strengths comparable to that of the lower skin formingthe tank floor, and that panels on existing aircraft which donot meet this criteria are modified. It is further consideredthat both engine and airframe manufacturers, and the airworthinessauthorities, should at the design stage take greater account ofthe potential energy contained within the high pressure sectionsof all gas turbine engines and, where necessary, incorporate impactstrength into the design requirements for potentially affectedstructure.

2.6 The fire

2.6.1 The external fire

Although there is no direct evidence of when the fire started,there can be little doubt that it ignited immediately fuel releasedfrom the punctured wing came into contact with hot material andcombustion flames escaping from the damaged engine. The delayedresponse of the left engine fire detector was to be expected,given that the fire was burning external to the engine nacelleand the engine casing and cowls had burst open, allowing slipstream-airto cool those sections of the detector elements most exposed tothe fire. However, the delay in alerting the crew was a criticalfactor in the accident.

An analysis of fire damage on the wreckage identified two quitedistinct and separate damage patterns, which were clearly causedby the two phases of the fire: its initial 'dynamic' phase whilstthe aircraft was still at speed on the runway, and the later 'static'phase after the aircraft had slowed and turned off. The characteristicsof these damage regions provided a valuable insight into the essentialfeatures of each mechanism.

2.6.1.1 The dynamic fire

The fire damage pattern associated with the dynamic phase of thefire comprised:-

i) a region of lower skin burn-through over the outboard sectionof the left tailplane;

ii) oily-soot streamlining over the central area of the left tailplaneleading edge;

iii) paint bubbling and light heating over the lower fuselageon the left side aft of the rear door (Appendix 8 Fig a).

This pattern of damage was consistent with a large plume of fireand partially burnt fuel residues trailing aft from a region behindthe left engine. A general analysis of the features associatedwith this fire, drawing on known aerodynamic, thermodynamic andphysical behaviour characteristics of the elements involved, hasenabled the nature of the fire plume to be determined. From thisknowledge, its impact upon the fuselage can be assessed.

The mechanism giving rise to the dynamic fire plume was as follows:(Appendix 8 Figs d-e)

(1) Fuel released from the wing tank puncture fell mainly as acolumn of liquid, hitting the ground just forward of the lowerreverser bucket, where it broke up into a coarse spray. Some ofthe fuel around the periphery of the main column was ignited byflame escaping from the ruptured engine.

(2) Much of the fuel bouncing up from the tarmac was entrainedinto the intensely turbulent vortex behind the deployed reverserbuckets. Within this turbulent wake, efficient mixing of the fueland air occurred, resulting in a hot, stable flame which burnedwithin, and was controlled by, the turbulent wake boundary.

(3) Some of the fuel splashing off the ground was caught by thebottom lip of the lower reverser bucket and carried around theinside (ie forward) surfaces of the buckets, rather in the mannerof tap-water being deflected by a spoon. This fuel emerged atthe upper lip of the buckets and was

immediately entrained backin the slipstream, forming a sheet of fuel droplets just abovethe wake upper boundary. Some of this fuel was entrained intothe wake where it added to the fire, but most remained unburntand is visible in the first photograph of the fire sequence (Appendix 4Photo a) as a white 'vapour' plume, trailing above the fire plumeproper.

It will be seen that the turbulent wake, and the fire which itcontrolled, were dynamic phenomena dependent upon a large inputof energy from the slipstream. (Hence the reference to this phaseas the 'dynamic' phase - to distinguish it from the 'static' pool-firephase which followed.)

From a consideration of the aerodynamic factors involved, theturbulent wake behind the reverser buckets would be expected totake the form of a roughly elliptical cylinder, with the majorcross-sectional axis lying in the 7 o'clock/1 o'clock plane (viewedfrom behind), in line with the axis of the canted reverser bucketdoors. This assessment of the wake's shape is supported by thephysical evidence; the fire plume burning inside the wake traileddirectly rearwards and passed beneath the left tailplane, whereit produced the intense, localised damage on its under-surface.The unburnt fuel and partially burnt residues forming the 'vapour'plume produced the oily soot streamlines on the tailplane leadingedge, slightly inboard of the fire damage.

In the aftermath of the accident, there was considerable speculationon the (perceived) influence of reverse thrust. In particular,because of the apparent correlation between the area of fire penetrationon the fuselage and the exhaust efflux from the inclined reverserbuckets, it was suggested that the reverser system must have deflectedor blown the fire onto the fuselage, resulting in premature penetrationof the hull. This could not have occurred for several reasons:

(1) In order to deflect the fire plume laterally by a distanceof several feet, the exhaust efflux velocity would have had tohave been significant. In fact, FDR evidence has shown that theengine ceased to deliver thrust from the instant the combustioncasing ruptured (as would be expected), and therefore there wouldhave been no active exhaust efflux from that engine.

(2) With the combustion sectioned burst completely open, muchof the air mass passing through the (windmilling) engine wouldhave spilled out of the open casing, in preference to passingthrough the more restricted turbine section of the engine. Evenif the engine had been intact, but idling at the same RPM as thatrecorded on the FDR for the damaged engine, the efflux velocitieswould still not have been sufficient to have had any significantinfluence on the plume.

(3) The actual grazing contact of the efflux pattern from an activereverser system is significantly higher up on the hull than thelocation of the burn-through zone.(Appendix 6 Fig a)

(4) There was a complete absence of any significant fire damageon the left side of the fuselage aft of the penetration zone.

Several mechanisms which may have the potential to distort orexpand the dynamic fire plume sufficiently to bring it into directcontact with the fuselage were also considered, including theinfluence of reverse thrust developed by the opposite engine,but none were viable.

The effect of the plume on the fuselage could not be determineddirectly because of the destruction of evidence caused by thecontinuing fire. However, the absence of any significant radiantheat damage on the aft fuselage, in combination with the cylindricalform of the fire plume, suggests that the radiant heat damagein the area of fuselage penetration would have been similarlylight. This assessment is re-enforced by a calculated estimateof the radiant heat flux at the fuselage surface adjacent to thecore of the fire plume, which suggests that it would, at most,have produced some slight pre-heating, but would not by itselfhave threatened the integrity of the fuselage skins. When theestimated convective cooling due to the slipstream is taken intoaccount, the indications are that the fuselage would have beenlargely unaffected by the heat from the dynamic fire plume. However,this convective cooling would not have reduced the heat flux transmittedthrough the window transparencies and it is possible that materialimmediately inboard of the windows could have felt heat fluxesin the order of 1 to 2 BTU/Ft2sec,

2.6.1.2 The static fire

As the aircraft decelerated, the turbulent wake which had entrainedmuch of the fuel and sustained the dynamic fire plume decayed,and the fire transitioned into a quasi-static fire burning abovethe increasingly large pool of fuel trailing behind the aircraft.As the aircraft turned into link Delta, the relative wind changedfrom a slight crosswind component from the right to a larger butstill slight crosswind component from the left, placing the cabindownwind of the fire for the first time. The series of witnessphotographs show that whilst the aircraft continued moving, theresultant velocity vector trailed aft sufficiently to preventthe pool-fire plume from being swept over the cabin section ofthe fuselage. However, as it slowed to a halt, the resultant vectorswung progressively forward until, as the aircraft came to rest,smoke completely enveloped the rear fuselage, including the R2door which had been opened just as the aircraft started to turnoff. From that stage onwards the fire was driven directly againstthe fuselage where it was concentrated in the region between thewing trailing edge and the fin leading edge by the blocking effectsof the tail and wing surfaces. (Appendix 8 Figs f-g)

The curved lower surface of the hull and the ground formed a venturi,which entrained a large part of the fire under the hull. Thisfire emerged on the downwind side of the aircraft, forward ofthe R2 door, partly as a secondary plume of fire clinging to thefuselage skin, and partly as a more billowing fire burning insidethe region of turbulence in the lee of the aft fuselage and fin.Within this region of turbulence, the fire was intensified bya mixing of partially burnt fuel residues with air, and its damagepotential increased still further by the presence of large volumesof soot particles, which enhanced the fire's radiative efficiency.

The fire damage pattern in the vicinity of the R2 door aperturedid not suggest that the door was a major point of entry for fire,although it is likely that occasional flame transients may haveentered the doorway, and the curtain immediately inside the doorwould have been subject to substantial radiant heat from the fireplume burning in the lee of the fin.

Although the wind was only some 5-7 kt - a strength so slightthat it would have been a relatively insignificant factor in termsof aircraft handling - there is a powerful body of evidence whichclearly shows that the influence of the wind onthis accident wasparamount. Not only did it drive the static fire plume againstand beneath the hull, making a more rapid penetration of the aluminiumalloy fuselage skins inevitable, it created an aerodynamic pressurefield around the fuselage which, once doors and exits had beenopened on the side opposite to the fire, induced the productsof the external fire into and down the length of the cabin interior.In turn, some interior materials ignited leading to the developmentof a fire inside the cabin.

2.6.2 The internal fire

2.6.2.1 Penetration of the hull

Analysis of the wreckage has shown that the fire initially penetratedthe skins on the left side in the vicinity of seat rows 17 to19, below the level of the cabin floor. Having breached the outerskin, the only barrier which prevented the fire gaining accessto the cavity formed between the outer skin and the cargo bayside-liner panels, which communicated directly with the cabininterior above via floor level air-conditioning grills (Appendix8 Fig h), was a 1 inch thick fibreglass wool accoustic insulationblanket contained in a thin plastic bag. Although fibreglass insulationmaterial of this type is temperature resistant, the indicationsare that it provides very little protection against penetrationby fires of the type which occurred at Manchester14: in the flameturbulence associated with such fires, the material is erodedand quickly breaks down. Consequently, once the fire had penetratedthe fuselage skin, it would have quickly gained potential accessto the cabin. (Note: The normal outflow of conditioning air wouldnot have been present at that time because the R2 door had alreadybeen opened, venting any residual cabin pressure and short circuitingthe normal outflow paths.)

In addition to the relatively direct entry route into the cabinthrough the air conditioning grills, there also existed a secondaryroute under the cabin floor, which the fire appears to have exploited.The principal floor beams above the cargo hold run cross-shipand are attached to the fuselage frames, forming a series of cavitiesbetween the fuselage floor panels and the cargo bay liner. Thesecavities communicate directly with the side cavities (betweenthe fuselage skin and the cargo hold liner) and the air conditioninggrills on both sides of the cabin. However, in certain areas theflow path through the conditioning grills is restricted; abovethe cargo door on the right side, due to the presence of the cargodoor mechanism, and on both sides of the cabin at the aft endof the cargo hold, where fuselage taper restricts access.

The pattern of floor collapse on G-BGJL was consistent with sub-floorfire transfer having taken place, with fire entering in the regionof skin penetration on the left side and then moving across inthe floor cavity, branching fore and aft of the cargo door areato follow the least restricted path into the cabin on the rightside. This fire transfer mechanism can only have been active whilstthe cabin as a whole was intact (ie whilst there existed an appropriatepressure gradient into the cabin interior - prior to significantroof penetration), and before floor collapse occurred. The resultingdamage would have reduced significantly the fuselage strengthin the area of the aft hold.

Estimates of the time of initial fire penetration of the fuselageskin, using published data15 for large pooled fuel fires, indicatethat rear fuselage skin penetration should be expected withina period of 13 to 22 seconds from the time when thefire is established enough for significant flame coverage to occur.Depending upon the assumptions made about the 'pre-burn' effectof the aircraft taxiing as it turned cross wind whilst trailinga pool fire with it, and the extent to which the dynamic firewould have 'pre-conditioned' the pool fire, the estimates of penetrationtime in the specific case of G-BGJL range from 13 to 22seconds at the upper end of the scale down to a minimum periodspanning the range 5 seconds before to 5 seconds after theaircraft came to a halt.

After the fire penetrated the side skins, the lower sector ofthe hull around seat row 20 became so weakened by heat that theskins and longerons locally crippled. Making due allowance forthe additional time needed to weaken the stiffeners and associatedstructure over a reasonably large area, it is estimated that thisprobably occurred some 20 to 40 seconds after the aircraft stopped.

Using the external skin penetration estimates as a guide, butallowing for the additional time necessary for the fire to penetratethe aluminium cabin side liners and the thicker fibreglass woolinsulation layer above cabin floor level, the indications arethat the cabin side wall would have been penetrated within 1 minuteof the aircraft stopping. This mechanism would have allowed thefire direct access to the cabin.

At some stage the combined weakening of the rear fuselage, dueto the lower hull and cabin floor damage, allowed the tail sectionto collapse to the ground and fire to enter the cabin throughthe disrupted cabin floor. It was not possible to produce an accuratetheoretical estimate of when collapse occurred.

Some witnesses spoke of the fire penetrating the windows veryearly. However, the weight of evidence from previous researchinto window fire penetration13 suggests that the type of windowfitted to G-BGJL should typically withstand a pooled fuel firefor at least 40 seconds, and possibly would present a barrierto the fire for 60 to 90 seconds, or more. It may be significantthat, when under attack by fire, windows of that type give anillusion of penetration, including a spider-web cracking patternon the outer panel with a focus or apparent hole in the centre,and the panels give off smoke. It is possible that this, togetherwith the entry of fire and smoke through the floor level grillsand cabin side-walls, led those witnesses to believe that thewindows had been breached. On balance, it is considered more likelythat window failure occurred later, probably after the cabin sidewall had itself failed.

It is likely that some flame transients would have entered atthe open R2 door but the damage to the door aperture and surroundingskins was not consistent with this being a major point of fireentry.

2.6.2.2 Entry of external fire

During the critical period when survivors were still in the processof evacuation, conditions in the cabin would have been controlledby the combined influence of the wind and the various openingsin the fuselage. Later, as the internal fire became fully establishedand the roof started to burn through, the influence of the windwould have diminished somewhat.

The effect of a crosswind blowing over a fuselage is principallyto create a region of high aerodynamic pressure on the upwindside of the hull, and a low pressure region on the downwind side,relative to the ambient pressure (Appendix 8 Fig i). Consequently,once the fuselage is opened to the outside atmosphere, whetheras a result of penetration by the fire or because of doors andescape hatches being opened, there will be flows set up throughthe cabin interior dependent upon the pressure differential betweenthe various apertures in the hull. (It is of extreme importanceto appreciate that the wind strength necessary for this pressure-fieldmechanism to operate in practice has been shown to be very low17- as little as 1 or 2 kt is sufficient.(Appendix 8 Fig j) Theseflows are crucial, because they have the capability to draw fireand toxic combustion products from the external fire into anddown the length of the cabin, with disastrous consequences forthose still inside.

Because the R2 door had been opened as the aircraft began turningoff the runway and the R1 door was cracked as the aircraft cameto a halt, there existed from the outset one large aperture, andone much smaller aperture, into the low pressure regions downwindof the fuselage. Although there may have existed a slight pressuredifferential between the R1 and R2 doors (caused by the angleof wind against the fuselage and by the aerodymanic 'end effect',due to the proximity of the R1 door to the nose) which may initiallyhave drawn smoke and possibly some fire into the R2 door, oncethe fire penetrated the fuselage skins on the high pressure (upwind)side of the hull, a dominant pressure gradient would have beenset up between the fire aperture and the open rear door whichwould have drawn the fire into the interior via the conditioningair grills. This fire would have predominantly passed across therear cabin, exiting through the R2 door, and to a lesser extentdown the cabin towards the R1 door. This entrainment of fire,combined with the proximity of fire to the rear right door, wouldhave rapidly produced fatal conditions in the rear cabin. However,the direct 'through-path' for fire products at the rear of thecabin, towards the R2 door, would have minimised any tendencyfor them to migrate forward and, during the period when the R1door remained partially closed, the forward cabin would have remainedrelatively immune from the effects of the fire at the back ofthe aircraft.

The jamming of the R1 door is cause for concern. However, havingcreated a delay in the start of the evacuation at the front ofthe aircraft it may have had some secondary beneficial effectin the context of this specific accident as it forced the crewto fully open the L1 door first. This limited the size of aperturewhich was opened into a low pressure zone at the front of theaircraft, minimising the adverse internal pressure gradient whichwould otherwise have drawn fire forward into the cabin, creatinginstead a beneficial pressure gradient. This helped to keep thefire confined to the rear of the aircraft and minimised the adversedepression created in the forward cabin when the R1 door was eventuallyopened fully. This effect will have served to benefit the passengerswaiting to exit at the front of the aircraft. However, if thedoor had not jammed, an earlier commencement of the evacuationwould probably have benefitted the passengers at both front andrear. Once the R1 door and the overwing exit were opened fully,there would have been an immediate loss of any positive pressuregradient and fire products would have filled the cabin.

2.6.2.3 Cabin fire

The establishment of an internal fire in the rear of the cabin,as distinct from the entrainment of external fire through theinterior, probably occurred relatively early - certainly whilsta majority of the passengers were still on board. The progressof the internal fire remains largely obscure because of the substantialdestruction of evidence which it caused as it progressed, andthere is no reliable evidence from which a timescale might bedeveloped. However, several features of the internal fire wereidentified as having important implications for survival. Contraryto conventional wisdom, a full flashover in the cabin did notoccur, although clearly a number of brief flash fires did occuras vapours in the ceiling space ignited. This is important becausemuch of the literature in the field of aircraft fire safety, particularlythat relating to improved cabin materials, implies that flashoverwill inevitably occur. This assumption is not supported by theevidence of this fire's behaviour, and is discussed further inpara 2.6.4..

Prior to the roof being penetrated, the fire burnt in the uppercabin and roof space. After roof penetration, the fire was ventedto atmosphere and thereafter burnt as a series of localised fireswithin the cabin. No overall pattern of fire development couldbe seen, nor was any single propagation mechanism evident, althoughwithin some areas the fire appears to have used the plastic surfacefilm on the side liner panels as a 'wick', allowing the fire toprogress from one group of seats to another some distance awaywithout affecting the intervening furnishings. Generally, themore damaged regions of seating appear to be associated with thecollapse of burning overhead lockers. The very localised areasof extremely severe fire damage were possibly the result of burningduty-free spirits, or the discharge of oxygen from the therapeuticoxygen cyclinders carried in the (collapsed) overhead lockers.

This accident has confirmed the very steep rates of change ofboth temperature and soot (smoke) as a function of height in thecabin, commented upon consistently in the research literature.This stratification was clearly evident as a grading of the burningand sooting on panel surfaces in the forward galley area (Appendix19), and probably explains the survival of those few passengerswho collapsed during the initial evacuation. This has significancein the discussion, later in this analysis, of floor marking andlighting schemes.

2.6.2.4 Additional hazards

There was evidence in the wreckage that certain very localisedzones within the cabin had burnt with exceptional ferocity. Nopositive evidence could be found to indicate the cause of thisdamage, but the burn characteristics were indicative of the presenceof flammable agents, several of which are known to have been presentin the cabin; duty-free spirits, therapeutic oxygen, and aerosolsprays. Because of the inevitable disturbance of the cabin interiorduring the emergency phase, it has not been possible to correlatethese areas of intensive fire damage with the locations of flammableitems during the period of the fire.

It is not clear precisely how duty-free spirits affected the fire,but it is likely that some did contribute. Alcohol spirits, ifreleased onto absorbant material, would have had the potentialto produce a local enhancement of the fire for a significant period.Those spirits stored in baggage on the cabin floor are unlikelyto have contributed actively to the fire until quite late, probablytoo late to have affected survival. However, because of the temperaturestratification which is a feature of all cabin fires, any spiritsplaced in the overhead lockers would have been subject to veryhigh temperatures early in the fire and their hazard potentialwould have been correspondingly greater. The early involvmentof such materials would add significantly to the transfer of firefrom the ceiling region down onto seats, carpets and other materialsin the lower levels of the cabin.

All therapeutic (portable) oxygen cylinders became overheatedin the fire and either ruptured or vented (via the over-pressurerelief mechanism incorporated into the pressure gauge), dischargingthe whole of their contents into the fire. The effects of thesedischarges cannot be precisely established from the evidence,but they are likely to have produced sudden, very severe but shortlived enhancements of the fire. They are unlikely to have causedsignificant (explosive) pressure-fronts unless, by enriching anoxygen deficient atmosphere, this led to the flash ignition offlammable decomposition products. Nevertheless they were extremelyhazardous and unpredictable elements which could have caused severecasualties amongst rescue personnel.

The stowage of therapeutic oxygen cylinders in the overhead lockerson G-BGJL was doubly hazardous. The ceiling temperatures in aninternal fire will reach high levels very rapidly, but becauseof the steep temperature gradient the lower part of the cabinis likely be at habitable temperatures long after extreme temperaturesare reached at ceiling level. Consequently, there is a risk ofoverheating oxygen cylinders venting or rupturing and releasingoxygen into the fire whilst survivors are still in the cabin.It is therefore recommended that the stowage of oxygen (and anyvessel holding flammable material) is confined to fire proofedcontainers at floor level.

Although the extent to which aerosols played a part in this firecannot be determined, there is little doubt that they made somecontribution. The damage potential of typical domestic aerosolshas only recently come to light and their implications as 'dangerouscargo' are still being studied by the UK CAA. However, there isno doubt that these items are extremely hazardous if they areinvolved in an aircraft cabin fire.

It is considered that the carriage of aerosols in hand baggagepresents an unnecessary risk, and it is recommended that thesematerials are subject to the same controls as other flammablegas cylinders (eg camping gas cylinders).

2.6.3 Relevance of this accident to post-crash aircraft firesin general

The early penetration of fire into the cabin appears to conflictmarkedly with the air transport industry's expectations (at thattime) of survival in a 'typical' pooled-fuel fire. Although thereexisted no formal yardstick of survival in a fire of this type,the general expectation appears to have been that, with an initiallyintact fuselage, a period of between 1 and 3 minutes would beavailable for evacuation before the external fire was in a positionto directly threaten the occupants. The 90 second evacuation criterion,whilst it was never put forward by the airworthiness authoritiesas a measure of the expected survival time in a fire, has nevertheless,through widespread misinterpretation of its intent, contributedsignificantly to this belief.

The evident disparity between these expectations and what actuallyhappened at Manchester raises a fundamental question - was theManchester fire typical of what should be expected from any pooledfuel fire, or was there some unique factor involved?

All the indications are that Manchester was not in itself unusualso far as the principal controlling factors were concerned:-

(1) Both G-BGJL specifically, and the aircraft type in general,were typical of aircraft of the same class in use worldwide.

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(2) The dynamic fire, although visually dramatic, had only a secondaryinfluence so far as fire penetration was concerned, speeding uphull penetration by 10 to 20 seconds at the most.

(3) The fire principally responsible for cabin penetration wasa 'typical static pooled fuel fire', involving modest quantitiesof fuel.

(4) The weather conditions were not at all extreme.

(5) The fire and rescue services were well equipped and respondedquickly, indeed the response was much more rapid than could bereasonably expected for a 'typical' accident on an airfield.

(6) The fire and rescue capability far exceeded that deemed necessaryto handle 737 category aircraft.

(7) There were no other complicating factors peculiar to the Manchesteraccident.

The open R2 door was an unusual feature which was of some significance,particularly in terms of smoke entry, the impact of radiant heatin the aft vestibule area and, probably, the intermittant entryof flame transients. However, whilst it must be stressed thatopening any door into an area of fire, or prematurely before theaircraft stops and the fire conditions can properly be assessed,is potentially extemely hazardous, the analysis of this fire hassuggested that the R2 door played a secondary role only, withfire penetration of the rear fuselage left side forming the principalpoint of entry.

Overall, it would appear that the 'basic ingredients' of the Manchesterfire affecting fire penetration were not particularly unusual.Therefore, the lessons to be learned from the investigation ofthis fire are of direct relevance to the operation of all passengeraircraft.

2.6.4 The effectiveness of the current fire hardening strategyin limiting fire damage

Research into aircraft fire hardening has been under way for manyyears, but is only now starting to bear fruit in terms of theintroduction of advanced materials into service. G-BGJL was typicalof the majority of commercial aircraft in service at the timeof the accident in that it was of conventional construction andwas fitted out with standard cabin furnishing materials, which,although conforming to the appropriate regulatory requirements,were not specifically fire hardened in the currently acceptedmeaning of the term. It is not possible to quantify the advantages(or otherwise) which specific fire hardening materials and techniquesmay have had at Manchester, had they been used on G-BGJL. Nevertheless,all possible effort must be made to use the knowledge gained fromthe investigation of this accident to reduce both the risk offire occurring, and the threat to life posed by aircraft groundfires in general. Consideration must therefore be given as towhether or not the routes currently being taken to reduce firerisks are actually addressing those problems in most need of urgentsolutions.

A fully developed flashover condition did not occur at Manchester,although a number of brief flash ignition fires clearly did. Thisis somewhat at variance with the implied message contained inmuch of the research literature, from which the inference thatflashover will occur comes through strongly, and that this conditionwill therefore be the primary factor controlling survival time.This difference between expectation and reality probably has itsroots in the methods currently in use to assess the value of firehardened materials.

The results of research into fire hardening are often quoted interms of how effective the material is at either delaying flashoveror preventing it altogether. This method of describing the benefitsof new materials provides a useful measure of fire performancebecause the primary factor influencing flashover is the rate ofheat and smoke generation by burning interior materials; thesesame properties also control the environmental conditions in thecabin prior to flashover. A further reason for using the 'timeto flashover' is that flashover is a very clearly defined pointwhen conditions inside the cabin change from being (arguably)survivable to being (generally) non-survivable, allowing materialsto be compared one against another. Using this method of ratingimplies that flashover is inevitable. However, there are powerfulreasons to question whether flashover occurs at all often in realaircraft fires, as opposed to test fires.

At Manchester, as in many other serious aircraft fires, a numberof exits were open and the fuselage crown was penetrated allowingventing of the hot gas and soot which are essential elements ofthe flashover mechanism. In contrast, most fire tests have utilisedfire hardened test fuselages with a single door open at the oppositeend of the cabin to the fire aperture; conditions under whichflashover is much more likely to occur.

Prior to this accident, the principal thrust of the fire survivalprogram has been in the area of fire hardening of cabin materials,to slow down the fire development in the cabin, thereby reducingthe rate of temperature rise and extending the time interval beforeflashover occurs. These avenues of endeavour are entirely properand valid. However, as an aim in itself, preventing flashover,whilst laudable, is somewhat reduced in its relative importanceif, in practice, flashover is unlikely to occur. It is consideredthat the widespread assumption that flashover will occur has producedan imbalance in the way the problems of fire protection are currentlybeing tackled by the regulatory authorities worldwide. So faras the majority of the occupants of the cabin are concerned, thereare other avenues which need to be pursued with equal or greaterurgency - aimed at preventing or delaying the penetration of externalfire into the cabin interior, mitigating the effects of toxic(and irritant) fumes and smoke and improving exit paths.

In contrast to the extensive research into fire hardening interiors,research into fire hardening of the hull itself has been muchmore limited. Mainly, this work has been directed towards obtainingdata on fuselage skin penetration times and improving the fireresistance of windows and their fixing systems. Whilst it is understoodthat manufacturers and airworthiness authorities have devotedtime and effort to the effects of fire on the fuselage structure,there is little evidence that fuselage penetration by an externalfire, or the subsequent transmission of that fire through theinternal structure, has been addressed with anything like thevigour applied to the fire hardening of interior materials. Thequestion therefore arises as to whether the balance of effortbetween work on fire hardening interiors and improving the fireresistance of the hull itself is appropriate, particularly inthe light of the Manchester experience.

Aircraft fires fall broadly into three principal categories:-

(1) In-flight engine fires and airframe fires outside the pressurehull.

Typically, these involve fuel or hydraulic oil. The problems whichthey generate and the fire mechanisms involved are quite differentfrom those under consideration here, and therefore further discussionof this type of fire is not relevant.

(2) Fuselage fires inside the pressure hull.

Cargo hold fires are already the subject of more stringent designcriteria - intended to prevent the spread of a cargo fire beyondthe hold itself.

Cabin fires are normally small and, generally, are successfullycontrolled by cabin crew using the on board hand-held extinguishingequipment. However, if the fire cannot be dealt with rapidly,perhaps because of a lack of access, they have the potential tocause heavy loss of life, as witnessed in the Saudia L1011 accidentin 1980. It is in this category of fire that the current effortsto fire harden interior materials can, arguably, offer the greatestpotential to save lives. However, it must be borne in mind thatfatalities in these types of fire invariably result from the inhalationof toxic fire products rather than from the fire itself. Therefore,in order to be really effective, these materials must not onlybe fire resistant, but must produce much lower emissions of toxicmaterial - even in a smouldering, as distinct from an open flamingtype of fire. In this respect, progress has been disappointing.The indications are that for the forseeable future fires involvingcabin materials will continue to produce highly toxic fumes, evenif flame spread characteristics are much improved. The corolloryto this is that whilst the current effort to reduce flammabilitywill open the door to survival in terms of the aircraft itselfand the crew, passengers, without effective smoke protection,will not be in a position to reap a similar benefit.

Despite the evident problems concerning toxic fire products, itis clear that the current efforts to fire harden interior furnishingmaterials and cargo hold liners are, so far as they go, entirelyappropriate for this category of fire, and should receive continuedencouragement.

(3) Pooled fuel fires

This type of fire, which results in a large and intense fire outsidethe hull, falls into two sub-categories:

(a) those where the fuselage has been ruptured to some degree,as result of crash damage for example, giving the fire directaccess to the cabin interior, and

(b) those in which the hull is initially intact and capable (theoretically)of presenting a barrier to the external fire (as was the caseat Manchester).

If the fuselage is ruptured by impact or other forces in a regionadjoining the fire, the first link in the defensive chain is broken,and any means of strengthening the secondary links will be ofpotential value. In these circumstances therefore, fire hardeningof the interior materials will play an important role by retardingthe development of active burning within the cabin. In the caseof an intact fuselage however, fire hardening the interior, althoughstill necessary, is of secondary importance compared with theneed to maintain the integrity of the hull, not only in termsof fire penetration, but also the maintenance of structural stability.At Manchester, skin penetration occurred whilst there were substantialnumbers of passengers still in the process of evacuating.

It is essential that increased effort is made to seek improvementsin the fire hardening of fuselage structures. In the short term,interim measures could be implemented so as to provide a breathingspace, whilst the more fundamental issues are addressed in thelong term, when fire criteria must feature in the design philosophyof new aircraft, not relating just to materials but to structuresalso, backed by appropriate legislation.

As a part of the short term approach, the experience gained inthe building, maritime and industrial fields should be criticallyexamined to see whether techniques used in these areas could beused, or developed to make them suitable for use, in aircraft.The application of intumescent coatings* to structural membersin buildings, and to critical parts of ships and submarines, isan example of a technique which may have application to the firehardening of aircraft. Even though these materials might previouslyhave been rejected as an exterior finish for the fuselage, itmay be possible to use them in other ways, eg to fire harden theinner (ie hidden) surfaces of the cabin side-liner panels andfloor panels, providing an effective secondary fire barrier.

This same class of materials also appears to have potential forthe local protection of critical structure, such as floor beamsand, if applied to honeycomb 'grills', for sealing off cavitiesand gaps in the internal structure to provide fire stoppers -limiting the communication of fire through internal cavities.The use of water misting sprays inside the cabin, and also withinfuselage cavities, is another technique which should be exploredfully.

In the long term, a more fundamental review of attitudes to fireis required. Historically, the aircraft industry has adopted asomewhat fatalistic attitude to the problems of aircraft firesand it is quite apparent that the hull has received scant attentionwhen it comes to the consideration of fire at the design stage.

To summarise, there currently appears to be something of a mismatchbetween the effort being expended on limiting the flammabilityof interior materials and that aimed at inhibiting the fire'sprogress through the hull to the interior of the cabin in thefirst place. Although no suggestion is being made that an improvementin interior materials is not necessary, it is considered essentialthat balance is restored by increased effort to address the problemsof:-

i) hull penetration;

ii) the internal communication of fire through the structure;

iii) premature structural collapse. .

2.6.5 Aircraft positioning relative to the wind

Although the effects of wind on fire generally were well known,there was a widespread belief that only strong winds are significant.There is overwhelming evidence that this is not so: in the contextof a typical pooled fuel fire, wind velocities as low as 1 or2 kt can critically influence the fire's damage potential.

These influences not only control the severity of the fire's attackon the hull, but they also control how the fire propagates throughthe aircraft interior14.

Aircraft operating procedures generally in use at the time ofthe accident made little active allowance for wind in the eventof a fire, beyond a generalised directive to stop on the runwayif the wind was likely to have an adverse effect. Certainly BritishAirtours did not include any active consideration of the wind(in terms of its effect on a fire) in their simulator training,nor was active consideration given to these aspects in any otherarea of their operation. In this respect, Airtours was typicalof most operators. This does not reflect a lack of care or judgmenton the part of British Airtours (or the other operators), rathera lack of understanding of aircraft fire behaviour. Indeed, itconfirms that knowledge within the fire research community aboutthe importance of wind had not (and to a large extent still hasnot) been assimilated by the aviation community at large. Theinvestigation of this fire has given a new perspective to thatknowledge, which has been freely available for many years, andhas focussed attention on the need to encourage ways of reducingthe wind's destructive power. In practical terms, this means developingoperational techniques which ensure that aircraft orientationrelative to the wind does not compromise the safety of those onboard, and, if at all possible, creates beneficial relative windswhich enhance prospects for survival.

The importance of the wind, in terms of both the external andinternal fire development, was recognised during full scale fireresearch carried out as early as the nineteen sixties, and itsinfluence has been repeatedly noted and commented upon withinthe fire research community ever since then - often as an explanationfor variability in the test data. Consequently, there has beena tendency to view the wind as a problem; a barrier preventinga precise understanding of aircraft fires. However, although thewind undoubtedly does make the mathematical analysis of firesimpossibly complex, its prime influence in practical terms isnot so complicated - it sets the trend of behaviour of a fireand, usually, magnifies its destructive potential.

Initially an aircraft fire involving pooled fuel behaves in aneutrally stable way, ie the physical processes it is undergoingare very easily disturbed by small external influences. Consequently,any disturbances at this stage, however small, will produce significantchanges in the fire's characteristics. It is at this stage thatthe wind, even if it is very light, will exert a disproportionatelylarge influence on the fire's subsequent development. In fact,published data has shown that wind strengths as low as 2 kt cancritically alter the severity of a fire, both directly (in termsof its external attack) and indirectly (in terms of ventilationand the entrainment of fire products into the cabin).

As the fire becomes more established, it also becomes more stable,and as a result, much greater disturbing forces are required toproduce any change in the fire process. This general trend ofbehaviour applies not only to the physical processes of the fire,but it extends to all aspects of the fire, including the 'behaviouralprocesses' of the occupants and those involved in firefightingand rescue, whose actions are controlled by, and hence are subservientto, the fire processes.

It is notable that almost all aspects of fire which are criticalfrom the point of view of survival are ones which are controlled,either directly or indirectly, by the wind. Further, these factorstend to act in unison either to enhance, or alternatively prejudice,survival prospects. This is illustrated by considering two simpleexamples, representative of the two extremes of wind (in termsof direction only) applicable to a 'typical' pooled fuel fire.

In Appendix 8 Fig k, the fire is shown on the upwind side of thecabin. The occupants' perception of where the threat lies willencourage them to open those doors furthest removed longitudinallyfrom the fire, and on the opposite side to the fire, ie into lowpressure regions. Even if no door is opened directly onto thefire, the fire will be driven by the wind against the fuselageand, in the case of a conventional narrow body aircraft such asthe 737, penetration of the cabin is likely to occur almost beforethe evacuation has got properly under way. (Even in the case ofthe larger wide body types, penetration by the fire is likelyto occur before evacuation is complete.) A 'fire aperture' willalmost certainly form, therefore, on the upwind (high pressure)side of the hull, and the resulting pressure differential betweenthe upwind fire aperture and the opened doors downwind will drivethe fire the length of the cabin, greatly reducing the chancesof survival. Those passengers who might succeed in evacuatingthe cabin will find themselves in the hazardous region downwindof the fire - a far from ideal position to be in. In this scenario,which is broadly representative of Manchester, it can be seenthat all of the factors are working adversely, ie more rapid firepenetration, door availability limited to those giving rise toan adverse pressure gradient leading to rapid fire involvementof the cabin, and poor external escape paths - all of which arecontrolled by the relative wind direction.

In Appendix 8 Fig l the opposite case is illustrated, ie oppositerelative wind (fire downwind), but all other conditions unchanged.In this instance, the doors will again tend to be opened at positionsas far removed as possible from the fire and on the side oppositeto the fire, which in this case will be the upwind (high pressure)side of the hull. The external fire on the downwind side willtend to be carried away from the fuselage, and penetration willtherefore be less likely to occur. If penetration does occur,it will take longer, delaying the potential for direct transferof fire to the interior and increasing the time for escape. Thefire aperture (if fire penetrates the hull) will be on the lowpressure side of the hull, giving rise to a pressure gradientwhich will tend to purge the cabin with fresh air and keep thefire out. In this example, evacuation would take place into thefire-free up-wind zone. It can be clearly seen that in this case,all of the factors which worked adversely in the previous example,have, purely as a result of the difference in wind direction,been either minimised or redirected to act beneficially.

Therefore, rather than viewing the wind solely as a negative factor,there is a powerful argument to be made for actively strivingto harness the wind's potential to bias the fire's behaviour ina positive, or helpful, direction. In practice the task of correctpositioning does present formidable problems because of the impliedneed to analyse the wind direction, the fire location, the availabilityof suitable manoeuvring areas and the risk of introducing unacceptabledelays in evacuation - all whilst a fire-related accident (orincident) is in progress. Clearly such additional tasks couldwell raise the crew workload above a level which they could safelymanage, possibly leading to a loss of control or some other moreimmediate hazard.

Because of the many operational difficulties involved, it hashitherto been viewed as impractical to actively seek to positionaircraft with the fire on the downwind side, and the only movetowards this aim has been one of damage limitation, ie stoppingon runway heading to minimise the cross-wind. This, together withthe widespread belief that such a requirement is only necessaryin strong wind conditions, has led to the wind being virtuallyignored from the point of view of practical emergency procedurestraining. Consequently, aircrew have a low awareness of the windunless it is of sufficient strength to affect the performanceor handling characteristics of their aircraft.

This accident has tragically illustrated the significance of thewind. Furthermore, because crosswind components as low as 1 or2 kt are critical, simply stopping on runway heading, or even'into wind', is not sufficient to guarantee that, in typicallyvariable conditions, an adverse crosswind component will not bepresent. Therefore, it is essential to reconsider ways in whichcrew might be assisted in the difficult task of positioning theiraircraft so as to ensure that any crosswind puts the fire downwindof the fuselage.

The formulation of the best approach to this problem is not somethingwhich will be attempted in this report; it will require informedinput from many quarters and the consideration of many interlinkingfactors. However, there would be many advantages in includingan appropriate item in the pre-take off emergencies brief. Inthis way the flight deck crew's level of awareness of the windwould be raised, even if the wind was otherwise insignificant,and the procedure could be incorporated into simulator training,which could be extended to include positioning and stopping theaircraft in the event of a fire. By practicing for fire in thisway, it should be possible to ensure that crew workload is keptto an acceptable level.

As an aid to the crew, direct visual cues should be enhanced whereverpossible. For example, windsocks located in the threshold areascould provide a rapid and easily assimilated picture of the actualwind conditions in areas where an aircraft is likely to stop inthe event of a fire (as distinct from the wind at the anemometerlocation). It is also considered that there is a need for researchinto devising practical methods of alerting crews to fire (andpossibly other external damage) outside their field of directview, perhaps by use of cameras or mirrors.

2.7 Evacuation and survival

Perhaps the most striking feature of this accident was the factthat although the aircraft never became airborne and was broughtto a halt in a position which allowed an extremely rapid fire-serviceattack on the external fire, it resulted in 55 deaths. The majorquestion is why the passengers did not get off the aircraft sufficientlyquickly.

2.7.1 Opening of and access to exits

The opening of the R1, R2 and L1 doors along with the actionsof the cabin crew is analysed in paragraph 2.3.2..

There was no drill requiring the crew to instruct the passengersto open the overwing hatch and such an instruction was not given.However, due to some of the passengers having moved forward beforethe aircraft stopped a queue had developed in the forward aislewhich precipitated urgent action by the passengers in the centrecabin to open the right overwing escape hatch. This was only achievedwith some difficulty, contributed to by the adjacent passengerslack of knowledge of the hatch operating procedure and the practicaldifficulties in handling the hatch in the confined space available.The gap between the row 10 and row 9 seats was small enough tomake standing difficult, leading to the occupant of the seat nextto the hatch attempting to open it whilst seated. She tried toopen it by pulling on her seat's outboard armrest, which was mountedon the hatch. This led to the passenger in the next seat, 10 E,who was better placed to see the release handle and adjacent instructions,coming to her assistance.

Without any appreciation of how the hatch would open, they wereunprepared for it to fall inboard, pivoting about its lower edgeand trapping the occupant of 10 F. It was only with difficultyand the help of a male passenger that the hatch (weighing 48 lbs)was finally lifted into the cabin and placed on seat 11D. To avoidthe hatch becoming a further obstacle to evacuating passengersit would appear beneficial to throw it out of the aperture ratherthan retain it in the cabin. Although it is possible to inventa scenario where reclosure of the exit is desireable, in practicalterms, it is likely to prove impossible. This exit was openedabout 45 seconds after the aircraft stopped. Passengers startedto evacuate from the right overwing exit after the L1 door wasopen but before the R1 door was fully opened and slide deployed.Two passengers (12A,19B) referred to becoming tangled with a whitestrap, the lifeline. However, one passenger reported catchinghold of it as she collapsed, to recover consciousness with herhead outside the exit.

Although it is generally accepted as undesireable to have infants/childrenwith separate child lap straps seated on adult laps in the seatrow adjacent to an overwing exit, in this case the occupants ofseats 10C and 10D evacuated quickly with their charges. No survivorsmade reference to the child lap straps.

The failure of 10F seat-back hinge baulk reflects the pressureof passengers struggling towards the right overwing exit, forcingthe seat-back forwards. Folded forwards it could only become afurther significant obstacle to passengers attempting to escape.

Even had the 10F seat-back hinge baulk not failed, the presenceof a full row of seats at row 10, immediately inboard of the overwingType III exit, with a pitch of 31 inches between rows 9 and 10is considered likely to have obstructed access to and reducedthe effectiveness of this exit. It is therefore difficult to reconcilethe certification of such a cabin configuration with the requirementsof BCAR's, which state that:-

"Easy means of access to the exits shall be provided to facilitateuse at all times, including darkness; exceptional agility shallnot be required of persons using the exits.

Access shall be provided from the main aisle to Type III and TypeIV exits and such exits shall not be obstructed by seats, berthsor other protrusions to an extent which would reduce the effectivenessof the exit."

It must be kept in mind that whilst such obstacles might wellbe accommodated by passengers evacuating in clear air conditions,they can have a severely detrimental effect in dense smoke ofthe type which existed in the cabin at Manchester. Indeed theminimal 1 - 2 inch increase in seat pitch at rows 9 - 10, theonly concession to provide access to the overwing exit, is notonly of little, if any, significance in providing additional spacein which to manoeuvre between the seats, but also fails to provideidentification of the route to the exit from the aisle for passengersengulfed in dense smoke and feeling their way along the seat rows.

Not only did the requirements of BCARs appear not to be met, butthe requirements themselves in some areas are in need of review.Specifically:-

(i) For aeroplanes that have a passenger seating of 20 or morethe projected opening of the exit provided shall not be obstructedby seats, berths or other protrusions (including seat backs inany position) for a distance from the exit not less than the widthof the narrowest passenger seat installed in the aeroplane".

This, in a typical modern high density seat layout with seatsdown to 17 inches in width, as at Manchester, provides a minimalclear zone for the projected aperture. This permits seat armrestsor any cabin furnishing obstruction as close as 17 inches to theexit within the projected aperture.

Removal of the outboard single seat adjacent to each exit, inthe light of the evacuation difficulties encountered at Manchester,does not address the total problem of identification of and accessto the exit in dense smoke.

Although the seat armrests of row 10 were capable of being foldedup there was nothing to indicate this facility and if left down,the required position for take-off, they represent an obstacleto anyone trying to move over the seats to the exits, either walkingor crawling.

Although some 27 survivors including 1 infant and a child escapedthrough the right overwing exit, this number must be comparedwith the 76 passengers from the rear of the aircraft for whomthis was the first available exit, and the 100 for whom it wasthe nearest.

Although there is little doubt that had the R1 door opened athis first attempt, the purser would not have opened the L1 door,having both front doors available should have enhanced the evacuationrate from the forward end of the aisle. However, the existenceof the twin forward bulkheads with only a gap of some 22¤inches between them effectively restricted passenger flow to single-file.The effects of this restriction were only too apparent for themany passengers who successfully made their way forwards overthe seats only to be confronted by the bulkheads. The potentialegress rate of both forward doors was therefore never realisedand a consequent delay was thus directly imposed on those waitingto exit via the forward end of the cabin.

2.7.2 Effects of toxic/irritant gases and smoke

It is significant that, of the 51 passengers who successfullyevacuated from the two forward doors, some 23 escaped before thethick smoke had reached them - ie 45%. Of the remaining 28 whobecame engulfed in smoke, the stewardess had to pull two femalepassengers on to her slide at the L1 door, after they had collapsed.Two male passengers collapsed near the forward aisle before recoveringlater and getting out and a third was recovered alive but unconsciousafter some 33 minutes.

Shortly after the right overwing exit was opened and passengersbegan evacuation onto the wing, the centre section area was rapidlyengulfed in thick black smoke, which had flowed into the aft cabinas the aircraft stopped. This smoke was drawn out of the rightoverwing exit due to this aperture being on the 'downwind' sideof the fuselage. Delays rapidly built up at this exit due to therestricted egress, which caused a fatal crowding of passengersaround the centre section, who were rapidly engulfed in the chokingirritant/toxic gases and smoke.

Many passengers who suddently felt their respiration severelyaffected by the atmosphere decided to climb over seat backs inorder to get to the exit. This was forced upon them by other passengerscollapsing in the aisle as they became debilitated and then incapacitatedby the toxic gases. Some 46% of those survivors who successfullyevacuated from the right overwing exit stated that they had goneover the seats. Many passengers in the forward cabin did likewiseas the smoke quickly flowed forward from the centre section.

As was the case with evacuees queuing at the forward galley restriction,a number of survivors who evacuated out of the right overwingexit nevertheless collapsed temporarily due to smoke and toxic/irritantgas inhalation before recovering sufficiently to get out. Onepassenger stated that the doorway was blocked with peoples' bodieslying half in and half out of the aircraft. The male passengerfrom seat 16C died during evacuation after becoming lodged inthis right overwing exit. It was not possible to positively identifythe mechanism by which he became trapped. However, the failureof the seat 10F hinge-baulk, which allowed the seat back to foldfully forwards, probably under a weight of bodies, may have trappedhis legs against the seat cushion. In addition it is probablethat he had become weakened by the dense smoke atmosphere andwould have been unable to extricate himself. The majority of thebodies (approximately 38) were eventually recovered from the areaaround row 10 (ie rows 8-12).

Clearly survival chances in this accident were significantly reducedfor all who became engulfed in the smoke. Only 47% of those whohad been engulfed in thick smoke survived. Some of these survivorshad to be pulled to safety and many others collapsed before recoveringto escape, their survival being ultimately fortuitous.

2.7.3 Additional effects of the dense smoke atmosphere

As well as the choking and debilitating effects of the smoke manysurvivors spoke of their inability to see. This problem is notsolely a function of the extreme density of the smoke, since researchhas shown that it is also due to chemical effects on the eyes.At Manchester a number of survivors' eyes were seen by rescuepersonnel to be "frosted over", consistent with theanticipated effects of the high concentrations of acid gases insuch atmospheres. Against this background of research and survivorevidence it is difficult to substantiate the rationale behindcurrent regulatory moves towards the introduction of low-level'escape-path' lighting to assist evacuations from smoke filledcabins. Under such circumstances the net safety-gains from sucha requirement are likely to be minimal unless the passengers'eyes are protected.

A survivor from Manchester recalled that the heavy smoke atmosphereappeared to 'blanket' sound within the cabin, an effect that hasbeen confirmed by Fire Service personnel from their general experience.In addition it is also apparent that the effect of such atmospheresis to rapidly suppress any ability of those affected to shout,due to respiratory and acidic gas 'burning' effects on their throats.

These sensory deprivations might be effectively countered by theuse of automatic audio-attraction devices to guide evacuees towardsviable exits. Such systems must be designed to optimise the audiosignal to accomodate any attenuation associated with such atmospheres.

The combined physical and psychological effects of the dense blacksmoke atmosphere on evacuees at Manchester created fear and panicin a manner strikingly similar to that reported in many previousfire accidents.

2.7.4 Thermal effects of the combustion atmosphere

The survival of the 14 year old boy recovered from his positionlying over the body of the male passenger from seat 16C, is significant.His rescue by a fireman about 5¤ minutes after the aircraftstopped, with only superficial burns to his hands, is indicativethat the temperatures within the cabin were not totally unsurvivableat that stage. This observation is reinforced by the survivalfor 6 days of the male passenger from seat 8B who was found inthe forward aisle, between rows 2-3, some 33 minutes after theaircraft stopped, and whose death was due primarily to lung damageand associated pneumonia rather than external burns.

In this context it is also notable that approximately 50% of thenon-fireblocked seats survived the cabin fire, as indeed did manyplastic safety cards and magazines stored in the 'net' pocketson the seat-backs.

Such evidence is in sharp contrast to the fire test results fromthe FAA Technical Centre at Atlantic City which have shown 'flashover'to occur within 2› minutes of fire penetration into a furnishedcabin, with attendant temperatures of 1800°F and a criticalreduction in oxygen levels. It is considered that the major differencebetween that test model and many real accidents is the enhancedventilation which occurs due to multi-door openings, cabin ruptures,roof burn throughs and external wind/fire-convection (chimney)effects within the cabin. These cause 'purging' of the flammablecombustion gases and smoke particulate, thereby delaying or suppressingflashover.

However, the flashover scenario depicted by such tests, an extremesituation, can occur, particularly where cabin ventilation isminimal. This appeared to be the case in the Lockheed L1011 accidentat Riyadh after the engines were shut down and the air conditioningceased, with no doors open.

Only between 6 and 9 of the fatalities at Manchester resultedprimarily from excessive thermal exposure, the remaining 45 diedas a result of incapacitation from carbon monoxide and hydrogencyanide (ie some 83%). It is interesting to note that this resultcompares closely with fatalities from other aircraft fire accidentsand domestic fires where around 80%, on average, die due to smoke/gasinhalation, as opposed to burns.

The evidence from survivors is entirely consistent with the resultsof the pathological examinations and indicated that passengerswere not in general being 'burned to death', but that the majoritywere being rapidly incapacitated as a result of a few breathsof the dense toxic/irritant gas atmosphere.

2.7.5 The interelationship between delay and debilitation

Some of the survivors who were seated close to the forward exitsescaped without experiencing the smoke and without too much difficulty.However, the majority of the survivors were affected by the atmosphereand many were temporarily overcome within the cabin, having sufferedevacuation delays for various reasons. Those who succumbed fatallyto the atmosphere within the cabin are unable to relate what preventedtheir timely escape but it is reasonable to conclude that most,if not all, experienced similar, but more acute evacuation effectsand resulting debilitation/incapacitation effects.

The 25 second delay in opening a forward door, followed by furtherdelays due to the small gap between the forward bulkheads andaccess problems associated with the overwing exit, had a catastrophiceffect on the survivability for some on board G-BGJL.

Any delay in a critical evacuation - ie one where the cabin isthreatened by fire/smoke invasion - is potentially very seriousdue to the attendant debilitation/incapacitation of the evacuatingpassengers. The onset of debilitation increases the delay, whichin turn increases the inhalation of toxics leading to incapacitation/collapseof increasing numbers of passengers, rapidly escalating the problemof egress. This closed loop process can thus lead to stagnationof the evacuation.

Whilst such delays can be minimised by improved design and reliabilityof exits/slides and a more 'evacuation orientated' approach tocabin seating densities and configuration, in real accidents delayswill occur for a variety of both unforeseen and predictable reasons- eg exit doors can jam due to impact-induced distortion, slidesmay be affected by strong winds or fire, etc.

Another situation when evacuation cannot be started immediatelyis when fire/smoke penetrates the cabin before the aircraft stops,as in the case of the accident to the Boeing 727 at Salt LakeCity in 1965.

The most critical examples of this type of imposed delay are,of course, in-flight smoke situations where the cabin is invadedby combustion products and passengers cannot evacuate, but mayonly try to move away from the area of threat.

As delays will always be a threat, for any one or a combinationof many reasons, passengers must be protected from the debilitatingeffects of such atmospheres, being kept conscious and mobile untilsuch time as they can successfully evacuate.

2.7.6 Evacuation certification requirements

The Boeing 737-200 was required to demonstrate an emergency evacuationto the requirements of FAR part 25.803, which applies to all publictransport aircraft with seating capacities greater than 44. (Appendix7)

As stated in paragraph 1.6.8. the UK type certification of the737-200 took place at Luton airport on 26 November 1970, when130 passengers and 5 crew evacuated in only 75 seconds, some 15seconds within the specified 90 second requirement. During thistest, only the left forward, aft and overwing exits were used- in accordance with the requirement that only the emergency exitsand emergency evacuation equipment on one side of the fuselagebe used.

Such certification tests do not explore the effects on evacuationtimes when the exits at one end of a cabin are unavailable andtherefore do not examine:-

i) The effect of twin bulkheads throttling the passenger flow.eg the forward galley bulkheads in G-BGJL;

ii) Increased mean aisle distances to available exits;

iii) Increased importance of the overwing escape routes.

These are clearly major deficiencies.

The regulatory authorities have stated that such tests are notintended to represent a realistic evacuation, but are merely regardedas a 'yardstick' test - ie to compare the evacuation potentialof one aircraft with another.

FAR 25.803 nevertheless requires amongst other things that thedemonstration must be conducted under the following conditions:-

1) It must be conducted either during the dark of night or duringdaylight with the dark of night simulated, utilising only theemergency lighting system.

5) A representative passenger load of persons in normal healthmust be used as follows:-

(i) at least 30% must be female.

(ii) approximately 5% must be over 60 years of age with a proportionatenumber of females.

(iii) At least 5% but no more than 10% must be children under12 years of age, prorated through that age group.

The above requirements conflict with the view that this test wasintended as purely a yardstick comparison and raise questionsas to precisely what such a test is intended to demonstrate. Themain reason for evacuating an aircraft quickly is that associatedwith a potential fire/smoke threat to the passengers. The 90 secondrequirement cannot guarantee that all passengers will have evacuatedthe cabin before it has been penetrated by fire or smoke. Indeed,as soon as smoke invades the cabin this '90 second' criterionceases to have any relevance, ie because this type of certificationdoes not, by intent, address itself to the effects of smoke andtoxic/irritant gases upon evacuating passengers with the attendantbreathing difficulty, loss of vision, induced panic and therefore'irrational' (non-ordered) behaviour - eg egress over seat-backs.

Because of this certification perspective, evacuating passengersin the test are in an ordered 'queuing' situation. The statementsfrom passengers in this accident indicate that such ordered behaviourdid not prevail. Furthermore it is important to appreciate thatthis type of evacuation certification test has strongly influencedthe type of subsidiary testing carried out within the industryto establish evacuation rates from aisles, past obstacles (e.g.bulkheads or seats), towards and through exits. Although suchtests are invariably conducted in clear air conditions, the resultsare used to influence aircraft design when critical evacuationscan occur in conditions of thick smoke with associated lack ofvisibility and disorientation. Quite apart from other considerations,this does not explore the obvious problem of how passengers areexpected to recognise where their exit is located and the factthat some obstacles encountered during an evacuation are readilyaccommodated in visual conditions, but might stagnate the flowof evacuees in smoke.

2.7.7 Evacuation logic

The 90 second requirement does indicate, however, that given aclosely ordered evacuation the egress time can be minimised. Thekey question is how behaviour in a real, critical evacuation canbe influenced to bias it towards optimum ordered egress. The startingpoint here must be to recognise the obvious prime requirementto maintain the evacuating passengers in a conscious, mobile state- for as soon as even a few begin to collapse and block aislesand exits, the egress problems escalate. Secondly, as indicatedin the survivor statements, the onset of breathing problems providesa strong stimulus to escape by whatever means. It is thereforeclear that the assurance of continued respiration for evacuatingpassengers would bias behaviour towards improved order.

With passengers maintained in a conscious, mobile and more orderedstate, the next requirement is that of guidance towards exits.A notable feature of the passenger statements was that whilstthey were in the aisle, they were moved along by the column ofother evacuating passengers. A major problem with this type oftransportation is that if one passenger falls, a critical blockagequickly results. The chances of such occurrences must be reducedif debilitation and incapacitation are not factors.

It is apparent that protection of both the eyes and the respiratorysystem from the effects of the fire atmosphere will contributegreatly towards achieving the kind of ordered evacuation whichthe 90 second test has shown minimises egress time, and whichthe regulatory authorities are seeking to achieve.

2.7.8 The effectiveness of the current fire hardening strategyrelated to the evacuation environment

Some 50% of the passenger seats, which were of the standard nonfire-blocked type, survived the fire at Manchester. By contrast,the cabin wall panelling, and overhead stowage-compartments andceiling panels were completely consumed.

Furthermore, it is evident from the statements of those survivorsfrom the aft cabin that dense black toxic/irritant smoke rapidlyfilled that area without any observations of widespread fire inthe cabin. Only 2 of the survivors who escaped from the rightoverwing exit recall seeing any fire in the aft cabin prior totheir egress. The point which emerges from such testimony is thatthe seats do not appear to have played a significant part in theproduction of the heavy smoke which suddenly engulfed the aftcabin immediately after the aircraft stopped, and yet this smokewas very potent in its debilitating effects. It is thus probablethat the smoke was largely from the external fuel fire, with significantamounts entering through the open R2 door, and the air conditioninggrills located at floor level from the fire which had penetratedthe outer skin adjacent to the aft cargo compartment.

Such evidence indicates that whilst the advent of fire-blockedseats is a positive step towards improved fire resistance in aircraftcabins, it is only one part of the overall problem of aircraftmaterials and associated pooled-fuel fires. It must also be emphasisedthat although the term 'fire-blocker' is used, when such seatsare exposed to the heat flux from a major fuel fire, the blockinglayer of material merely delays the combustion of the seat materials,typically by some 50 seconds. If during this delay the cabin overheadlockers, ceiling and wall panels are burning (due to higher temperaturesat ceiling level), passengers will still be exposed to the associatedcombustion gases in addition to dense particulate smoke.

Such fire-blocked seats are the main outcome thus far of the 'fire-hardening'strategy, which has been the main approach to the problem of aircraftfire. This approach, which is almost solely based on the ignition,flame-spread, and heat release characteristics of materials, tothe exclusion of any regulatory requirements for smoke or toxic/irritantgas emission criteria, cannot, even in the longer term, effecta complete solution to the problem.

Indeed, an example of the inadequacy of the flammability approachemployed in materials certification thus far has been the rangeof flame-retardant materials developed by chlorination of previousmaterials which, when burnt in a real fire, generate even moresmoke and toxic gas than their non fire-hardened equivalents.

The two main findings of the C133 fire test programme3 at theFAA Technical Centre upon which the rationale for the currentflammability approach to materials certification rests are:

"i) There is a correlation between flammability characteristicsand toxic emissions.

ii) The severe hazard from toxic emissions occurs as a resultof flashover in fires involving interior materials. The levelsof toxic gases measured before flashover, or when flashover didnot occur, were below levels estimated to prevent occupant survival.After flashover occupant survival is virtually impossible, regardlessof the level of toxic emission."

In the light of the most recent C133 fire test, which took placeat Atlantic City in 1987, conclusion ii) appears incorrect. Aconcentration of some 200 ppm of hydrogen cyanide was detectedbefore flashover, -sufficient to induce rapid incapacitation anddeath. In addition this finding would appear to undermine statementi).

Statement ii) also overlooks the evidence from previous fire relatedaccidents such as the Denver DC8, Salt Lake City Boeing 727, VarigBoeing 707, Cincinnati DC9 and others. Such a view is also incomplete conflict with the results of the pathology and the evidencefrom survivors at Manchester. The clear message from all theseaccidents has been that the smoke and toxic/irritant gases whichengulf the cabin, producing debilitation/incapacitation effects,were being generated without flashover having taken place.

It is therefore concluded that the FAA was correct in its attemptsto add smoke and toxic gas emission criteria to their existingmaterials certification requirements in 1974/5. Although theirlatest ' Improved Flammability Test Standards for Cabin InteriorMaterials' as required by FAR amendments, FAR parts 25-61 and121-189; and CAA Airworthiness Notice No 61 (16 March 1987), representan improved flammability certification test, they neverthelessfall short of addressing the total problem of smoke and toxicgas emission.

The radiant heat flux from the OSU radiant apparatus, used forthe revised certification, is 3.5 watts/square cm. Whilst thislevel of radiant heat flux is a vast improvement on the simplebunsen burner flame test, when it is compared against a typicalheat flux from a pooled-fuel fire of 20 watts/square cm, it maybe seen that it does not approach the realistic conditions encounteredin such situations.

In view of the foregoing it may be seen that materials which meetthis latest test standard, based purely on flammability and heatrelease criteria, will nevertheless still continue to burn whensubjected to the high radiant heat flux from a kerosene pooled-fuelfire and will, consequently, produce smoke and toxic irritantgases. Since this test does not check such emissions, the associatedgases, their concentrations and effects will be subject to nolimitation.

Against this background, the second discussion document issuedby the FAA in July 1986, which requested further comments relatingto their ' Improved Flammability Standards for Materials Usedin Interiors of Transport Airplane Cabins', is notable. In reponseto requests for assurance that no further rule making with respectto smoke and toxicity was anticipated in the forseeable future,the FAA replied:-

"Based on the information currently available, the FAA hasno plans to establish standards for either smoke or toxicity."

The position of the regulatory bodies, as it appears in the requirementsconcerning these issues, contrasts with that of many manufacturers,including Boeing, McDonnell Douglas, and European Airbus Industries,whose materials specifications do include, in addition to flammabilitycriteria, smoke and toxicity limitations. However, the associatedradiant heat flux used within such specifications is still lowat 2.5 watts/square cm. The Airbus Industries ATS 1000 specificationis regarded by British Airways as the best specification presentlyavailable world wide, and they have operated to it for the last5 years.

Even if substantially improved materials were available whichcould withstand the heat flux from a kerosene pooled-fuel fire,the cost of retro-fitting current aircraft worldwide would ensurethat the majority of aircraft flying would not be so equippedbefore the turn of the century. Furthermore, even if a stage werereached where substantially improved materials were generallyin use, the problem would not have been completely solved; egwhere a kerosene fuel fire break-through had occurred into a cabin,either due to burn through (as at Manchester) or due to cabinrupture, passengers would still be engulfed in dense kerosenesmoke, albeit with less toxic/irritant effects, but neverthelesscapable of disabling evacuees, as occurred at Denver in 1961.It should be borne in mind that passenger baggage in cargo compartmentswould also generate these toxic/irritant gases. Thus, whilst itis desirable that materials improvements are accelerated withconsequent expansion of the escape-time window, before temperaturesexceed human tolerance, the 'fire-hardening' approach is complexand essentially a long term strategy because of the inherent difficultiesassociated with materials development, evaluation and cost ofthe introduction of new materials into service.

One of the major problems caused by the current over-emphasisof the 'fire-hardening' approach to the problem of aircraft fire,has been its depressive effect on other means of combating thisproblem. Other solutions which appear to be more direct and maybe applicable in the near to medium term are available. Theseother solutions include passenger smoke protection, water sprayand related fire suppressant systems.

This accident highlights the fact that passengers are requiredto self evacuate, essentially unaided as quickly as possible whenthe cabin environment is becoming very hostile. Clearly the passengersmust be provided with a survivable environment for as long asit takes to escape. This can be done by providing each passengerwith his own mobile environment and/or by influencing the cabinenvironment as a whole. Whatever the approach, the strategy mustprovide for both the in-flight and ground fire situations.

2.7.9 The case for passenger smokehood protection

Passenger smokehood protection has been advocated repeatedly byvarious highly respected aviation bodies over the last 20 years,usually in the wake of a major aircraft accident which had, onceagain, illustrated the major effect of smoke and toxic/irritantgas incapacitation upon survivability.

The FAA proposed a requirement for passenger smokehood protectionon passenger transport aircraft in the associated NPRM issuedon 11 January 1969. This was withdrawn on 11 August 1970 due totechnical objections raised by the aviation industry.

The US National Research Council then issued a comprehensive reporton smokehoods, recommending further smokehood development.

In June 1980, the FAA Technical Centre at Atlantic City, requestedthe FAA, CAMI to re-examine passenger smokehood protection. Thisrequest was prompted by findings from the SAFER Committee TechnicalGroup which had highlighted the survival suppression effects ofsmoke and toxic gases on evacuating passengers, and the limitedprogress which had been achieved in the reduction of cabin firehazards.

In 1983, as a result of their investigation into the in-flightfire and emergency landing accident to the Air Canada DC9 at Cincinnation 2 June 1983, in which 23 of the 41 passengers died before theycould evacuate the cabin, and survivors had breathed through handtowels, the NTSB issued Safety Recommendation A-83-76 on 31 October1983. This recommended the FAA to accelerate research into passengersmoke protection at CAMI.

A comprehensive FAA report 10, published in July 1982, examinedall the applicable approaches which could be utilised to combataircraft fires and their effects. This report also included avery detailed cost benefit analysis of these concepts. This analysisindicated that passenger smokehoods were by far the most cost-effectiveapproach and would achieve the greatest improvement in survivability,with the lowest cost per death prevented. It estimated that passengersmokehoods would cost $140,326 per death prevented, compared to$1,154,720 per death prevented for a zoned water spray concept,which would give almost the same improvement in survivability.(Appendix 17) This report also concluded that passenger smokehoodprotection could be implemented in the near term.

The passenger smokehood approach to survivability in aircraftfire situations has the following benefits:-

1. It is the most cost-effective solution to the problem of passengersurvivability in aircraft fires, according to the above FAA report.

2. It can be implemented in the near term.

3. It will protect passengers respiratory systems and therebymaintain consciousness and mobility, without which passengersare not able to successfully evacuate aircraft in critical smoke/toxicgas conditions.

4. Smokehoods would reduce the level of 'panic' during a criticalevacuation, which is triggered frequently by the sudden envelopmentof passengers in dense black smoke and toxic/irritant gasses.This should bias the situation towards improved order, and thereis little doubt that the closely ordered evacuation is the mostefficient way to achieve minimum egress times, as demonstratedin the '90 second' evacuation certification test.

5. Smokehoods would protect the eyes from the irritant gas effectswhich cause blinding due to lachrymation and soot deposition.This would enable passengers to make full use of the proposedlow level escape-path lighting, the benefits of which will beseverely limited without such eye-protection.

6. The provision of smokehoods for cabin crew has already beenagreed by the FAA and CAA. Such smoke protection is primarilyintended to protect cabin crew whilst they are attempting to extinguisha cabin fire. There can be no guarantee that such attempts willalways be successful, particularly where the fire source is remote,ie behind panelling or within a cargo compartment. In such situationswhere the fire cannot be extinguished, the provision of smokehoodprotection for crew members only is illogical and may introducecompetitive behaviour, with critical disorder on board the aircraft.The additional provision of passenger smokehoods is thus clearlyrequired under such conditions, if disorder is to be avoided.

2.7.10 The AAIB passenger smokehood trials:

These trials were originally directed towards the evaluation ofsmokehoods for passenger protection in a ground fire situation,such as occurred at Manchester. A target endurance of 5 minutesprotection was thus chosen to afford sufficient time to evacuatein critical conditions. Tests were carried out on smokehoods whichwere already in quantity production and on prototype smokehoods,some of which had been in development before this accident. Onesmokehood was designed and developed in response to the AAIB tests.

The performance demonstrated by some of these lightweight hoodsduring tests in 1986 indicated that the original 5 minutes protectiontarget could readily be exceeded. It was apparent that such protectioncould be extended to combat in-flight incapacitation of passengers,where fire had occurred in the air.

Nevertheless, the postulation of a 20 minute endurance for passengersmokehood protection in the first CAA draft specification issuedin July 1986 represented a formidable challenge to the manufacturers.The scale of this new proposal was particularly striking whencompared to that proposed (and later required) by the CAA andFAA for cabin crew smokehood protection - ie that of 15 minutesprotection, from units which weighed some 3-4 lbs, compared tothe 1 lb target weight for passenger smokehoods. The reason givenfor the disparity in protection endurance was that the passengerswould require an extra 5 minutes protection for the purposes ofground evacuation, whereas the cabin crew would not require thisadditional protection, since they would be positioned at the exits.The evidence from the surviving cabin crew at Manchester, andindeed other accidents, indicates quite clearly that cabin crewdo require protection under such conditions.

The results of the AAIB trials programme have demonstrated thatbreathable gas smokehoods designed for passenger use, can achieve(and in the case of one particular type greatly exceed) the 20minute endurance required by the CAA Draft 'Type 1' specification,even at the current stage of development. Indeed, two such smokehoodscompletely out-performed an existing cabin crew hood, manufacturedto French specifications and which weighed 3 lbs. This clearlydemonstrates the potential available within such lightweight smokeprotection, developed since the Manchester accident.

In addition, two filter-type smokehoods demonstrated that theycould successfully filter-out smoke particulate and toxic/irritantgases such as hydrogen cyanide, carbon monoxide, hydrogen fluoride,hydrogen chloride, nitrogen dioxide, sulphur dioxide, ammonia,acrolein in addition to benzene, toluene, styrene, acetaldehydeetc. Inhaled gas temperatures can be maintained within acceptablelimits. Even without carbon dioxide absorbers, the concentrationof carbon dioxide can be maintained within reasonable limits,if the challenge concentration does not rise above 4%. An interestingfinding from the AAIB tests on filters is that frequently a smallincrease in oxygen concentration (approximately 1%) occurred downstreamof the filter, due to removal of the other gases. With regardto the concentration of oxygen and carbon dioxide in aircraftfires, it is notable that the C133 results from the FAA TechnicalCentre indicate that the oxygen remained at 21% while temperatureswere still survivable, and the carbon dioxide concentration wasnegligible.

Filters have achieved an endurance of up to 10 minutes duringexposure to the AAIB challenge atmosphere. This additional endurancecapacity, above that required for ground evacuation, may be consideredwith respect to in-flight protection. The anticipated workloadfor the in-flight case would result in a respiration rate substantiallylower than the 30 litres/minute used in these filter tests, dueto passengers being in an essentially sedentary state. If a respiratoryrate of 10 litres/minute is assumed to apply in-flight, then thiswould increase the effective endurance of such a filter by a factorof 3. The overall endurance of filtered protection would thusbe equivalent to 15 minutes (in-flight) + 5 minutes (ground evacuation).

In addition, the CAA have indicated in their latest draft specification,that they would accept the assumption of an average in-flightchallenge concentration of smoke and gases of 25% of that applicableto the ground fire situation. This factor would also extend thepotential endurance of filter protection, which is generally limitedby smoke particulate densities, as opposed to gas filtration limitations.Indeed the AAIB tests demonstrated that filters, based on theHopcalite catalyst, can successfully block carbon monoxide forperiods of up to 30 minutes.

These tests have thus demonstrated that low weight smokehoodscan be made available for passenger protection, with endurancesof 20 minutes.

In addition, recent developments by some of these smokehood manufacturers,using potassium 'superoxide' units, has produced cabin crew hoodswith greatly increased breathing capacity and endurance. Developmentwork has also started with the aim of producing lightweight unitsof this type, for passenger use.

Whilst smokehoods cannot protect some of the passengers threatenedby direct thermal assault, thermal injuries are responsible typicallyfor about 20% of fatalities only; the remaining 80% stand to reapgreat benefit from the use of smokehoods, and their provisionon all public transport passenger flights is urgently recommended.

2.7.11 Water spray systems

Work on water mist systems to date indicates that they may havethe potential to rapidly and dramatically improve the environmentwithin the whole passenger cabin by reducing the temperature and'scrubbing' the particulate and soluble gases from the atmosphere.However, water sprays are not initially envisaged for use in thein-flight fire case and even if they become so, until their efficiencyin dealing with the toxic and irritant gases has been fully examinedthere is a need for a twin strategy.

2.7.12 The 'Twin strategy' of passenger smokehoods/cabin waterspray

The AAIB passenger smokehood trials have demonstrated that thetechnology is currently available to provide passenger smoke protection.

Cabin water spray systems have been examined by the FAA in thepast, and are currently being re-assessed by the CAA. There islittle doubt that such systems would provide a very effectivemeans of delaying/preventing fire ingress into an aircraft cabinor suppressing/extinguishing a cabin fire, increasing the timeavailable for passengers to evacuate. However, the relative costof retrofitting current aircraft in service raises questions concerninghow long it would take, even given a regulatory decision to adoptsuch an approach, for aircraft generally to be so equipped.

In addition, at present such systems are proposed for ground useonly. Passengers would still require smokehood protection againstan in-flight smoke situation, until such time as the aircraftcould carry out an emergency landing.

It is clearly important that the possibility of using such waterspray systems in-flight is examined. Whilst the problems of waterinteraction with the aircraft's electrical systems (which increasinglyplay a major role in flying-control systems) may be overcome,a major question remains over the ability of such systems to guaranteerapid extinguishing of an in-flight fire. Such a fire may be remotefrom the cabin, within an electrical equipment bay, cargo compartmentor behind panelling. In addition, if such systems are adopted,they will be severely restricted in the quantities of water available.It would thus appear prudent to also provide passenger smokehoodprotection, to give an added measure of safety for use where anin-flight fire is not immediately suppressed.

Furthermore, the additional cost of such smokehood protectionwould be very modest, in comparison with that associated withthe water spray system.

It is thus considered that the early adoption of passenger smokehoodprotection, followed by the introduction of such cabin water spraysystems, would combine to form a 'twin-strategy' which would greatlyincrease survivability in aircraft fires, be they in-flight oron the ground.

2.8 Firefighting and Rescue

In the course of the following analysis, it might appear thatcriticism is being levelled at rescue personnel; this is not theintention. It is fully recognised that it is one thing to analyseevents in the cold light of hindsight, but quite another to haveto deal with such events in practice. It is quite clear that theindividuals involved did their utmost under extremely hazardous,rapidly changing and stressful conditions. In particular, theindividual efforts to effect an early entry into the forward cabinand to help people trapped in the overwing area were extremelycourageous and contributed directly to the saving of lives. However,it is only from an objective look at such real emergencies thattechniques and equipment can be improved.

2.8.1 Initial response

The response of the MIAFS was commendably fast, resulting in thefirst firefighting vehicle arriving at the scene approximately25 seconds after the aircraft stopped, rapidly followed by theother available appliances. This was a much faster reponse thancould reasonably be assumed for the purpose of emergency planning(the regulations allow up to 3 minutes for the attendance of thefirst vehicle at an airport incident/accident).

The immediate deployment to recover the second 'jumbo' major foamtender (J2) from the hanger, where it was undergoing re-painting,made this vehicle available in time to contribute significantlyto the firefighting effort. Some aspects of the RFF service deploymentwere less helpful however, notably the deployment of the firestation ambulance to rendezvous with the GMC Fire Service. Thisvehicle's absence deprived the scene of a medical 'command post',which could have provided a focal point for those involved withhelping survivors, thereby reducing the confusion which developedover where they should be assembled. In addition, the ambulancewent to the wrong RVP and so did not fulfill the escort task either.The emergency orders current at the time required the ambulanceto attend the scene of the incident/accident, the airport policeproviding the escort.

The response of the GMC Fire Service was also commendably fast,but their efforts were frustrated by a series of communicationsblunders which, on the day, resulted in the Airport Police escortgoing to the West RVP while they waited at the North RVP. Theresulting 3 minute delay in the attendance of the GMC water tendersoccurred at a time when the officer in charge at the scene hadrecalled his breathing apparatus team from the cabin because ofconcern over diminishing water supplies. However, although thisdelay may potentially have cost lives, on this occasion it probablydid not significantly compromise the rescue effort. The rapidlydeteriorating conditions in the cabin were, by that stage, alreadylimiting access anyway, and would by then have probably causedfatal injury to those passengers still on board. Nevertheless,the possibility that the delay directly contributed to loss oflife cannot be discounted entirely and the communications breakdownwhich caused it is a matter for serious concern.

2.8.2 Fighting the external fire

The conventional firefighting and rescue techniques adopted byRFF agencies in the UK (and elsewhere) relied upon the speed ofresponse of the RIVs to provide 'first aid cover', pending arrivalof the larger foam tenders. The tasks of the RIVs were to providea quick knockdown of incipient or early stage fire, and to protectexit paths if passengers were already evacuating. Upon their arrival,at least one of the major foam tenders would normally adopt theposition on the nose so as to be in a position to deploy foamalong the length of the fuselage on the side affected, or likelyto be affected, by the fire. The remaining vehicles would be deployedin tackling the fire in whatever manner was most appropriate inthe particular circumstances, with the major emphasis being laidon the protection of passengers and the maintenance of escapepaths, rather than extinguishment of the fire as such.

The crew of the first RIV to arrive (RIV2) appear to have quicklyidentified the left engine area as the source of the fire, andpositioned themselves well, both to attack the main pooled-fuelfire in that area and to cover the left side exits. Having knockedback the fire in the left engine area, this vehicle was repositionedto address more effectively the fire which could then be seenattacking the rear fuselage. It is not clear whether the runningfuel fire was extinguished fully at that time. After running outof media, the vehicle was moved clear of the aircraft so as notto impede access by others. With the exception of J1, which waslater manoeuvred off the left side to deal with the resurgenceof fire under the left engine, this was the only vehicle usedto actively address the fire at its source; all other vehiclecrews appear to have adopted a tactic of general coverage of thefuselage and exits, mainly on the right side.

Whilst it is apparent that the actions of all crews fell broadlywithin the bounds of conventional practice, some aspects wereless than ideal. In particular RIV1 - the second vehicle to arrive- adopted the position on the nose normally taken by a major tender,forcing J1 to take up a position further off the nose. Furthermore,it was left in this position throughout the proceedings, evenafter its media had been exhausted, impeding J1 during its manoeuvreinto a new position on the left side. Although it was not obstructed,the Protector foam tender also positioned too far away initially,and needed to be re-positioned twice during its period of activeoperation.

The apron fire vehicle, despite a prompt attendance, was not usedin the firefighting effort - probably because it did not havea foam monitor and was therefore parked some distance away, possiblytoo far away for its presence to be noted by those directly involvedin tackling the fire. This vehicle carried 100 kgs of Monnex powder,which is an agent specifically intended for use on '3 dimensional'fires. In all probability, this could have been used to good effectduring the attempts to extinguish the intractable running fuelfire which flared up (or re-ignited) after the initial foamingoperations had ceased. The absence of any training in the useof Monnex powder during the 3 months prior to the accident mayhave been significant, in that the personnel involved would havebeen less aware of its potential value than they might otherwisehave been, and therefore less likely to actively seek it out.

With the above exceptions, which probably did not have a greatimpact on the overall outcome, the firefighting and rescue effortwas about as effective as conventional techniques would allow;it is less certain whether such a 'conventional' approach is themost effective one for dealing with fires of this type.

2.8.3 Fighting the internal fire

RFF services in general were not, and indeed still are not, equippedto tackle internal fires effectively. This fact was distressinglyapparent at Manchester where, having achieved a good measure ofcontrol over the external fire, to a large extent rescuers hadto suffer the trauma of becoming impotent spectators to the deathsof those still inside.

Although entry was made into the cabin at the earliest opportunity,some 7 minutes into the fire, the internal fire was by that stagetoo severe to permit effective rescue or firefighting attemptsto be mounted; the hazard involved was all too evident when thefireman was blown out of the door by an internal explosion andthe roof was seen 'rippling'.

The cause of the explosion which blew the fireman out of the forwarddoor could not be positively identified. However, the ruptureof an aerosol-can as a result of heat induced overpressure andthe explosive ignition of the propellent gas (typically butane)so released, or the rupture of a therapeutic oxygen cylinder areconsidered to be possible candidates. The aircraft's in-builtoxygen system played no part in the fire but the discharge ofthe remainder of the therapeutic oxygen cylinders, clearly representeda very considerable hazard to firefighting personnel. Althoughtheir precise role in this fire could not be identified, the presenceof duty-free spirits in the cabin undoubtedly presented an additionalhazard for both passengers and rescue personnel.

2.8.4 Water shortage

The delay in obtaining water from the hydrant system occurredjust before the arrival of the GMC water tenders, but becauseof the time required for the foam tender to re-fill from a hydrant,some 15 to 18 minutes, the problems with the hydrant probablydid not have any detrimental effect on the outcome so far as theavailability of water to fight the fire was concerned. However,two RFF personnel spent long periods away from the scene becauseof the initial abortive attempt to find water and then the timetaken to fill a major appliance.

2.8.5 Communications

It is evident that poor communications were a major handicap throughoutthe period of firefighting activity. In particular, there wasno means for the officer in charge to contact RFF personnel outsidehis immediate vicinity, preventing him from re-directing resourcesto provide a more unified effort should he have considered thatnecessary, and no means for him to obtain feedback on the progressof, or to process requests from, individual teams. This was illustratedgraphically by the variety of individual instructions issued andactions taken during attempts to obtain water from the hydrants,all of which were carried out in isolation and without the individualsconcerned being aware of the actions of others.

It is considered that the lack of a helmet mounted communicationssystem is a serious handicap which limits the potential effectivenssof both the aerodrome RFF services and the local authority fireservices which attend. It is considered necessary that a requirementfor suitable communication systems be introduced as part of thelicencing requirements for all major airports, and that theserequirements include provision for communication on the same systemby (at least) the officer in charge of any local authority fireservice having standing arrangements to attend aircraft emergenciesat such aerodromes. It is further considered necessary that therecruitment and training of airport fire officers be amended tofacilitate a more command orientated approach.

The difficulty experienced by the GMC fire service in identifyingthe officer in charge of the MIAFS at the scene demonstrates theneed for this officer to be visually distinctive. It is recommendedthat some form of high visibility clothing be worn by the officerin charge at any incident/accident scene.

2.8.6 Firefighting tactics

The belief that a 'prompt, mass application of foam' is all thatis needed from RFF crews is clearly a fallacy; this fire involvedless than 700 gallons of fuel, foaming began much more promptlythan one could reasonably have expected and the quantities ofmedia even met the requirements for much larger wide bodied aircraft,yet the fire burned out of control. Clearly, the whole approachto aircraft firefighting was called into question by this accident.

The present training of RFF personnel depends heavily on the developmentof each individual's skill, thus equipping him to assess the besttactics to adopt under widely differing conditions. This is aproper approach to adopt given the many permutations of circumstanceswhich can arise. There is, for example, no way of allocating specificcrews or vehicles to particular tasks or locations since the vehiclearrival sequence cannot be predicted and the requirements of onefire will be quite different from those of another. In all caseshowever, the fundamental requirement is to get the initial firefightingeffort under way with a minimum of delay, and to this end, theexisting approach is probably as good as one can practicably achieve.However, the initial positions and tactics adopted will of necessitybe a first guess at the requirements of the task; subsequently,the firefighting effort must be flexible enough to permit re-directionof resources, whilst continuing to provide a unified and co-ordinatedattack, if its full potential is to be realised.

During the period of active foaming, individual RFF personnelwill be occupied with their own firefighting tasks and cannotbe expected to look to the overall requirements of the operation,neither would it be desirable for them to do so since to act individuallycould lead to an unco-ordinated and confused firefighting effort.The co-ordination and direction of the firefighting operationis a management role, which must be the responsibility of theofficer in charge. No suggestion is being made that such a rolewould be an easy one, particularly in view of the difficultiesin achieving rapid access, or a good 'vantage point' from whichto make an assessment of priorities. However, difficult thoughit may be, the requirement to actively manage resources is bornof the need for a more effective solution to the firefightingproblem.

At the present time, the lack of helmet mounted radios seriouslyhandicaps the effective management of the firefighting resources.Arguably, the running fuel fire which caused such difficulty atManchester might have been addressed more effectively had thosedirectly involved in dealing with it been able to communicatemore effectively.

Currently, fire crews can only fight an internal fire by makingan entry into the cabin in breathing apparatus and deploying branchlines to attack the fire directly, and the policy is to commitfire crews to the inside of the aircraft at the earliest opportunity.However, committing firemen into the cabin during the period whenpassengers are self-evacuating could clearly lead to conflictbetween passengers trying to get out and firemen trying to getin. In an incident such as this one the approach should be toeffectively suppress any fire which is affecting means of escapewhich are not in use , so as to bring them into use or effectan entry via these into the aircraft.

Immediately fire takes hold inside the cabin, the 'knock down'effect of toxic combustion products will result in a majorityof those still inside, if left unprotected, rapidly losing consciousness.At this stage there will be an abrupt transition from a relativelyordered evacuation of mobile, uninjured passengers - whose interestsare best served by allowing them to continue evacuating withouthindrance - to a rapidly deteriorating evacuation process in whichpanic rules and people collapse, impeding the progress of fellowpassengers and blocking exits. Once this transition has occurred,it is crucial that rescuers effect immediate entry to recoverthose who have lost consciousness.

Although a number of alternative methods of fighting internalfires have been examined in the past, and some, including theuse of 'harpoons' or 'lances' to penetrate the hull and delivermedia into the interior, have been used operationally, none hasbeen introduced for general use on passenger aircraft fires. Itmust be concluded that current aerodrome firefighting policy makesno realistic provision for dealing with internal fires and, equallyimportant, there is no licencing requirement for them to be ableto do so.

Some form of automatic or semi-automatic fire fighting system,built into the passenger cabin, is essential if internal fireis to be tackled early enough to limit its development effectively.This requirement has long been acknowledged within the aircraftfire research community and a number of theoretical and practicalstudies have been undertaken to assess systems using both waterand alternative extinguishing agents. Of the alternative agents,the halons appeared initially to offer a good performance, butwere later found to have serious deficiencies when used in a cabinenvironment; principally the production of extremely toxic decompositionproducts if extinguishment was incomplete. It was also found thatin winds exceeding 2 mph, halon agents tended to become dispersedto the point where they became ineffective. Work on water dischargesystems has shown that spray nozzles designed to provide a controlledmist coverage have great potential to extinguish fire, reducetemperatures within the cabin and to 'scrub' the atmosphere.

It is considered important that on-board extinguishing systems,designed to limit and extinguish internal fires, should be developedas a matter of urgency. On the evidence available to date, watermist/spray systems appear to offer the most viable solution. Inparticular, a water based system has the potential to operatein two modes; an independent mode using existing on-board waterto enable an attack to be made before, or as breakthrough occurs,and a tender-supplied mode using water from firefighting vehiclesconnected to valves at the aircraft's extremities. Such a dualmode operation is seen as an essential attribute if the systemis to realise its full potential.

Because of the problems of survivors collapsing in and aroundexits, particularly the overwings, and the evident problems thiscreates, it is desirable that where possible, RFF personnel inbreathing apparatus should be positioned by overwing and otherexits at the earliest opportunity to assist those evacuating andto help keep the exits clear. This would require the airport fireservice to be equipped with additional breathing apparatus andall fire fighting personnel to be trained in its use.

3. CONCLUSIONS

(a) Findings

The flight deck crew

1 The flight deck crew were properly licenced, trained, experiencedand rested to undertake the flight.

2. The flight deck crew discussed defect and rectification entriesin the technical log relating to the performance of the left engine;they monitored it closely during start-up and acceleration totake-off power and were satisfied with its performance.

3 The flight deck crew responded to the 'thud', later to be identifiedas an engine failure, in a prompt manner in accordance with theirexperience and training.

4 The first indication to the flight deck crew of fire, a leftengine fire warning, occurred 9 seconds after the 'thud', at atime of extremely high workload. The commander had no direct meansof assessing the extent of the fire and sought advice from airtraffic control on the need for passenger evacuation.

5 The decision to turn the aircraft to the right into link Delta,given the sequence and timing of the information available tothe commander, in particular the initial lack of a fire warning,was understandable.

6 Turning the aircraft to the right had a critical effect on thefire, placing it upwind of the fuselage.

7 The aircraft was turning off the runway when the commander saidover the public address system "evacuate on the starboardside please", intending the cabin crew to prepare in anticipationof the imminent full stop.

8 The left engine fire drill was actioned immediately the aircraftstopped and the right engine then shut down.

9 The Passenger Evacuation (Land) Drill was inappropriate forsuch an emergency and has since been modified. However, the evacuationwas not delayed as a result.

10 The commander and co-pilot evacuated the aircraft via the flightdeck right sliding window because of the fire on the left sideof the aircraft.

The cabin crew

11 Each member of the cabin crew was properly trained and qualifiedto operate at any station within the cabin.

12 The two most experienced cabin crew members were seated inthe forward cabin leaving two relatively inexperienced stewardessesat the rear. However, it is unlikely to have significantly influencedthe outcome in this instance.

13 The forward cabin crew seats were positioned such that, whenseated, the crew members had a restricted view of the passengercabin.

14 On failure of the left engine the public address volume automaticallyswitched to the lower level.

15 One of the rear stewardesses opened the right rear door asthe aircraft turned off the runway, either as a rapid responseto the commander's evacuation instruction or as a direct reponseto the deteriorating conditions in the aft cabin.

16 The motion of the right forward door as it was rapidly openedby the purser, exposed a design fault associated with the slidebox lid release lanyard, causing the door to jam in the aperture.

17 The purser showed initiative under pressure in opening theleft forward door and then returning to the right forward doorand clearing the jam.

18 The forward stewardess had to pull passengers free who hadbecome wedged in the forward aisle at the galley restriction tostart the flow of evacuees.

19 The forward cabin crew members remained on board until theywere on the point of being overcome by the smoke themselves. Anumber of survivors owe their lives to their direct actions.

20 The two stewardesses in the rear cabin were faced with an impossiblesituation. However, the little evidence that there was indicatedthat they carried out their duties to the best of their abilityuntil they succumbed to the rapidly deteriorating conditions.

21 The cabin interphone was not used throughout the emergency.

22 Some of the emergency equipment for use by the cabin crew,including two loud hailers, was in overhead bins in the passengercabin, not at the cabin crew stations. In an emergency evacuationthe cabin crew may find it impossible to reach this equipmentas passengers move towards the exits.

The left engine

23 The aircraft had a valid Certificate of Airworthiness in theTransport Category (passenger) and had been maintained in accordancewith an approved schedule.

24 The left engine failure was caused by an explosive ruptureof the combustion chamber outer case. The rupture immediatelycaused the engine to run down.

25 The instantaneous release of high pressure air from the combustionchamber outer case caused the forward (dome) part of the disruptedNo 9 combustor can to fracture its locating pin and be ejectedradially from the engine.

26 The combustion chamber outer case rupture was caused by localisedoverheating in the area adjacent to the No 9 combustor can whichcaused a reduction in material strength over a critical lengthof the casing.

27 Overheating of the combustion chamber outer case occurred dueto a 360° separation of the No 9 combustor can in the 3/4liner joint area which allowed hot combustion gases to escapefrom the can and impinge upon the inner surface of the combustionchamber outer case.

28 Post-separation mechanical and thermal damage prevented fullanalysis of the precise nature of the 360° fracture. Theavailable evidence, however, suggested that previously crackedand repaired areas of the circumference and a further area withoutvisible cracking at the time of repair, had cracked first frommultiple origins typical of a thermal fatigue mechanism. The natureof the fracture linking these areas suggested that a mechanicalmode of fatigue had been present, but still with some evidenceof multiple origins.

29 Multiple embryonic thermal fatigue origins would not be detectableby normal inspection techniques employed during overhaul and repair.

30 The can had been inspected and circumferential cracking of180 mm combined length in the 3/4 liner joint area had been repairedin November 1983 after 7,482 hours/3,371 cycles time since new.It then ran a further 4,611 hours/2,036 cycles until it failed.

31 The repair carried out in 1983 used the direct fusion weldmethod described in the British Airways Engine Overhaul Manual.Solution heat treatment and optional post-weld stress relief,which formed part of the repair procedure in the Pratt and WhitneyEngine Manual at that time, were not carried out.

32 Omission of the above two heat treatments and a further processknown as 'braze/reinforcement' was permissible in accordance withthe approval granted to British Airways/British Airways EngineOverhaul Ltd by the Civil Aviation Authority.

33 Conflicting evidence was presented on the effectiveness ofsolution heat treatment, but on balance it is considered thatit would not have had a significant effect on the fatigue lifeof the can. It was accepted, however, that its inclusion wouldhave facilitated weld repair of the can.

34 The Pratt and Whitney Engine Manual did not preclude directfusion weld repair of a circumferential crack of any length. Localareas of "severe distortion and oxidation" were notpermitted to be weld repaired.

35 A 3 inch circumferential crack length limit had existed inthe Engine Manual prior to 1977 at which time it was removed byPratt and Whitney. British Airways were unaware of this pre-existinglimit, starting operation of the JT8D in 1980.

36 A small area of parallel cracking, possibly associated withthermally distressed material, was present on liner 3 of can No9 prior to repair and was addressed by fusion weld repair. Theprecise nature and appearance of this area at that time is notknown.

37 The repair failed to impart sufficient residual life to thecan to enable it to remain in service until the next scheduledinspection.

38 No abnormalities or other defects were found within the engineor its accessories which could have precipitated the early failureof No 9 can.

39 The manufacturer had advised operators that direct fusion weldrepaired cans have lower fatigue lives than ones repaired usingmaterial replacement techniques but had not quantified this reduction.British Airways interpreted this as applicable to cans with amuch greater time-in-service than any they operated at the time.

40 Whilst direct fusion weld repair appears to have proved a worthwhilemethod for many operators, some did not employ this techniquefor circumferential cracks. A large proportion of operators whodid had self-imposed circumferential crack length limits in theregion of 3 inches.

41 A fleet survey of British Airways engines resulting from theEmergency Airworthiness Directive after the accident to G-BGJL,revealed that weld repair of circumferential cracks was providinglittle, if any, recovery of can life. Had this accident not occurredBritish Airways would not have been aware of this until the nextscheduled inspection of a repaired can, or if earlier, until someincident of can distress had been detected.

42 The can life reduction resulting from the possible repair ofa localised hot-spot, and the ommision of one required and oneoptional heat treatment process, could not be quantified. However,the abnormally long circumferential cracking which existed incan No 9 prior to repair was an easily detectible and quantifiableindication that the can had suffered abnormal thermal fatiguedamage during first run.

43 Since the method of direct fusion weld repair addresses onlythe visibly cracked areas and not embryonic fatigue damage inthe remainder of the can, the residual life of a can repairedby this method remains an unknown quantity compared with the demonstratedperformance of new cans.

44 Material or complete can replacement techniques theoreticallyrepresent the only satisfactory way to ensure complete life recoveryin vulnerable areas. Some airlines which employ direct fusionweld repair of circumferential cracks would appear, however, tohave demonstrated satisfactory performance within their patternof operations and inspection programmes.

45 British Airways regarded the JT8D as a well proven and developedengine which they were operating well behind the lead operators.Whilst this was true, certain areas, including combustor can durability,continued to cause problems and were the subject of continuingdevelopment by the manufacturer.

46 After the accident to G-BGJL, the CAA and FAA issued mandatorydirectives requiring operators to perform inspections on theirJT8D engines at intervals designed to detect circumferential combustorcan cracking at an early stage before it could develop into afull 360° separation.

47 Inadequate exchange of information between operator and manufacturerled to under-reaction by the operator to previous similar incidents,which were notified to them through the medium of advisory communications.The content of these communications gave insufficient informationto enable the operator to make accurate judgements regarding theirsubsequent course of action and the operator did not seek clarification.

48 The Pratt and Whitney Maintenance Manual gave no guidance fortrouble shooting an engine with low idle RPM. British Airwaysregarded low idle as the prime reason for the slow accelerationof the No 1 engine, also reported by the crew on 21 August. Noneof the Pratt and Whitney communications referred to low idle asa symptom of a disrupted can.

49 The action taken by British Airways to address the low idleRPM pilot report on the 21 August involved adjustment of the engineidle trim without performing a part power trim run, contrary tothe Pratt and Whitney and Boeing Maintenance Manuals.

50 It appears unlikely that a part power trim run on the 21 Augustwould have revealed distress to the No 9 combustor can. However,application of low idle/slow acceleration trouble-shooting proceduresemployed by the operator over a period of time had the potentialto impair accurate fault diagnosis.

51 Routine trend analysis of the flight recorder data from G-BGJLwould not have provided warning of the impending failure of No9 combustor can. Although such trend analysis, given that thenecessary parameters are recorded, can indicate severe combustioncan distress it cannot be relied upon to do so in every case.

52 The left engine thrust reverser deployed on selection but fallingoil pressure accompanying the engine run down inhibited the systemand it remained locked out after reverse thrust was de-selected.

The fire

53 The ejected dome of the No 9 combustor can and a small sectionof the fan case struck an underwing fuel tank access panel creatinga hole which had an area of 42 square inches.

54 The wing tank access panel had an impact strength approximatelyone quarter that of the lower wing skin; had the dome struck theadjacent skin penetration of the tank probably would not haveoccurred. Neither the access panel nor the lower wing skin weredesigned to any impact resistance criteria, nor were they requiredto be.

55 The fire ignited when fuel from the punctured wing tank accesspanel came into contact with combustion gases escaping from thedamaged engine.

56 The left engine fire detection system was serviceable and indicatedto the flight deck crew an 'engine fire' 9 seconds after the combustionchamber outer case ruptured; the delay occurred because the firewas burning external to the engine nacelle.

57 The operation of the engine fire extinguisher system had nosignificant effect on the fire, and could not have been expectedto do so.

58 The fire burnt in two separate but overlapping phases, involvingfundamentally different fire mechanisms:-

i) Whilst the aircraft was moving at speed on the runway, fuelbecame entrained into the strong turbulent wake generated by theextended thrust reverser buckets and burnt vigorously as a 'dynamicfire plume'.

ii) As the aircraft decelerated and the turbulent wake decayed,the fire transitioned into a quasi-static fire burning above thepool of fuel trailing behind the aircraft. By the time the aircraftstopped, a fully established 'static' pooled fuel fire was burningadjacent to the left rear fuselage.

59 The application of reverse thrust did not at any stage playan active role in controlling or influencing the fire beyond theestablishment of the turbulent wake referred to in (i) above.

60 Although the 'dynamic' fire plume was visually very dramatic,hull penetration was caused primarily by the 'quasi-static/static'pooled fuel fire.

61 The aft right door aperture allowed the early entry of smokeand possibly some flame transients, but was not the principalpoint of entry of the fire into the cabin.

62 The wind was the principal factor controlling the fire's behaviour.It carried the external pooled fuel fire against and beneath therear fuselage, giving rise to rapid fire penetration. Subsequentlythe wind induced aerodynamic pressure field around the fuselagedrew fire products into the hull, through the cabin interior andout through open exists on the right side of the fuselage.

63 The initial fire penetration of the fuselage occurred within20 seconds of the aircraft stopping, when the lower skin panelson the left side adjacent to the aft cargo hold were burnt through,followed shortly afterwards by penetration of the fibreglass accousticinsulation blanket. This gave the fire access to a cavity surroundingthe cargo hold, from which it entered the aft cabin via floor-levelair-conditioning grills located on each side of the aircraft.

64 It is estimated that within 1 minute of the aircraft stopping,the fire penetrated the cabin sidewalls just above floor leveladjacent to seats 17A to 19A, giving the fire direct access tothe cabin interior.

65 It is estimated that the windows resisted penetration by thefire for at least 40 to 50 seconds after the aircraft stopped.However, visible signs of damage to the outer panels, includingcracking and apparent melting, were evident much earlier.

66 The fire was entrained by the wind beneath the rear fuselage,creating a large area of fire-contact with a high rate of heattransfer into the hull, resulting in the rear fuselage and tailcollapsing onto the ground. The time when collapse occurred couldnot be determined.

67 Initially, the internal fire burnt in the aft section of thecabin, spreading forwards as roof panels and overhead lockersignited and collapsed down onto seats.

68 Approximately 50% of the seats suffered little or no fire damage,and many plastic safety instruction cards, magazines and otherfragile items survived undamaged in the seat-back pockets andon seat cushions. In contrast, all ceiling panels and overheadlockers were destroyed and all side-liner panels above cushionlevel were extensively damaged by fire.

69 A marked stratification of both temperature and smoke was evidentthroughout the cabin; in areas not actually combusting, therewas comparatively little heat or smoke below a level of approximately18 inches above the cabin floor.

70 Several areas of very intense damage were caused by the combustionof flammable materials, possibly alcohol or aerosol sprays, orby the release of therapeutic oxygen.

71 A fully developed flashover did not occur, although a numberof flash ignitions of gaseous material did. This is contrary tomuch of the evidence from fire research which implied that flashoverwas inevitable and focused attention on the fire hardening ofcabin interior materials as the primary strategy in fire management.

72 Of 27 aerosol sprays recovered from the cabin, 15 had rupturedas a result of thermal overpressure, and 3 of these had been propelledat high speed into seat frames or other obstructions. The practiceof routinely permitting the carriage in hand baggage of aerosolcans containing butane or other flammable gases, represents anunnecessary risk in the event of a cabin fire.

73 Nine of ten therapeutic oxygen cylinders carried in the overheadlockers had discharged their contents into the fire. It is consideredthat the practice of storing therapeutic oxygen cylinders in overheadlockers is undesireable in view of the high temperatures experiencedby ceiling lockers at

an early stage in a fire, and the attendantrisk of thermal discharge occurring whilst passengers are stillevacuating or when rescue personnel are inside the cabin.

74 All the 'basic ingredients' of the fire at Manchester weretypical of those which could apply to any other aircraft involvedin such an incident.

75 This accident has confirmed what was known to a small sectionof the aviation community; that a slight wind (2kt or more), oflittle or no operational significance from an aircraft handlingand performance standpoint, is nevertheless critically importantso far as aircraft orientation in a fire is concerned.

76 The accident has highlighted a general ignorance of the importanceof light winds within the aviation community at large. Operationalprocedures in widespread use at the time of the accident madelittle or no allowance of practical value for such winds and providedminimal guidance to aircrew.

77 Procedures should be devised to enable aircrew to positionthe aircraft most beneficially against the wind in the event ofa ground fire.

Firefighting tactics

78 The scale of the firefighting and rescue protection at ManchesterInternational Airport, even without the major foam tender whichwas undergoing repainting, met CAP 168, Category 8 requirements.Operation of a Boeing 737, only requires protection at Category6 level at best.

79 The speed of response of the Manchester Airport Fire Servicewas rapid, resulting in the commencement of firefighting approximately25 seconds after the aircraft stopped.

80 The external fire was quickly brought under control exceptfor a small running-fuel fire in the area immediately beneaththe wing puncture, which proved difficult to extinguish fully.

81 There had been no recent training in the use of Monnex powder,carried by the apron fire vehicle for use in tackling runningfuel fires, and no attempt was made to use this agent.

82 Despite the early containment of the external fire, fire-penetrationof the rear fuselage led to an internal fire which the ManchesterInternational Airport Fire Service were not equipped effectivelyto deal with, nor were they required to be so equipped.

83 The early recovery of J2 from the paint shop made that vehicleavailable at the scene in time to play a significant role in thefirefighting effort.

84 Approximately 7 to 8 minutes after the aircraft stopped thewater carried by the airport fire vehicles had effectively beenexhausted. Initial attempts to replenish from nearby hydrantswere unsuccessful because the ring main supplying the hydrantshad been isolated. A later attempt to draw water from the hydrantswas successful.

85 The hydrant water flow rates were such that, when operatingnormally, it would have taken between 15 and 18 minutes to completelyreplenish a major foam tender. This time is considered too longa period to permit effective re-deployment after replenishment.

86 The Greater Manchester Council fire service was in attendanceat the rendezvous point within 8 minutes of the accident, butwas unable to gain access to the aircraft for a further 3 minutesbecause there was no Police escort vehicle to meet them.

87 The absence of an escort vehicle had arisen because of recentchanges in emergency procedures which had been agreed betweenthe Manchester International Airport Fire Service and the GreaterManchester Council, but which the Airport Police had not beena party to and of which they were not aware.

88 A further (short) delay in bringing the Greater ManchesterCouncil firefighting effort to bear on the fire occurred becausetheir officer in charge was unable to identify the officer incharge of the Manchester International Airport Fire Service.

89 The delay in replenishment of the water, due to both the unavailabilityof water from the hydrant and the delay in escorting the GreaterManchester Council fire vehicles from the rendezvous point, occurredat a time when attempts to fight the internal fire by means ofhand lines had been curtailed by lack of water. Although it isconsidered unlikely, the possibility that the lack of water atthat critical time led to loss of life cannot be discounted.

90 The potential for an officer in charge of airport firefightingcrews to manage resources effectively is compromised by a lackof helmet-mounted communication,

91 Entry into the cabin to tackle the fire did not take placeuntil some 7 minutes after the aircraft stopped, by which timea severe fire was established in the cabin which could not betackled effectively using hand-held branch lines.

92 The firefighting techniques used at Manchester fell broadlywithin the bounds of established practice. The efforts of theManchester International Airport Fire Service personnel directlyresulted in the saving of life.

93 Using current techniques and equipment, the unavoidable delayin entering an aircraft cabin imposed by the need to avoid conflictwith evacuating passengers makes effective control of an internalfire extremely unlikely.

94 Recent tests have demonstrated that water-mist spray systemsbuilt into the fuselage, supplied either with onboard water orwater from a firefighting vehicle, have great potential in limiting/extinguishingcabin fires.

95 Because of the potential for fire penetration occurring beforethe arrival of airport fire vehicles, the 'on-board' water capabilityof water-mist systems is seen as essential for the early limitationof the fire and the maintenance of a survivable temperatures throughoutthe evacuation period.

Fire hardening

96 There has been an imbalance of effort between the amount ofresearch being undertaken into the fire hardening of interiormaterials and that directed towards fire hardening of the hullitself.

Survival/Evacuation

97 Of the 131 passengers and 6 crew on board G-BGJL, 52 passengersand 2 aft cabin crew died on the aircraft. A further male passenger,who was found still alive but unconscious in the forward aislesome 33 minutes after the aircraft stopped, died from lung damageand associated pneumonia 6 days later.

98 Only 47% of those engulfed in the dense smoke atmosphere survivedand of these eight collapsed due to toxic/irritant gas and smokeinhalation during their evacuation. Two of those who collapsedwere dragged onto the front left slide by the surviving hostessand a 14 year old boy was pulled out of the right overwing exitby a fireman, 5¤ minutes after the aircraft stopped.

99 The primary reason for the majority of the fatalities was rapidincapacitation due to inhalation of the toxic smoke atmosphere,the effects of which were made more critical by evacuation delays.Of the 54 fatalities on board, 48 had absorbed levels of CarbonMonoxide and/or Hydrogen Cyanide in excess of that required toinduce incapacitation.

100 Eighteen survivors escaped from the front/left door, whichwas opened by the purser approximately 25 seconds after the aircraftstopped; 27 used the right overwing exit, which was opened byadjacent passengers approximately 20 seconds later; and 35 escapedfrom the forward/right door, which was opened by the purser some1 minute 10 seconds after the aircraft stopped.

101 Although 26 survivors including 1 infant and 1 child escapedthrough the right overwing exit unaided, for the 76 passengersfrom the rear of the aircraft this was the first available exitand for 100 passengers it was the nearest. The exit routes throughthe aft left and right doors plus the left overwing exit wereunavailable due to the fire.

102 The narrow gap of 10¤ inches available between row 9and 10 seats impeded passengers' access to the right overwingexit. The pressure of passengers on the 10F seat back caused failureof the seat back hinge baulk allowing the backrest to fold forwardscreating a further obstacle to egress. Twin bulkheads in the forwardcabin restricted evacuation flow to the forward exits after bothwere open.

103 The present regulatory Evacuation Certification Requirementsare inadequate in their evaluation of important potential egressrestrictions and make no attempt to demonstrate evacuation timesin the conditions where speed of evacuation is of prime importance- that of egress in conditions of dense smoke.

104 The current regulatory Certification Requirements for aircraftcabin materials are inadequate in their omission of any restrictionon smoke and toxic/irritant gas emissions, whilst unable to giveassurance that such materials shall not undergo thermal degradationor combustion when subjected to large fuel-fed fires.

105 A comprehensive test programme has shown that lightweight,easily donned smokehoods have the performance to protect evacuees,keeping them conscious and mobile in typical aircraft fire environmentsand, in addition, can offer significant protection against in-flightfires.

106 Water-mist systems have demonstrated the potential dramaticallyto improve the cabin thermal environment and to scrub particulatefrom fire atmospheres but their effect on the overall toxicityhas not been fully examined.

(b) Cause

The cause of the accident was an uncontained failure of the leftengine, intitiated by a failure of the No 9 combustor can whichhad been the subject of a repair. A section of the combustor can,which was ejected forcibly from the engine, struck and fracturedan underwing fuel tank access panel. The fire which resulted developedcatastrophically, primarily because of adverse orientation ofthe parked aircraft relative to the wind, even though the windwas light.

Major contributory factors were the vulnerability of the wingtank access panels to impact, a lack of any effective provisionfor fighting major fires inside the aircraft cabin, the vulnerabilityof the aircraft hull to external fire and the extremely toxicnature of the emissions from the burning interior materials.

The major cause of the fatalities was rapid incapacitation dueto the inhalation of the dense toxic/irritant smoke atmospherewithin the cabin, aggravated by evacuation delays caused by aforward right door malfunction and restricted access to the exits.

4 Safety recommendations

4.1 Procedures should be developed to enable the crew to positionan aircraft, when a ground fire emergency exists, with the firedownwind of the fuselage. Visual indicators of local wind directionlocated within the manoeuvre areas would be valuable aids to theimplementation of such a procedure. (letter to CAA 14 March 1986)

4.2 Research should be undertaken into methods of providing theflight deck crew with an external view of the aircraft, enablingthem to assess the nature and extent of external damage and fires.

4.3 Operators should amend their Operations Manuals, if necessary,to direct crews on any rejected take-off or emergency landingto stop on the runway and review the situation before a decisionon clearing the runway is made.

4.4 Consideration should be given to the requirement to fit anevacuation alarm permitting flight deck crew to instruct cabincrew to initiate an evacuation immediately, or if the aircraftis still moving to prime for an evacuation immediately the aircraftis brought to a halt.

4.5 Emergency equipment for use by cabin crew during an emergencyevacuation should be stowed at the cabin crew stations. (letterto CAA 19 September 1985)

4.6 The Civil Aviation Authority should continue to work withother regulatory authorities to define a mandatory internationalcode of practice for identifying the appropriate method of promulgationfor manufacturers' safety information. This code should includea procedure for ensuring that, at the earliest opportunity, preliminary/advisoryinformation should be followed up and superseded by appropriateBulletins, Airworthiness Directives or manual ammendments.

4.7 If manufacturers are to continue to supply maintenance guidelineswhich require the operator and his regulatory authority to determinemaintenance intervals, particularly for critical components, are-evaluation should be undertaken of the methods employed tojudge residual component lives, particularly following repair.

4.8 Direct fusion weld repair of circumferential cracks in JT8Dengines combustor cans should be deleted from all approved EngineOverhaul Manuals, unless the safe life of the repaired can hasbeen demonstrated for the anticipated overhaul/inspection period.

4.9 Operators should seek the manufacturers comments when makingchanges to approved technical manuals, under the terms of approvalgranted by the CAA.

4.10 A review of the approval of the cabin configuration as itexisted on G-BGJL should be conducted, with particular referenceto the following features of that configuration:-

(letter to CAA 19 September 1985)

i) The restricted view of the passenger cabin afforded the forwardcabin crew when seated.

ii) The forward aisle restriction created by the floor to ceilingforward galleys.

iii) Access to the overwing exit where the presence of row 10seats appeared to conflict with the British Civil AirworthinessRequirements. It is recommended that all row 10 seats be removed.

The approval of other configurations on Boeing 737 and other typesshould also be reviewed with the intention of addressing any similarproblems. (letter to CAA 19 September 1985)

4.11 A review should be conducted to examine the adequacy of existingBritish Civil Airworthiness Requirements relating to 'unobstructedaccess' to exits and these updated where necessary to take accountof modern high density seating configurations.

4.12 A requirement should be introduced for passenger public addresssystems that can continue to function largely independently ofengine or airframe system condition, and provide a high gain modefor use in emergencies. (letter to CAA 4 December 1985)

4.13 Operators should adopt a policy of distributing the mostexperienced cabin crew throughout the passenger cabin.

4.14 A requirement should be introduced for an effective communicationsystem for Rescue and Fire Fighting personnel as part of the licensingrequirements for all major airports. That requirement should includeprovision for communication on the same system by the officerin charge of the units deployed by any local authority fire servicehaving standing arrangements to attend such airports.

4.15 The recruitment and training of airport fire officers shouldbe amended to facilitate a more management orientated approach.

4.16 RFF personnel in breathing apparatus should be positionedby overwing and other exits at the earliest opportunity to assistthose evacuating and to help keep the exits clear. This wouldrequire the airport fire service to be equipped with additionalbreathing apparatus and all RFF personnel to be trained in itsuse.

4.17 A requirement should be introduced for some form of standardisedhigh visibility clothing to be worn by the officer in charge ofthe Rescue and Fire Fighting personnel at any incident/accidentscene.

4.18 A thorough review should be undertaken into techniques forextinguishing fires inside the passenger cabins of public transportaircraft, with a view to rectifying the current deficiencies inairfield firefighting capability when dealing with internal fires.

4.19 Onboard water spray/mist fire extinguishing systems havingthe capability of operating both from on-board water and fromtender-fed water should be developed as a matter of urgency andintroduced at the earliest opportunity on all commercial passengercarrying aircraft.

4.20 The balance of effort in aircraft fire research should berestored by increased effort directed towards fire hardening ofthe hull, the limitation of fire transmission through the structureand the prevention of structural collapse in critical areas. Shortterm measures should be devised for application to existing typesbut, in the long term, fire criteria should form a part of internationalairworthiness requirements.

4.21 A requirement should be introduced to ensure that existingexternal fuel tank access panels which are vulnerable to impactfrom engine or wheel/tyre failures on aircraft in service areat least as impact resistant as the surrounding structure. Thepotential risk of damage from debris impacts should be addressedin future by appropriate design reqirements covering debris ejectionfrom engines and/or impact strength requirements for the airframe.

4.22 Aerosols with hydro-carbon propellants should be treatedin the same way as other cylinders of flammable gas and theircarriage on board aircraft controlled accordingly.

4.23 A requirement should be introduced to ensure that all portableoxygen bottles carried on board public transport aircraft arefitted with pressure relief valves and are stowed in thermallyprotected areas, preferably at low level.

4.24 The Civil Aviation Authority should urgently give considerationto the formulation of a requirement for the provision of smokehoods/masksto afford passengers an effective level of protection during fireswhich produce a toxic environment within the aircraft cabin.

(Made December 1985)

4.25 The proposed requirement for cabin crew smokehood protectionbe extended to include training for crew donning and use duringaircraft emergency evacuations associated with a fire and/or smokethreat during the evacuation.

4.26 The applicable regulatory requirements for aircraft cabinmaterials certification should be amended at the earliest opportunityto include strict limitations of smoke and toxic/irritant gasemissions.

4.27 A research program should be undertaken to establish theeffect of water mist/spray extinguishing systems on the toxic/irritantconstituents of fire atmospheres.

4.28 The existing regulatory requirements governing the EvacuationCertification of public transport aircraft should be reviewedand amended to include:

i) A demonstration of an acceptable evacuation time when the cabinis evacuated using half the total number of exits, disposed towardsone end of the cabin; that end being chosen which represents thegreatest restriction to passenger egress.

ii) Simulation of a defined dense smoke atmosphere within thecabin, existent from the initiation of the evacuation until itscompletion.

iii) All other sub-testing associated with cabin evacuation, includingpassenger aisle flow, the identification of exits and apertureegress rates, upon which design and configuration certificationdecisions are based, be conducted in the same simulated smokeatmosphere.

4.29 The design strength of the break-forward 'baulks' fittedto the seats adjacent to overwing exits should be increased toprevent failure due to passenger pressure-loads on the backs ofthese seats.

4.30 Research should be undertaken to assess the viability of'audio-attraction' and other techniques designed to attract passengerstowards viable exits when speech and vision is impaired in smokeand toxic/irritant gases.

4.31 Research should be undertaken into the effects of cabin airflowon smoke/gas venting and flashover delay/suppression, with a viewtowards the possible benefits of changing current cabin air-conditioningdesign and/or associated procedures.

D F KING Inspector of Accidents
Air Accidents Investigation Branch Department of Transport December1988