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 (SO2)

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 (NH3)

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 (CH2 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

Class 1 Medical Certi

Last medical examination: 30 September 1985, for distant vision an exercising the privil

Part 1 Pilot-in-Command ratings: PA 18, 22, 25, 28 and 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

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