AIRCRAFT ACCIDENT REPORT 8/88

Air Accidents Investigation Branch

Department of Transport

Report on the accident to Boeing 737-236 series 1, G-BGJL at Manchester International Airport on 22 August 1985

LONDON

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BRITISH AIRTOURS
River Orrin

Department of Transport
Air Accidents Investigation Branch
Royal Aerospace Establishment
Farnborough
Hants GU14 6TD

15 December 1988

The Right Honourable Paul Channon
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr D F King, an Inspector of Accidents, on the circumstances of the accident to Boeing 737-236 series 1, G-BGJL which occurred at Manchester International Airport on 22 August 1985.

I have the honour to be
Sir
Your obedient servant

D A COOPER
Chief Inspector of Accidents

Contents

Air Accidents Investigation Branch

Aircraft Accident Report No:8/88
(EW/C929)

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 charter flight to Corfu, began its take-off from runway 24 at Manchester with 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 leaking from 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 wing tank 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 a scheduled 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[1*] (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 were 129 passengers plus 2 infants, a total of 131 passengers on board. A child and one of the infants were seated on their parents' laps at 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 part of the aircraft strapped themselves into their seats, each with a full harness. They were sitting on a stowable bench seat in the left forward galley with their backs to the forward

[1*] V1 - Decision speed in the event of an engine failure on take-off; at which the take-off may be either abandoned or continued

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 3 were 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 full nose-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 7 kt (para. 1.7), and the co-pilot requested take-off power. The commander 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 "eighty knots" 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 maximum Indicated 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 approximately 5 seconds, after which reverse was de-selected on both engines at 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 (N_2) decayed more gradually, with the result that the reverser buckets on the left engine were able to deploy fully. However, by the time reverse was de-selected the N_2 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-off run, 9 seconds after the 'thud', as the aircraft decelerated through 85 kt groundspeed the commander started to inform Air Traffic Control (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 transmission the fire bell was inhibited and as the ground speed reduced below 50 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 right hand 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 Handbook by the co-pilot. Before they were able to complete the drill the commander saw fuel and fire spreading forward on the left side of the aircraft, opened the co-pilot's sliding window on the right side 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 ground by 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 galley area 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 the wing and flowing back over the wing's top surface. There was no smoke 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 spending a short time trying to clear the restriction he postponed further effort and crossed to the L1 door. He cracked it open, ascertained that 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 foam discharge 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 other passengers, 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 companion in 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 the passenger 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 black smoke 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 after the 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 including 1 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 service station (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 alarm siren sounded.

Two Rapid Intervention Vehicles (RIVs) attended first, one arriving at the aircraft coincident with, the other just after the L1 door had 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 keep the escape routes clear of fire, and to attack the source of the fire.

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 coaches for 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 paint shop. On arrival the driver saw a hand move above a man trapped in 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 5½ 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 the wings 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 West RVP, 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 section of 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.(Appendix 5 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 tail section had collapsed to the ground. Most of the cabin interior was extensively burnt and the floor in the rear of the passenger cabin had collapsed down into the rear cargo hold. Those areas of the cabin interior which had escaped direct damage by the fire were covered with a thick coating of viscous soot. (Appendix 3 photos 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

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 HS 121, 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 Pilot's Licence valid until 29 November 1985
Last medical examination:	Class 1 Medical Certificate valid until 30 September 1985, the holder to wear spectacles which correct for distant vision and to have available a second pair whilst exercising the privileges of the licence.
Part 1 Pilot-in-Command ratings:	PA 18, 22, 25, 28 and 32, BAC 1-11 Boeing 737-200; -300
Certificate of Test: Instrument Rating:	Valid until 30 November 1985 Valid until 25 March 1986
Emergency equipment and procedures check:	Valid until 5 March 1986
Flying experience:	Total all types: 12,277 hours Total Boeing 737: 345 hours Total last 28 days: 31 hours 20 minutes P1(U/S) 36 hours 05 minutes P2

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.

Certified as having achieved a satisfactory standard on Boeing 737, and L 1011 Tristar aircraft 4 January 1985.

Duty time: Worked a duty period of
7 hours 39 minutes the previous day.
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: Total airframe landings:	12,977 hours 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 combustor cans enclosed by a Combustion Chamber Outer Case (CCOC) (Appendix 5 Fig b). Compressor delivery air enters the CCOC, where a small proportion is mixed with fuel in the combustor cans and ignited to produce the combustion flame. The remainder of the compressor air flows around the inner and outer walls of the cans to provide a cooling flow (note: the combustion temperatures are above the melting point of the can materials and thus the cooling flow is essential to maintain can integrity). Whilst the combustor cans contain the combustion process, the CCOC must withstand the compressor delivery pressure (in the order of 240 psi at take-off conditions) and it is therefore essentially a pressure vessel. It is basically a one-piece tube of AMS 5603 steel alloy with flanges fore and aft which attach to the engine casing by two rings of steel bolts.

The combustor cans themselves comprise a cast Stellite dome, or head, and 11 liners of Hastelloy X sheet material (Appendix 5 Fig c). The dome incorporates swirl vanes which direct the incoming compressor delivery airflow into the can prior to mixing with fuel from the fuel nozzle which is inserted into the centre of the dome. The fuel nozzle also provides radial location of the forward end of the can. Axial location is achieved via an integral lug on the dome which picks up on a mounting pin bolted to the diffuser case. The remainder of the can is constructed from 11 rings (liners) of sheet Hastelloy X material of varying diameters to achieve the desired profile of the can. Liner 3 incorporates the flame transfer ports to adjacent cans. The liners are resistance seam-welded to each other. The aft end of liner 11 is a sliding fit in the transition duct bulkhead, which provides radial support for the rear of the can but allows movement in an axial direction to accommodate thermal expansion and contraction. Can numbers 4 and

7 also have an igniter plug boss incorporated in Liner 2. All cans are fitted with an "air scoop" over the top of liner 2, as part of a programme to reduce the engine's smoke emission.

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

The combustor cans fitted to G-BGJL's engines were to Pratt and Whitney modification standard 5192, *ie*. the latest standard applicable to the JT8D-15 at the time of the accident. The modification was intended to overcome various problems encountered on the previous standard of can, including cracking of the seam weld between liner numbers 2 and 3. This was felt to be particularly undesirable because it occurred under the air scoop and could only be detected by radiographic techniques. It was stated by the manufacturer that this modification standard would provide a combustor can of "improved durability".

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

Each engine was fitted with a thrust reverser system typical of reverser systems fitted to this category of aircraft, comprising a pair of clam-shell doors which swung on linkages from their stowed position (around the exhaust duct) into a position aft of the engine, where they deflected the exhaust gases sideways and slightly forwards to provide reverse thrust (Appendix 6 Fig a). Boeing 737 installations differed from the norm however, by having the 'split plane' of the reverser doors inclined at approximately 45° to the horizontal, with the lower door inclined outboard, so as to limit the ingestion of debris blown up by the reversed exhaust efflux. The thrust reverser door actuating system was inhibited 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 1980 whilst fitted to aircraft G-BGJG. In the winter of 1983/1984, the engine was removed and stripped for a sample layout (see paragraph 1.17.2). At that time a Light Maintenance Inspection (LMI) was performed and the engine was re-assembled with repaired combustor cans from another engine, serial number P702946. This engine had been prematurely removed, having run 7482 hours/3371 cycles since new, in September 1983 due to a pilot report of high exhaust gas temperature and visible compressor damage. The engine was stripped and it was found that a failure of the 13th stage compressor outer shroud had caused damage to the 13th stage compressor blades. It was considered economically advantageous to perform an LMI at this shop visit, thus the combustor cans were inspected and repaired as necessary - this work being completed on 16 November 1983. Although the actual lengths of cracks found in the cans were not recorded, the Engine Strip Report for P702946 noted that "5 off combustion chambers (combustor cans) exhibited considerable burning and cracking to the 3rd liners adjacent to cross-over tubes". After the accident to G-BGJL, it was possible to determine the crack lengths from radiographic plates which had been retained. These radiographs had been taken to inspect for cracking in the 2/3 liner area (*ie* under the air scoop) but, fortuitously, the film also covered the area up to liner 5, specifically the 3/4 liner joint.

Examination of the radiographs showed that the can exhibiting the most cracking in the 3/4 liner joint was can No 9, serial number TS351 (installation position was the same on both engines). A circumferential crack 160 mm in length extended in the third liner from the male flame transfer tube around the outboard face of 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 (Appendix 5 Fig d).

Can No 7 exhibited cracking in a similar area to the main crack in can No 9 but only some 75 mm in length. Can No 6 also had a crack of about 60 mm in this area. The remaining cans had either minor 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 radiographs of the can set that can No1 had a distinctive area of multiple "branchy" cracking in the 3rd liner area - some of the cracks having joined together and liberated a small triangular piece roughly 2.5 mm along each side. The length of the circumferential cracking was, however, only some 35 mm.

All the above mentioned cracks in the cans were addressed by direct fusion weld repairs during the LMI. Pre-weld Solution Heat Treatment (SHT) and post-weld stress relief (see paragraph 1.17.2) were not carried out.

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

(b) *Engine serial number P 702841 (Right)*

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

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

The aircraft's technical log and technical records were examined to determine the number and nature of crew-reported defects on the left engine since the installation of engine serial No P702868 in February 1984. Of particular interest were flight crew reports of slow acceleration, slow start and throttle stagger (see paragraph 1.17.2). 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 crew also commented on a low ground idle N_2.

Slow acceleration is based on the time taken for the engine to reach the "stand up" setting of 1.4 EPR from ground idle.(" stand up" - both throttle levers moved to the vertical)

"Throttle stagger" refers to a mismatch in the position of the pilot's throttle levers when the EPR for both engines are matched. In all cases where throttle stagger was reported, the left engine lever was forward of the right engine lever to achieve the same EPR.

The three log entries for the month of August, 1985 are discussed in greater detail later in this section. The other 16 entries were dealt with in a variety of ways, including times when the crew were asked to accept the aircraft and to report further on the symptoms - on occasions no further crew comment was made. Where actual work was performed on the aircraft, it was always of a minor nature (*eg* checking the PS4 line for leaks and moisture contamination, checking engine bleed air for leaks). This rectification action appeared to cure the symptoms and, consequently, at no time was the engine combustion section checked for a disrupted gas path. Trim runs (see paragraph 1.17.2.3) were performed on 16 February 1984 and 18 June 1985 but the log merely records that they were carried out with no indication of any Fuel Control Unit (FCU) adjustment having been performed. Following the "slow acceleration" report on 17 January 85, the ground crew reported that they found the left engine ground idle N_2 speed to be 1% low and adjusted the FCU accordingly.

The following is a verbatim extract from the Technical Log for the 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 1½-2 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% N_1 and 50% N_2. 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 carried 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 of 7 hours 14 minutes, arriving back at Manchester at 0431 hours on 22nd August 1985. No flight crew comment was made in the Aircraft Technical Log regarding the condition of either engine.

Statements made by the two technicians tasked with attending to the log entry on 21st August confirm the information contained in the "action" column above. Having consulted with British Airtours Base Engineering at Gatwick, they elected to remove and replace the PS4 filter water-drain trap and adjust the ground idle trim screw by one turn in the 'increase RPM' direction. Both engines were then started normally and it was observed that both N_2 gauges were reading 58%. The throttles were advanced to a point where the EPR gauges began to register a change. They reported that there was still about 0.5 inches of throttle stagger at the top of the levers when the EPR readings matched but were evidently satisfied that the acceleration times of both engines were similar and acceptable. Subsequent examination of the aircraft's Flight Data Recorder indicates that the left engine accelerated at about the same rate as the right but did not achieve the same levels of N_2 and EPR during the ground run. This is consistent with the comments regarding throttle stagger and "still seems slow compared with No 2" (right) *ie* if both throttles were advanced together, then the right engine would achieve higher RPMs and EPRs than the left engine.

The ground crew also raised an ADD entry in the log to perform a trim run at the next visit to Gatwick (where a trim test-set was held). It would also appear that, had the flight crews remained dissatisfied with the performance of the engine, the aircraft would have been re-rostered into Gatwick on the 22nd August for this work to be performed.

1.6.3 *Engine fire warning and suppression systems*

The aircraft was fitted with separate FIRE and OVERHEAT detection systems designed to alert the crew to excessive temperatures within the engine nacelles. Flight deck indications were by means of warning captions and indicators, augmented in the case of a FIRE warning by an audio warning (bell sound). Built-in test equipment enabled serviceability checks to be carried out on both fire and overheat 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 integrally formed within the aircraft's wing structure. The two main tanks of 4,590 Kg capacity each were formed (one in each wing) by the main torsion box, and extended from the root rib outboard to a position close to the wing tip. The wing centre section formed the centre auxiliary tank, which had a capacity of 7,416 Kg.

Access to the interior of each main wing tank was provided by means of a total of 13 elliptically shaped removable access panels varying in size from approximately 18" by 10" inboard to 16" by 6" outboard, which were secured flush with the lower skin surface and sealed against fuel seepage by an '0' ring gasket. The access panels were manufactured from a cast aluminium alloy material and had stiffening webs integrally formed on the upper (internal) surface. The panels were nominally non-stressed components so far as flight-loads on the wing were concerned; impact strength did not form a part of the design requirements for the wing lower skin, nor the access panel. The cast aluminium material had an impact strength approximately one quarter that of 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 maximum delivery rate of 78 lb/min, which were supplied by the main engines or by the Auxiliary Power Unit (APU). The conditioned air was distributed throughout the cabin via a system of manifolds and ducts leading to the overhead nozzles and zone supply louvres. Exhaust (stale) air left the cabin via floor level louvres located in the cabin side-wall panels, and made its way into the cavities surrounding the cargo hold liners, ie the interspaces between the fuselage outer skin and the cargo hold side-lining, and the cargo hold roof-lining and the cabin floor (Appendix 6 Fig b). (The fibreglass wool insulation blankets, which fill the structural cavities between the cabin liners and the outer skin, were reduced in thickness around the hold areas to facilitate the passage of exhaust air). Approximately 56% of the total cabin exhaust air was routed via the floor louvres aft of the wing into the aft cargo hold cavity, from where it was dumped overboard via the main outflow valve situated in the rear fuselage underbelly. Approximately 36% was routed via floor level grills in the forward cabin, into the forward hold cavity, and thence into the electronic equipment bay where it was used to cool the equipment before being dumped overboard via the electronic equipment bay exhaust. The remainder of the exhaust air left the aircraft via various local vents and as 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. The centre panels, which were failsafe load-bearing panels designed to provide a back-up in case of a failure of the outer panel, were manufactured from cast acrylic. The inner transparencies were thin panels designed primarily to protect the load-bearing panels from damage.

The two load-bearing panels in each aperture were located mainly by the recessed shape of the aperture housing, and were held into the aperture by a series of retention clips arranged around the periphery. The edges of the acrylic load-bearing panels were fitted with rubber gaskets to provide an air seal. The inner transparency panels were attached to, and effectively formed a part of, the decorative window reveal panels.

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

1.6.7 *Fuselage construction*

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

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

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

The cabin floor comprised a number of fibreglass/nomex honeycomb panels, which were attached to the floor beams. In the web sections of the crease beams there were a series of large holes to allow the passage of air conditioning exhaust air from the cabin section above the floor through to the cavity surrounding the cargo hold below.

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

Within each cargo hold area, the internal space was lined by a thin, wear resistant fibreglass laminate, known as the cargo hold liner. The cavity formed between the cargo hold liner and the outer fuselage skins and between the liner and the cabin floor panels was used to provide an exit path for air conditioning exhaust-air leaving the cabin interior.

1.6.8 *Internal configuration - Approval and evacuation certification:*

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

This configuration was in compliance with British Airways Configuration Modification No 25C211, Drawing No 1-54378 certified by the British Airways authorised engineer as being in compliance with the appropriate regulations 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 at row 10, *ie* 10A and 10F, should be of a type modified to prevent the seat-backs from hinging forward and row 9 seats should have no recline, in order that access to both overwing exits should not be impeded.The seat backs of row 9, in common with the majority of seats, could be folded forwards to create more room for the upper body of any person moving between rows 9 and 10 to the overwing exits. The Boeing 737 Type Certificate allowed the 737/200 model to be equipped with 130 passenger seats provided there was compliance with Federal Airworthiness Regulations (FAR) 25.2(b),(c) and (d). The Emergency Evacuation requirements for this Public Transport aircraft 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 on the 26 November 1970 using a Britannia Airways Boeing 737-204 model. The 130 passengers and 5 crew were evacuated from the left exits (*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 two sliding-window emergency exits on the Flight Deck (Appendix 3 Fig a).

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

The overwing emergency exits were located at either side of row 10 and were intended for ground evacuation of centre cabin passengers, or as the primary exits for use after a sea-ditching (Appendix 3 Fig c). For the latter purpose, these exits were each equipped with a webbing-type escape rope/lifeline, anchored to the upper/forward corner of the aperture, with a snap-hook on the other end for attachment to a lug located on the upper surface of each wing near the trailing edge. These lifelines were some 17 feet in length and designed to provide evacuees with a means of stabilising themselves while on the wing upper surface prior to boarding the rafts. From the anchor point a single thickness of line ran along the top of 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 by retaining clips. The remaining line was stored in the tube attached to the structure with the exception of the snap hook which was located in a pouch at the upper aft corner of the exit. For ground evacuation, arrows painted on the upper surface of each wing were intended to lead evacuees to the trailing edge and down the extended flaps.

On pulling the overwing exit hatch release handle the hatch, weighing 48 lbs, pivots inboard about its lower edge and requires lifting to remove it from the aperture to make the exit available.

The passenger flight safety card exercised a large amount of artistic licence in representing the area local to the overwing exit.(Appendix 3 Fig d) It indicated a large area in which to stand to remove the hatch and showed the hatch then being placed on the row 10 seats, the armrests raised. Even if this was achievable, bearing in mind the weight of the hatch and the fact that armrests are normally down, (always for take-off and landing), in this position it represents a further obstacle to anyone trying to reach the exit from the aisle. Furthermore the person opening the hatch was depicted in an all blue 'uniform' in the same way as were cabin crew in other sections of the safety card, possibly leading passengers to think that the hatch would be opened by a member of the crew.

The Flight Deck had two sliding-window emergency exits for use by the pilots, with two associated webbing-type escape ropes stored in 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 passenger address microphone. The forward cabin crew were also provided with two 'Scott' smokehoods, located in a cupboard stowage facing their 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 other three smokehoods, for use by the cabin crew, were stored in the overhead 'bin' at row 18 (right). One 1.5 lbs capacity water fire extinguisher was stored in this area of the cabin within the right overhead at row 20. A further two, 1.5 Kg BCF extinguishers were located on the aft wall of the rear right bulkhead. Two megaphones were available for cabin crew use, one stored in the forward left overhead bin at row 2 and the other in the aft right overhead at row 18.

Ten portable oxygen bottles were stored in the cabin overheads; two (for crew use) were located at row 2 right, two units either side of the aisle at row 10 (for passengers) and four units within the overhead at rows 20-21 right, of which three were designated for 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 surface wind 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 Very High Frequency (VHF) communications were entirely normal.

Communications on the Ultra High Frequency (UHF) frequencies used by the fire service and ATC, together with those on the telephone links, were normal.

1.9.2 Aircraft public address (PA)

The aircraft's PA system allowed announcements to the passengers to be made from the flight deck, the forward galley area, and the rear galley area. The system had two gain (volume) levels, the lower for use before engine start, and the higher gain (by 6 decibels) selected automatically by the operation of the left engine oil pressure switch, for use after engine start and during flight. The failure of the left engine therefore caused the system gain to revert to the 'low' setting, significantly lowering the volume at the time the purser instructed the passengers to remain seated and the commander ordered the evacuation A number of passengers did not hear these announcements, however, whether this was due to the lower volume or the effect of the noise level in the cabin could 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 and ground engineers, and a Flight Interphone to permit communication between the flight crew and a ground crew member without interference from the Service Interphone.

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

1.10 Aerodrome information

1.10.1 Manchester International Airport (Appendix 2)

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

The main terminal and manoeuvring areas were all on the northern side of the runway. The southern area was used almost exclusively for light aircraft and general aviation activities.

The scale of rescue and fire fighting (RFF) protection at Manchester International Airport met the requirements of CAP 168 for a Category 8 Aerodrome. Operation of a Boeing 737 only requires protection at Category 6 level at best.

1.10.2 Media requirements, media provision and discharge rates

Under clause 2 of the aerodrome licence, Manchester International Airport was required to provide the following minimum amounts of 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 Carbon Dioxide or a combination of the above. 50% of the complementary media could be substituted by water for production of fluorochemical foam. In that event a substitution rate of 1 kg for 1 litre of water applied.

The following amounts of media were available for immediate response at 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 had the 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 and had a maximum (mixed) foam discharge rate of 908 litres/minute. These vehicles were based on modified Range Rover chassis and their purpose was to provide rapid access to the fire - to give 'first aid' fire protection pending the arrival of the major foam tenders.

One 'Protector' major foam tender, carrying:-

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

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

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

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

These appliances, together with a small ambulance, were on standby in the airport fire station located just north of the intersection between taxiways 2-North and 3, some 825 metres from the position where the aircraft stopped. A second fully equipped Jumbo foam tender (J2) was undergoing re-painting in hangar 3, some 550 metres from the fire station. Additionally, a Land Rover fire vehicle, which at the time of the incident was providing fire cover at the apron area, responded to the incident. This vehicle carried 50 kgs of Halon BCF and 100 kgs of Monnex powder (100 kgs of Monnex is deemed equivalent to 200 kgs of Halon BCF), but it had no foam capability. Even with the absence of J2, the fire cover available at the time of the accident exceeded the licencing requirements then applicable at Manchester.

1.10.4 *Airport hydrants*

Manchester Airport was equipped with a series of water hydrants spaced 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 hydrants in the area of link Delta were measured and found to be between 40 and 50 psi, giving flow rates of between 165 and 190 imperial gallons per minute.

At the time of the accident, the water hydrant system on the airfield was in the process of being modified by the installation of an additional water main, which was being laid alongside the existing main south of the runway to provide increased flow rates. This work had been in progress for some considerable time prior to the date of the accident. To facilitate the interconnection of the new and original pipework it had been necessary from time to time to isolate sections of the system.

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

Investigation of the circumstances surrounding the hydrant failure has revealed that the system of work permits had not been adhered to; valves had been turned on and off by the contractor's personnel without any form of control and without the knowledge of the fire service. On the morning of the accident, contractors arriving for work observed firemen attempting to obtain water from the hydrants. 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 provided for the immediate notification of the Local Authority emergency services in the event of an aircraft accident. This notification was to be communicated by land line from the Airport Fire Service watch room.

For some considerable time prior to the accident it had been the practice of the external emergency services to respond to the West RVP, which is located near the airport fire station, where they met with a police escort vehicle. However, on the 25th July 1985, 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 the RVP for external emergency services would be changed to the North RVP. The Police were not informed of the meeting and did not attend; they were not informed about the changes in procedure, nor were the changes promulgated. When the accident occurred, the external emergency services were told to report to the (new) North RVP, but this detail was not passed to the police, who dispatched their escort vehicle to the original West RVP. The fire service ambulance, departing from established procedure, acted as an escort vehicle but it too went to the old meeting point at the West RVP.

The delay in attendance by the GMC fire service, caused directly by the confusion over RVPs, was approximately 3 minutes, and occurred at a time when the effectiveness of the airport fire service was being 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 hours and was part of a Plessey PV1940 recording system. This system also incorporated a quick-access cassette which recorded essentially the same information as the accident protected recorder. A total of 27 analogue parameters plus 73 discrete parameters (events) were recorded.

The FDR was mounted overhead in the rear passenger cabin, just forward of the rear pressure bulkhead. It was recovered intact, the exterior being smoke blackened. The mechanism showed no sign of 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 with a duration of 30 minutes, was installed in the aircraft. The allocation of 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. It was recovered slightly fire damaged and with some physical damage to the casing. The plastic based recording medium had not suffered any damage whatsoever and after removal a satisfactory replay was 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 probable that the data had been corrupted due to electrical transients caused by the automatic bus bar switching which took place as a consequence of the engine failure.

A transcript of the CVR over the relevant period was produced and synchronised with the FDR data by comparing the recorded VHF key switch position with the ATC calls on the CVR.

The airspeed measuring system was of a type which did not record below 40 kt, and as such was not suitable for deriving the aircraft's position along the runway. This was derived by calculating the groundspeed by means of an integration of the recorded longitudinal acceleration which had been corrected for datum error and pitch attitude changes. This was then used in conjunction with the recorded heading to calculate the aircraft's position, assuming that there had been no sideslip. The fixed datum position used was the known point at which the aircraft had come to rest.

It was known that the aircraft had executed a rolling take-off and from the calculations it would appear that the ground speed at power up was of the order of 5 kt. The airspeeds derived from the calculated groundspeeds and reported windspeed agreed well with the recorded airspeeds.The points along the runway at which significant 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, fragments of left wing tank access panel and other debris from the vicinity of the ruptured left engine combustor case were found on the runway between link 'C' and runway 06 fast turnoff.

A trail of fuel was identified from characteristic damage to the runway paved surface, caused in part by the solvent action of the fuel alone and in some areas by a combination of solvent and heat damage. The outline of this trail, which could be identified on airborne photographs taken by a Royal Air Force reconnaissance aircraft shortly after the accident, began in the same area of runway that the engine debris was found. Initially, the trail took the form of a series of increasingly large patches of unburnt fuel, which merged into a continuous but irregular trail approximately 1.5m wide running parallel with, and approximately 5m to the left of, the runway centre line. The width of the fuel trail remained irregular, but progressively widened until it appeared to stabilise in the region of runway 24 fast turn-off, where it was approximately 3.5m wide and was darker in colour with a sooty appearance, consistent with the fuel having been burning at that stage. This burnt fuel trail continued around into link Delta and up to the position where the aircraft came to rest, where, in the area around the left engine, it merged into a larger area of fuel and fire-stained tarmac.

It was not possible to directly determine the boundary of the pooled fuel fire because of the extent of general heating of the tarmac in the area of the wing puncture and the rear fuselage. However, a topographical survey carried out specifically to determine the ground slopes in the area where the aircraft stopped identified a general slope away from the area of the left engine into the region forward and to the left of the fuselage. This coincided with a spur of tarmac damage clearly caused by fuel and/or fire running diagonally forward from the area of the wing puncture (Appendix 8 fig g). The slope of the ground between the wing puncture and the rear fuselage was uphill, involving a rise of approximately 70 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 explosive rupture of the CCOC. The case had split along an axial line adjacent to No 9 combustor can and had then 'petalled' apart from approximately the 11 o'clock to 5 o'clock position (viewed from the front), failing the attachment bolts on the front flange and the flange itself on the rear face. The upper section of the CCOC had blown upwards onto the underside of the engine pylon, striking the fire/overheat detection system electrical loom. The lower section had blown downwards and outwards. Witness marks on the exterior surface of the CCOC adjacent to the rupture showed that it had struck the inner surface of the fan case as the rupture occurred. (Appendix 5 Fig e)

The aluminium alloy fan case had shattered into several pieces in the region of the CCOC rupture. The remainder of the outboard half had suffered severely from the post-rupture fire.

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

The aft portion of the can remained in the transition duct bulkhead in a crushed and burnt condition, and had rotated about 90° from its normal orientation. Hastelloy X metal spatter deposits could be seen on the adjacent cans 1 and 8, and more spatter was later found behind the can in the transition duct and on the first stage nozzle guide vanes. The dome recovered from the runway showed that separation had occurred around the 3rd/4th liner joint area - the aft portion of the can had then burnt and buckled in an irregular manner (Appendix 5 Fig f). A sizeable portion had broken off into the can and was found lodged against the nozzle guide vanes.

The dome portion, which embodied the majority of liner 3, had suffered comparatively little damage. Witness marks were found which matched those on the holed underwing fuel tank access panel, and a sizeable metal scrape deposit on the air scoop was later analysed and found to be of the same material as the access panel, proving conclusively that the dome had struck the panel. Two small indentation marks in the air scoop also showed that the can location pin retention bolts had contacted the scoop as the dome assembly was forced outwards, fracturing the pin with a single overload bending force. Some galling of the fuel nozzle shroud, associated with similar marks in the mating hole in the dome was also found, indicating movement of the dome relative to the nozzle. The dome itself, particularly the exposed fracture surface of liner 3, was noticeably free of burning or overheat damage although there had been some mechanical damage to the fracture surfaces. In addition to extensive cracking in the 3/4 liner joint area cans numbered 1 and 8 had clearly suffered extensive damage due to their proximity to the badly disrupted No 9 can, with material missing. The other six cans showed varying degrees of circumferential cracking in this area.

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

1.12.1.3 Airframe mechanical damage

The centre of a fuel tank access panel on the lower surface of the 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 panel exhibited signs of having been struck forcibly on its lower (outer) surface.

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

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

1.12.1.4 Airframe fire damage - general

The aircraft was extensively damaged by fire. Most of the light alloy components in the aft region of the left engine nacelle were melted or burnt away. The left wing lower aft surfaces, large sections of the trailing edge flaps inboard of the engine and the lower surfaces of the flaps outboard of the engine were melted, and the remaining regions of the left inner wing and the main landing gear bay were superficially fire-damaged. The lower skin of the left tailplane was burnt through over a region extending approximately 1 metre inboard from the tip.

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

Most of the passenger cabin ceiling and crown skins were burnt away (Appendix 8 Figs a-b) and all of the overhead luggage bins were destroyed. The support beams which carried the cabin floor above the rear cargo hold were burnt away in the central aisle area and on the right side of the cabin (in the areas immediately forward of, and aft of, the rear cargo door), allowing most of the cabin floor above the hold to collapse down onto the baggage. Most of the cabin interior fittings and seats in this section of the cabin were destroyed completely or were very extensively damaged. The interior fittings in the centre and forward sections of the cabin were generally less severely affected by the fire. However, there was considerable local variability, particularly in the severity of seat damage. Notably, seats 8C and 9C (left aisle seats just forward of the overwing exits) were completely destroyed, 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 an overhaul shop where it was stripped to its basic components. This showed that, apart from damage to the combustion section it appeared to be generally in good condition, although it was noted that some turbine blade rubbing had occurred, apparently due to engine case distortion after the CCOC rupture.

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

Only the dome portion of combustor can No 9 was subjected to detailed fractography, because the degree of burning and material loss on the aft portion of the can precluded examination of the 3rd/4th liner joint area. In the following description, positions of the can fracture surface are by reference to 'clock' positions, viewed from the front with 12 o'clock being the mounting lug.

From 10 o'clock to 2 o'clock, the fracture surface had suffered considerable rubbing and, in the vicinity of the cross-over tubes, severe burning prevented identification of the nature of the original fracture mechanism. (Appendix 5 Fig g) Most of the fracture surface which had not suffered secondary damage was identified as being of a fatigue nature - a significant proportion exhibiting fatigue facets. Generally, the cracking appeared to originate on the inner wall of the can and the facets appeared to originate at a multiplicity of origins. These multiple origins led to the simultaneous growth of many cracks at different positions around the circumference of can No 9. Indeed, as noted in paragraph 1.6.2.2., this can had exhibited two separate cracks, centred on the 11 o'clock and 2 o'clock positions, prior to its last shop visit for repair. These had been repaired but cracks at similar radial positions re-grew in service and were joined by a third major crack centred on the 6 o'clock position. On a microscopic scale, these major cracks were facetted, formed by the joining of smaller cracks growing from separate origins. Patches of fatigue growth linking the major cracks were found, some exhibiting very clear fatigue striations. The nature of this striated fatigue damage was different from that observed in the facetted crack areas in that it appeared to propagate from but a small number of origins, indicating that the striated areas propagated after the major crack areas had developed - *ie* the previously weld-repaired areas and a third area at the 6 o'clock position had cracked first from multiple origins and were subsequently joined together by a further fatigue mechanism, resulting from an increased mechanical influence, which resulted in 360° separation of the can.

Although it has been established that the weld-repaired areas appeared to have been the first to re-crack in service, it was noted that the crack did not necessarily follow the original pre-repair crack path. Whilst the re-cracking did exploit the repair in some areas, in others it carved a new path adjacent to the weld.

The quality of the weld repair was checked by microscopic examination of the material structure. Voids, cracks and included matter were detected in the weld repairs. Although these features indicated deficiencies in the welding technique, it was felt that a better indication of the strength of the weld would be the path of the re-cracking which occurred. As noted above, it did not necessarily follow the original crack path and it was felt that other factors, such as the build-up in material thickness after welding and the local temperature distribution in service, would be just as important in determining the re-cracking path as the quality of the weld per se.

The CCOC was examined metallurgically to confirm the nature of the rupture. It was obvious on a microscopic scale that a portion of the fracture surface in the region just aft of No 9 can dome had 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 that an elliptical-shaped bulge in the CCOC had occurred prior to the rupture and the material had thinned to effectively zero thickness and a 175mm slit had formed.

The engine manufacturer provided data gathered from previous CCOC failure incidents in which the length of pre-existing longitudinal cracks in the CCOC had been determined. Although these incidents resulted from primary fatigue cracks in the CCOC itself, it was felt that the situation was analogous to the loss of material properties resulting from softening/bulging. This data suggested that for the JT8D-15 engine, the nominal critical crack length would be 117 mm, beyond which explosive rupture would be likely to occur. It was therefore appreciated that CCOC overheating would not necessarily lead to explosive rupture if it occurred over a relatively small, discrete area, in which case burn-through or bulges might occur. In the case of the left engine of G-BGJL, the overheating had occurred over a length considerably exceeding the critical length and had resulted in catastrophic failure.

A check on the hardness of the CCOC in the vicinity of the bulged area suggested that temperatures of up to 930°C had been experienced by the casing, at which temperatures the material properties would have been significantly impaired.

The fuel nozzles from engine P 702868 were tested against the manufacturer's specifications for both the flow rate and flow pattern, which could affect the local heat distribution and thus the level of distress felt by the can. The conclusion of the tests was that they did not reveal any functional discrepancies compared with in-service standards.

The No 9 nozzle exhibited heavy wear of the outside diameter of the nozzle nut where it engages in the No 9 can, consistent with excessive movement of the can relative to the nozzle having occurred after 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 possible to bench test it and to extract various parameters relevant to the accident. In particular, it was found that there was no evidence to support a lack of 'idle speed repeatability' - *ie* failure to maintain an idle speed setting. The condition of the unit was generally as might be expected from a unit with about 15,000 hours since last bench calibration. The idle trim screw was found about mid-way in its 22-turn range. It was concluded that the unit was capable of running a JT8D-15 engine throughout its operational range.

FDR evidence indicated that both the right and left reverser systems deployed normally, but that only the right reverser retracted again into the stowed position; the left reverser remained fully deployed.

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

Analysis of the flight recorder data from preceding flights showed that the left engine oil pressure typically decayed to 35 psi at an N_2 of 26% (the oil pressure switch which inhibits the thrust reverser actuating system is set to trip at a nominal 35 psi). Recorder data for the accident flight indicates that the left engine oil pressure fell below this value 3 seconds after the reverser had deployed, but approximately 6.5 seconds before reverse thrust was de-selected (assuming right and left reverse were de-selected together), de-activating the operating system before reverse was cancelled.

1.12.2.2 *Fire (Appendix 8 Figs a-b)*

Fuselage

The whole of the rear fuselage aft of seat row 19 had collapsed onto the ground as a result of external fire attack on the fuselage lower skin and longerons between frames 867 and 907, and fire damage to the cabin floor structure which led to floor collapse over much of the area above the aft cargo hold. Aft of the wing trailing edge, between seat row 14 and the rear entrance vestibule, the fuselage was partially destroyed by a combination of external and internal fire. The greatest damage was concentrated on the left side in the vicinity of the aft baggage hold.

Empennage

The left tailplane lower skin panels were burnt through over a region extending from the tip inboard approximately 1m. The remaining lower skin panels over the outboard two thirds of the tailplane were burnt free of paint and buckled by heat, and the honeycomb panels and lower elevator structure had been partially destroyed. Inboard of this region, the damage tapered-off rapidly, leaving the innermost 50 cm almost undamaged and with little discolouration of the paint - comparable with the damage on the adjacent fuselage skin. The left tailplane upper surfaces exhibited little heat damage and were free of heavy sooting except for a small region approximately 2m wide at mid-span, extending from the leading edge back to approximately the half-chord position. The leading edge 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 droplets whilst the aircraft was moving at speed. This contaminated section of the tailplane leading edge was approximately in line with the outer lip of the deployed inboard (upper) bucket on the left engine thrust reverser. The upper surface of the elevator horn balance was heavily sooted and had suffered moderate heat damage. The left side of the fin and rudder were undamaged, with bright and clean painted surfaces.

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

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

Cabin interior (Appendix 3 Photos e-f)

The fire destroyed all of the overhead lockers except for a small section above seats 21B and 22B, which had remained in position but was badly charred. Remnants of overhead lockers were found randomly distributed throughout the cabin (there had been considerable disturbance by rescue personnel). The ceiling panels were all destroyed. The cabin side-liner panels were destroyed over most of the cabin aft of seat row 14, but forward of that location the panels had survived mostly intact below seat squab level; above squab level the aluminium backing panels had generally survived but the decorative plastic coating had mostly melted and peeled away in strips, or had been burnt off completely.

The carpet forward of seat row 14 was largely intact, except for some areas of localised burning from above, which matched damage on the adjoining seats. Aft of seat row 14, the carpet was burnt from below in the areas where the floor had collapsed, and from above where the floor panels had remained in position.

The seats on the right side of the rear cabin (seats 15 to 22 D, E & F) were completely burnt away leaving only the steel subframe 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 around the left overwing exit (rows 8 to 10), just forward of the floor collapse area on the right side (rows 13 and 14), and at the forward end of the cabin against the right sidewall (rows 1 to 5). Elsewhere, the seats were lightly or moderately damaged, but there was considerable variability and much of the damage appeared random. In particular, seats 8C and 9C were completely destroyed whereas the adjacent seats 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 the seats had been more severe than that above them. (Appendix 8 Fig c).

The upper halves of the forward entrance vestibules were sooted and, above chest height, the plastic decorative surfaces had partially burnt away. In contrast, the lower halves were free of significant soot deposits and there were no indications of heat damage. The rear vestibule was more severely damaged, but the fire's attack was mainly evident above waist level and was more pronounced on the 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 deck were heavily sooted and there were thick layers of oily soot on all horizontal surfaces, but each of these zones was free of heat damage.

There was no significant fire damage aft of the rear entrance vestibule nor below cabin floor level forward of the rear cargo hold.

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

The fire damage to the cabin interior as a whole did not fall into any single overall pattern, but it did reflect the general severity of damage to the adjacent structure, upon which was superimposed additional damage produced by burning overhead debris falling down onto the seats. Pockets of severe, isolated damage were present at several locations, but there was no direct evidence as to their cause.

Window panels

All three panels were missing from most of the window apertures in the rear cabin; some panels had remained in position in the three apertures immediately forward of the L2 door and the partially burnt remains of all three panels were still present in the aperture immediately forward of the R2 door. In the centre and forward sections of the cabin most window apertures had one or more panels present. All of the surviving outer window panels aft of the overwing exits displayed a cubic cracking pattern on their outer surfaces consistent with heating of the panel from outside. Forward of the overwing exits, many of the outer panels displayed similar damage but with the cracking on the inner surfaces - consistent with heating from inside the cabin.

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

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

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

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

The window apertures in which there were no panels remaining displayed widely differing degrees of heat damage and sooting in the areas normally protected by the silicone rubber window seals, giving an indication of the stage in the fire when the window panels became detached. Generally, the sooting and heating reflected the degree of fire damage evident in the adjoining area of cabin. However, in the apertures adjacent to seats 17A and 18A (in the left side burn-through zone) the paint was still present and relatively free of soot, although it had started to bubble due to heat - consistent with those panels and/or rubber seals having been in position until quite late in the overall fire sequence.

Cabin doors and overwing exits

All main cabin doors were found latched fully open. Both overwing exits had been opened and the hatches thrown to the ground. (There had been significant unrecorded disturbance of all cabin access points during the rescue.) Neither L1 nor R1 door had suffered significant damage during the fire, but sooting on the doors and apertures indicated that each had been open for most of the period of the fire. The fire damage on the doors and apertures at the rear of the aircraft was consistent with the R2 door having been open throughout the fire, and the L2 door having been closed throughout. The sooting pattern around the overwing exit hatches and hatch apertures indicated that the right exit had been opened during the 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 triggered 9 seconds after the combustion case ruptured, but the overheat detector did not trigger at all. Examination of the fire detector system was limited to the left engine sub-system.

The fire and overheat detector control modules were undamaged by the fire and performed satisfactorily when bench checked in accordance with the approved test procedures. The upper detector module overheat element was badly kinked and crushed during the engine rupture; all other detector elements were undamaged. All detector elements were electrically checked in the cold state and under hot conditions using approved test equipment; all performed within specification.

The power supply cable feeding the left engine overheat detector elements was severed in the area of damaged firewall above the ruptured engine casing, disabling the whole of the left engine overheat detector system. The remaining overheat detector wiring and 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 bottles had been discharged into the left engine. Subsequently, the then empty number 1 bottle had been "discharged" into the right engine.

The enclosure formed by the left engine cowls, upon which the system relies to contain the extinguishing agent, was lost as a result of the heavy damage sustained when the combustion case burst.

The APU fire extinguisher bottle was completely discharged.

1.12.2.4 *Fuel system*

The fuel system was in its normal take-off configuration with all 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 left tank was not damaged by the fire but had suffered extensive mechanical damage. The access panel on the lower surface immediately outboard of the ruptured engine combustion case had been broken out in its centre, producing an approximately 42 square inch hole directly into the tank interior (Appendix 9). Fragments of this access panel were recovered from the runway and one other fragment of the panel was recovered from inside the tank cavity. Reconstruction of the access panel fragments revealed witness marks and a pattern of distortion which matched exactly the shape of the No 9 combustor can dome and a fan case fragment.

Outboard of the engine, the skins forming the tank roof were torn upwards from the spars and the corresponding bottom skin, forming the tank floor, was severely bulged downwards. The tank ribs and internal structure were distorted in a manner compatible with chordwise tensile loading of the skins between the spars. With the exception of the damaged access panel, all damage to the left main fuel tank was consistent with a rapid overpressure of the tank cavity due to the ignition of fuel vapour in the outer section of the tank. The fracture surfaces at the upper skin/spar interface were relatively clean, whereas the adjoining skin surfaces were significantly sooted - indicating that the explosive overpressure occurred after the fire had been burning for some time.

At the start of the accident sequence the aircraft fuel load is estimated 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 directly because of the practical difficulty of emptying each tank separately. However, a tide mark of soot was found on the internal rib and spar surfaces inside the left tank at a height which corresponded to the level of the damaged access panel, enabling the post-accident fuel contents of the left tank to be determined and hence the total fuel loss to be estimated.

The total quantity of fuel lost from the punctured left wing tank is estimated to have been 2,109 kg (689 US gals at specific gravity 0.808), based on the position of soot 'tide-lines' on vertical surfaces wihin the interior of the left wing tank and the tank initial contents and taxi fuel consumption data.

The leak rate was estimated by the manufacturers, based upon their knowledge of fuel flow rates through the various baffles and the internal structure of the wing. This data suggested that the leak rate would initially be very high, in the order of 16 US gals per second, but this would decay rapidly as the tank compartment immediately above the puncture emptied. After about 40 seconds, the leak rate would have decayed to approximately 2 US gals per second and would remain at approximately that level until approximately 200 seconds. Beyond that stage,the rate would taper off and the flow would cease after a total time of approximately 250 seconds.(Appendix 9)

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

1.12.2.5 Oxygen

The emergency oxygen distribution system mounted in the overhead units was destroyed in the fire, but because the system was isolated there was no discharge of oxygen. Both passenger and crew reservoirs were 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 the slide container had fouled against the aft/lower radius of the aperture. A witness mark was present adjacent to the aft/lower corner of the lid which was consistent with contact between the lid and the door aperture.(Appendix 10 Photos a-c) The slide container lid is designed to be held closed by a latch mechanism, attached by a short length of cable to the 'girt-bar', which is manually engaged within two floor mounted brackets when the doors are 'selected to automatic' by the cabin crew as part of their pre take-off procedures. This latch will then automatically release the slide-box lid due to cable tension if the door is opened for emergency evacuation. The latch mechanism should not unlock until the door has cleared the aperture sufficiently to allow the slide to fall and deploy without any risk of fouling.

The R1 door slide was still inflated after the accident, as was that from the L1 door. The R2 slide had deployed fully, but had subsequently been partially burnt in the ground fire, causing deflation. The R2 girt-bar was still in position on the floor engagement brackets, with remnants of the slide 'apron' still attached and the manual inflation handle still fixed to its 'velcro' retainer.

Overwing exits

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

The seat next to this exit (*ie* seat 10F) was inspected in order to 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 on either side, could trap only a small foot if the seat cushion became displaced from its "velcro" retention.(Appendix 11) The photographs taken of this area immediately after the accident show this cushion to have been displaced but this mechanism could not have trapped this particular individual.

In addition, this seat (and seat 10A adjacent the left overwing exit) was of a type with a 'baulk' fitted to the seat-back hinge, designed to prevent the seat-back hinging forward and restricting access to the overwing exit. However, inspection of the baulk on the 10F seat showed that it had failed as a result of pressure applied from behind the seat-back. In addition, the position of the baulk was consistent with the seat-back having been displaced almost fully forward, onto the seat cushion. The corresponding seat at 10A was inspected and the associated hinge-baulk was found still intact.

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

In addition some survivors who had used this exit referred to a "white canvas strap" or "webbing" across the aperture. These descriptions were consistent with the ditching-strap/lifeline which is secured to the forward/upper corner of the overwing exit and 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 and gave the following results:-

> Access gap between front of row 10 seat cushions and back of row 9 seats: 10.5 inches
>
> Distance from front of seat 10F cushion to projected forward outside edge 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 width and also the width between the twin forward bulkheads gave the following 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 twin bench seat located on the left side adjacent the L2 door was found with the seat folded up, enclosing both sets of lap straps, with the associated buckles undone. The surfaces enclosed by the folded seat had escaped the effects of fire, in contrast to the upper area of the back-rest and associated shoulder straps, indicating that the seat had been unoccupied and folded-up before the heat had become intense. The cabin crew torch was still in its holder above this seat and was badly fire-affected. The interphone and passenger address microphone were still in their stored positions on the intercom panel located outboard of the seat-back. Although blackened by smoke, these units were not badly fire-damaged and the associated coiled wiring was intact. The aft-facing single cabin crew seat located on the right/aft bulkhead showed similar evidence of the seat having been in the folded-up position during the fire, with harness undone and protected by the seat.

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

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

Of the five cabin-crew 'Scott Aviation' smokehoods (15 minute endurance type), the three units which had been stored in the aft right overhead 'bin' at row 18 were found partially burnt and still in their respective cases. The two smokehoods for the forward cabin-crew were found undamaged and still in their bulkhead locker which faces the forward cabin-crew seat, together with the associated two pairs of asbestos gloves.

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

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

Of the ten portable oxygen bottles (of 120 litre capacity), nine were found in the cabin. One of these had explosively ruptured, leaving the bottom 6 inches on the cabin floor in the region of seat 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 board the aircraft was carried out by three teams of pathologists, each including one civilian pathologist and one aviation pathologist from the Institute of Pathology and Tropical Medicine (IPTM) at RAF Halton, Wendover. In addition, RAF odontologists assisted with the identification of the bodies. A special examination of the toxicology and histology aspects of the fatalities was carried out at the IPTM.(Appendix 12)

A marked deposition of carbon particles was found within the trachea of all victims, with some congestion of the mucosa (mucus lining) in 17 cases ("marked congestion" in the case of one passenger) with many instances of "excess mucus". The lungs of all fatalities showed marked general congestion and oedema (fluid), with carbon particles in the air passages, consistent with the inhalation of smoke. There was no evidence of organic disease which could have caused the death of any of the victims.

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

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

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

1.14 Fire fighting

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

The fire station ambulance, manned by RFF personnel, immediately departed for the West RVP to await the arrival of the GMC and Cheshire Fire Service appliances. The Airport Police also dispatched an escort vehicle to the West RVP. However, the GMC Fire Service had been alerted by the land line and told to report to the North RVP, which was in accordance with recently changed procedures.

RIV2 arrived at the scene approximately 25 seconds after the aircraft had stopped. It was positioned on the left side of the aircraft (Appendix 13 Figs a-d) and foam was applied initially onto the left side of the fuselage and then onto the left engine. RIV1 arrived shortly after RIV2, positioned off the nose slightly on the left side, and discharged the whole of its foam along the left side of the fuselage with the intention of protecting passengers, who by then were evacuating from the L1 chute, and cooling the left side of the fuselage. RIV2, having apparently knocked down the fire around the left engine, re-positioned to the rear on the left side, discharged its remaining foam into the rear fuselage, which by that time had collapsed to the ground, and was then re-positioned clear of the aircraft.

The Protector foam tender arrived at the aircraft approximately 30 to 40 seconds after the RIVs and positioned some distance off the nose, well on the right side. It then started to deliver foam into the area of the right overwing exit and the right rear fuselage, which appeared to be burning fiercely. Subsequently it was re-positioned twice, each time to bring it closer to the apparent seat of the fire on the right rear fuselage, before its water ran out. J1 arrived immediately behind the Protector, but was unable to position in the normally anticipated position on the nose of the aircraft because of the presence of RIV1. It was therefore positioned some 12 metres forward of the nose, slightly on the right side to the rear of RIV1, and foam was delivered down the length of the fuselage on the right side. This drove the flames rearwards, maintaining the forward and overwing exits clear of fire. Approximately 1 minute after commencing foaming, J1 was re-positioned onto the left side in order to attack more effectively the fire in the area of the left engine and rear fuselage.

J2 (the foam tender retrieved from the paint shop) arrived at the scene some 4 to 5 minutes after the aircraft stopped and positioned to the front of the aircraft in the area originally occupied by J1. Upon arrival, the driver of J2 saw an apparently lifeless body hanging out of the right overwing exit, and above this body a hand was moving. The driver immediately left his cab, climbed up onto the wing and pulled out a boy, who although unconscious was still alive and subsequently recovered. After this casuality had been handed down to officers on the ground, the fireman was forced off the wing by the smoke. Acting on the orders of the officer in charge, he then returned to J2 and applied foam along the top of the fuselage. Side lines were also deployed from J2 at this stage to cool a running fuel fire which was burning in the vicinity of the left engine. After some determined effort, this fire was eventually extinguished using two 50 kg units of Halon (BCF).

Approximately 7 minutes into the incident, after it became clear that no more passengers were likely to emerge unaided, a team with breathing apparatus made an entry via the R1 door. Conditions inside the cabin at that time were very bad, with thick smoke and a serious fire in progress at the rear of the cabin. Shortly after entering, an explosion occurred which blew one of the firemen out of the door onto the tarmac. The officer in charge was by that time becoming increasingly concerned about the reducing water supplies, especially with regard to the potential loss of water supplying sidelines deployed within the cabin, and directed that there would be no more attempts to gain entry until there was a reliable supply of water. In the interim, sidelines were used on the exterior only. At about this time a fire was seen to flash briefly along the cabin.

About 8 minutes into the incident the GMC appliances, carrying a total of 1,600 gallons (7,272 litres) of water, arrived at the North RVP but there was no police escort there to meet them. Some 3 minutes later, the GMC appliances were still without an escort and a radio call was made to GMC fire control advising them of the situation. Shortly after this transmission, a police escort arrived and the convoy set off for the scene.

By approximately 11 minutes into the incident, the internal fire appeared to have spread forward throughout the cabin, where breaches in the roof could be seen. J1 was dispatched to replenish with water from the hydrant system: the vehicle was positioned at three hydrants in succession, but no water could be obtained from any of them. This resulted in a delay of about 10 minutes, after which J1 returned to the scene empty. It was then dispatched to the hydrant behind the fire station, where replenishment was successful. However, the hydrant discharge rate was such that this took between 15 and 18 minutes and the vehicle returned to the scene too late to play any further active roll. The Protector foam tender was also despatched to the fire station to replenish with water.

The GMC fire appliances arrived at the aircraft approximately 13 minutes into the incident. Initially, the Station Officer (SO) in charge experienced some difficulty in identifying the officer commanding the airport fire service, resulting in some delay before the water requirements were identified and the transfer of the 1600 gallons of water from the GMC appliances to J2 could begin. Using a sideline from the newly replenished J2 tender, a two man team with breathing apparatus was then able to make an entry via the R1 door using a short ladder, and, for the first time, were in 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, took command of the emergency services. At +29 minutes, unaware of the earlier problems with the hydrants, he ordered a hose relay to be set up and this was done, using one of the RIVs to carry hose across to hydrant 130. On this occasion the hydrant supplied water. Shortly afterwards, the GMC DO and SO each donned breathing apparatus and entered the cabin via the R1 door. Conditions inside at this time were poor, with very limited visibility. Two bodies were visible and the DO left the aircraft to transmit a message advising that there were fatalities. Upon re-entering the aircraft, the smoke had cleared somewhat and further casualties could be seen at the rear of the aircraft.

At approximately +33 minutes a male survivor was found near the front of the aircraft. Regrettably this casualty, who was the last 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 effects of the fire on the left side of the aircraft rapidly instilled fear and alarm in many passengers, particularly those in the aft/left cabin - *ie* row 14 aft. These effects appear to have been marked heat radiation through the windows together with "cracking, melting and smoking" of the window transparency panels, which motivated some passengers from the aft cabin to enter the aisle and move forward before the purser's 'sit down' announcement on the PA, and therefore before the evacuation call 14 seconds prior to the aircraft stopping.

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

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

Many survivors from the front six rows of seats described a roll of thick black smoke clinging to the ceiling and moving rapidly forwards along the cabin. On reaching the forward bulkheads it curled down, began moving aft, lowering and filling the cabin. Some of these passengers became engulfed in the smoke despite their close proximity to the forward exits. All described a single breath as burning and painful, immediately causing choking. Some used clothing or hands over their mouths in an attempt to filter the smoke; others attempted to hold their breath. They experienced drowsiness and disorientation, and were forced to feel their way along the seat rows towards the exits, whilst being jostled and pushed.

Many, even in the forward cabin, resorted to going over the seat backs in order to avoid the congested aisle. This was reported by passengers in seats 7A, 6B, 5D, 3E, 3Fand 2F, in addition to statements from passengers who confirmed that they had gone forwards over the seats. Some stated that "the smoke generated an immediate sense of panic".

At the start of evacuation from the L1 door, the stewardess stated that passengers seemed to be jammed in the cabin aisle and entrance to the galley (*ie* between the twin forward bulkheads). She cleared the jam by pulling one young passenger forwards and the flow then started. Later she saw a young girl lying on the floor of the forward aisle. She pushed another youth back, pulled the girl forward by her collar and pushed her down the slide. As the passengers came forward through the bulkhead aperture so the smoke built up in the forward galley area. She recalled feeling a body slump against her legs, bent down and, due to improved visibility near the floor, saw that it was another girl passenger. Her face was black with soot, eyes fixed and dilated with no signs of breathing. The stewardess considered giving her the kiss of life when a fireman down below shouted for her to throw the girl down to him. With great difficulty she lifted her by the waist and threw her onto the chute. After being forced down by the smoke onto her hands and knees, the stewardess felt around for other passengers back as far as the galley cabin entrance. She was considering getting her smokehood when a fireman shouted at her to jump, concerned that she would perish if she delayed. Having been unable to locate any further passengers, she went down the slide.

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

The aisle aperture between the twin forward bulkheads in this configuration was 22½ inches wide, effectively restricting passengers approaching along the aisle and over the seat backs to a single-line exit flow in spite of both forward doors being open from approximately 1 minute 10 seconds after the aircraft stopped. Many passengers, in addition to the two females assisted by the stewardess, collapsed in this area but survived. Unfortunately one of these passengers, (from seat 8B) who was found some 33 minutes after the aircraft stopped, died some 6 days later due to lung damage and associated pneumonia. Four bodies were eventually recovered from the area of the forward aisle.

The 18 passengers from the front 3 rows of seats appear to have escaped from the forward exits before being affected by the smoke. In addition 3 passengers from row 13 and 2 passengers from row 14 were also unaffected. Thus, of the 17 passengers who escaped from 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 passengers themselves, motivated by the fact that the forward aisle was by this stage blocked with passengers waiting to exit through the forward galley area, with others already making their way over the seats. The female passenger in seat 10F adjacent to the right overwing hatch, upon being exhorted by passengers behind to open the door, undid her seat belt and turned in her seat to face the hatch. She saw the 'Emergency Pull' instruction at the top of the hatch, but pulled at the armrest which was fixed to the lower area of the hatch. She was not familiar with the door opening procedure and unaware if the door was hinged at the top, bottom, left or right, or if it would come straight off. Her female friend in seat 10E stood up and pulled at the release handle adjacent to the instruction. The hatch, which weighed 48 lbs, fell inboard across the chest of the passenger in 10F, trapping her in her seat. She managed to get out from under the door and a male passenger sitting behind her assisted by lifting the hatch over the back of row 10, depositing it on the vacant seat 11D. This exit was seen to be open by about 45 seconds after the aircraft stopped. The two female passengers escaped onto the right wing and both jumped down from the leading edge, the passenger from seat 10E twisting her ankle. At that stage, there was no foam on that side of the aircraft. A number of other passengers quickly followed them out including the occupants of 10C and 10D carrying their children.

The girl from seat 10E stated that there had not been enough room between the seats at row 10. A further passenger from 15D also commented on the lack of space at the overwing exit and more generally about "Far too little space to evacuate the plane in a panic situation, 2-3 exits not enough".

Shortly after the right overwing exit was opened, it was obscured by dense black smoke which came forward from the aft cabin. The smoke poured out of the overwing exit, which was on the down-wind side of the fuselage. The smoke was consistently described as heavy, thick , black, acidic, toxic and very hot. As observed by the forward cabin passengers the effects of this smoke on the respiratory system was rapid and for some catastrophic. Within one or two breaths of the dense atmosphere survivors recall burning acidic attack on their throats, immediate and severe breathing problems, weakness in their knees, debilitation and in some instances, collapse. A male passenger from seat 15C recalled taking one breath which immediately produced "tremendous pain" in his lungs and a feeling that they had "solidified".

Very rapidly the area around the overwing exit became a mass of bodies pushing forward to the exit. People all around were falling and collapsing to the floor. Many passengers who ultimately got out of the right overwing exit, nevertheless collapsed temporarily within, or adjacent to it. The exit was blocked with "people's bodies lying half-in and half-out of the aircraft". A male passenger, from 16C, died after becoming lodged in this right overwing exit. A young boy, from 12D, was pulled out over this man's body by a fireman about 5½ minutes after the aircraft stopped. It is notable that some passengers managed to escape forward from the worst area of the rear cabin only to succumb within the central area. Several of the survivors who used the overwing exit were impeded by becoming entangled in the ditching strap. However, one passenger recalled catching hold of it as she collapsed, to recover consciousness with her head outside the exit.

Of the 24 passengers who escaped from the right overwing (not including the 2 young children and the young boy pulled clear) some 11 passengers (46%) went over the seats as opposed to using the congested aisle to get there. Only two of the 24 reported seeing fire in the aft cabin. More observations of fire in the aft/centre cabin were reported by passengers before they evacuated from the forward exits. A passenger from 8D recalled looking around after the aircraft had stopped and seeing huge tongues of flame shooting into the cabin through the windows of the fuselage on the left side. He stated that flames commenced at the first window past the central emergency hatch with six or seven windows behind thus affected. The flames were lapping up to the ceiling. Several people who were in seats nearest these windows were seen engulfed in 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 separated the front half from the back. Another passenger from 6B, after seeing foam being sprayed over the fire on the left side of the aircraft, tried to move into the aisle but it was jammed with people and it was difficult to move. On turning he saw flames shooting in through the side windows and up through the floor area. The flames were several feet in length and continual.

The fireman who, after rescuing the young boy, attempted to rescue the man jammed in the overwing exit, reported feeling "dizzy" from the effects of the fumes and smoke. Comments on the effects of 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 aircraft with the intention of taking them to their flight office after clearing Customs. When the driver saw the aircraft on fire he informed his passengers that he was taking the coach to assist at the accident. Upon arrival (at approximately 4 minutes after the aircraft stopped) the cabin crew immediately went to the assistance of the survivors, many of whom ran towards the coach. The first evacuees were in a state of shock, but dry, whereas those following them were blackened with smoke and wet with foam. Several stewardesses assisted a woman who was lying approximately 100 yards forward of the aircraft and appeared unconscious. She was being given cardiac massage by a fireman. After resuscitation with oxygen, this passenger began to recover and a deep wound was found on the back of her head. She was taken to an ambulance. A young girl of approximately 17 years, was also found in the grass forward and to the left of the aircraft. Her face was black, hair wet, and her eyes "frosted over" with a white deposit. She had 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 having difficulty in breathing and thick mucus was pouring from his nose and mouth. A stewardess hit him in the back, the practised method of causing a cough reflex. As she did this, he started to cough and his breathing became easier.

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

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

The young boy, whose condition was deteriorating, was not taken directly to the hospital, but was taken to the Fire Station in a catering van by a British Airways stewardess, where he was reunited with his father. The remaining survivors had been taken to the fire station crew room by the Manchester Airport coaches. These survivors were later taken to Wythenshawe Hospital. Many British Airways cabin crew staff stayed at Wythenshawe Hospital to console the survivors and also to take names and addresses for dissemination to relatives.

A cabin seating plan showing which passengers used each exit and the 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 that uneven temperature distributions can occur, producing areas of locally relatively high temperatures. The combustor cans from the left engine of G-BGJL and others from the same operator showed evidence of localised 'hot-spots' *ie* areas of the can liner material exhibiting excessive overheat blistering and/or multiple cracking. Such local effects can also be produced by different causes, such as a distorted fuel nozzle flow pattern, distortion of the dimensions of the can or cooling airflow disturbance caused by repairs or faulty design/manufacture.

In order to measure the temperature of these hot-spots and the general temperature distribution and gradients around the can, a series of tests was undertaken using a JT8D-15 engine loaned by the operator and using the operators facilities. The engine was assembled with part-run cans which had been painted internally and externally with temperature sensitive paint. The engine was then run through a typical British Airtours cold day take-off and pull back sequence, returned to idle for a short time and shut down. The cans were removed and the paint examined. A suitable can was then selected to be instrumented for a further test. For this test, seven thermocouples were attached onto the outside of the can at various locations including on-and-around a hot spot in the 3rd/4th liner joint area identified from the heat-sensitive paint. An eighth thermocouple was used to record combustor inlet air temperature (T4). All the cans were re-coated with heat sensitive paint and then re-assembled into the engine.

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

a) Exhaust Gas Temperature (T7) changes approximately equivalent to a 15°C increase in ambient temperatures.

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

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

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

It was noted that the temperature of the hot spot rose dramatically as peak power was approached *ie.* at a greater rate than simple theory would have predicted. It is hypothesised that a concentration of combustible reactants in the wall cooling layers became rich enough for combustion to begin next to the wall itself, elevating the liner temperature disproportionately.

The results of these tests were used to estimate the stress levels generated by thermal cycles and a simplified mathematical model used to calculate the stress/cycle relationship for Hastelloy X material. The tests showed that temperature gradients of at least 150°C and possibly 200°C over 2-3 mm can be anticipated at peak power, and the calculation showed that thermal stresses in the order of 29,000 psi would therefore be generated in the liner material. Tests on sample Hastelloy X material at elevated temperatures showed that, at this stress level, the fatigue life of the material would vary between 100 cycles at 980°C to 1,000,000 at 815°C. These results serve to emphasise the very damaging effects of high temperatures and it can therefore be argued that hot spots in the can will suffer rapid localised cracking within, say, 1,000 flights from new or repair whilst the cooler regions would have a vastly greater life. The fatigue life of the can is thus essentially limited by the performance of the cooler, longer-life regions, rather than the performance of 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 synthetic foams used in cabin-seat cushions. Thermal decomposition of such foams in air produces a complex mixture of smoke and gases, which not only varies with the type of foam (*eg* polyurethane, polyetherurethane etc) and whether it has added constituents (*eg* flame-retardants), but is also dependent upon combustion conditions - *eg* flaming or non-flaming (*eg* smouldering) conditions. However, the other cabin materials such as wall panels, windows/surrounds, overhead passenger 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 of seat-foams and other cabin materials is contained in a Federal Aviation Administration (FAA) report[1] (Appendix 15a). These data indicate that the well known problems associated with the foams used in cabin seat-cushions represent only one part of the general problem concerning the products of combustion of aircraft cabin materials.

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

Polyurethane foam produces less hydrogen cyanide than modacrylic material, which can be used for curtains, carpets etc. Relatively small weights of any such materials can produce substantial concentrations of toxic/irritant gases and smoke when burnt within an aircraft cabin volume.

> *eg*. The burning of only some 5.7 lbs of modacrylic curtain material in 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, carpets etc (as was the case on G-BGJL), but also produces hydrogen cyanide, although in reduced quantities.

Fluorinated materials which are frequently applied in the form of decorative films to cabin wall panels (*eg* 'Tedlar' Polyvinylfluoride finish on the wall panels of G-BGJL at Manchester) emit the intensely irritant hydrogen fluoride acidic gas when burnt.

Fibreglass materials generally exhibit much lower toxic/irritant gas emissions, dependent upon the resin used - *eg* phenolic fibreglass is superior in this regard to epoxy fibreglass. Such materials can 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 15 Table c)*

The effects of those gases which are generally recognised as the important toxic/irritant components of such combustion atmospheres are listed below:

Carbon Monoxide (CO):

Carbon monoxide is produced when any combustible cabin material burns incompletely, or in reduced oxygen conditions. It is always present, often in high concentrations, in large uncontrolled fires. It is the agent that is generally accepted as being most responsible for deaths due to smoke inhalation. In large fires involving kerosene fuel, large concentrations of carbon monoxide can be expected.(eg the tests at Teesside, where carbon monoxide concentrations of several thousand ppm were measured inside a Trident fuselage during a large-scale test demonstrating water spray systems)

When carbon monoxide is inhaled, it is absorbed by the blood from the lungs and combines with haemoglobin to form carboxyhaemoglobin. This reaction inhibits the absorption and therefore the transport of oxygen to the body tissue. 10-20% carboxyhaemoglobin in the blood 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. Recovery can be effected from lower concentrations, since the reaction is reversible with the administration of oxygen to the victim.

The effects of a given concentration of carboxyhaemoglobin are influenced by physical activity.

Hydrogen Cyanide (HCN)

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

Nitrogen Dioxide (NO_2)

This gas often occurs with other nitrogen oxides, such as nitric oxide (NO), in fires and is often denoted as NO_x, for this reason. Nitrogen oxides combine with moisture to form nitric and nitrous acids. These can be absorbed directly, or with the carbon particles of smoke which have 'adsorbed' these acids. The acids attack the throat, trachea and lung tissues and are highly irritant. Some of the acid may also be neutralised by an alkaline reaction within the tissues producing nitrate of sodium. Nitrate absorption causes arterial dilation, hypo-tension, headache, vertigo and the formation of methaemoglobin.

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

Hydrogen Fluoride (HF)

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

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

Hydrogen Chloride (HCl)

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

Sulphur Dioxide (SO_2)

This gas is produced on combustion of both natural and synthetic rubbers and other compounds containing sulphur. It combines with moisture to produce sulphurous acid which is highly irritant to tissue, including the eyes. It attacks the mucous membranes of the respiratory tract, causing uncontrollable coughing. Very high concentrations can induce respiratory paralysis.

Ammonia (NH_3)

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

Acrolein (CH_2 CH CHO)

Acrolein is one of the most irritant of the aldehydes produced by the combustion of cabin materials. It is also produced in small amounts from burning kerosene and from the combustion of natural materials such as wood and cotton. It is an intense eye irritant and in concentrations as low as 5.5 ppm has been shown by Deichmann and Gerarde[2] to cause irritation of the upper respiratory tract. At higher concentrations, pulmonary oedema occurs, with death after a few minutes at only 10 ppm.

Aromatic hydrocarbons (*eg* Benzene, Toluene, Styrene etc)

A whole range of aromatic compounds are produced by the thermal degradation of synthetic (and natural) materials. They produce varying degrees of narcosis. Several of these aromatics such as benzene (from PVC) are not only absorbed due to inhalation, but can also be absorbed directly through the skin. Concentrations of 100 ppm are considered injurious to health. Toluene is less toxic than benzene but, conversely, represents a greater danger in chronic exposure.

Styrene is considered safe at concentrations less than 100 ppm, but above this is highly irritant to the mucous membranes, causing symptoms of toxicity with impairment of the neurological functions. In concentrations of approximately 800 ppm, it causes 'styrene disease', characterised by nausea, vomiting and total weakness.

Aliphatic hydrocarbons

Thermal degradation of all organic materials produces a variety of aliphatic compounds. Some of these compounds with the lower molecular weights can produce narcosis. Unsaturated hydrocarbons generally have a greater toxic effect than saturated compounds. Acids, alcohols and aldehydes may be present with their respective toxic effects.

Acetaldehyde

This is produced from the thermal degradation of a wide range of synthetic (and natural) materials. It is an irritant gas which can 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 into the atmospheres associated with aircraft fires, and much valuable work has been done particularly by the FAA Technical Centre at Atlantic City, the tests in general have been rather limited in terms of the fire-model used. There is a lack of information concerning the atmospheres generated in differing types of fire, covering a wide cross-section of situations. This has led to the 'read-across' of such results from rather specific test scenarios to general aircraft fire accidents.

The FAA Technical Centre has, for many years, carried out full size fire tests on a Lockheed C133 fuselage, extensively thermally insulated to withstand repeated fire tests. The test set-up was intended to simulate a pooled-fuel ground fire attack on the cabin interior via a door aperture (76" x 42") representing a breach in the fuselage. An 8 ft x 10 ft 'tray' of kerosene was ignited immediately outside the aperture and the resultant thermal radiation of 1.5 BTU/sq ft/second initiates an internal fire amongst the cabin furnishings. A second single door was used to exhaust the combustion products from the cabin.

This test series[3] has demonstrated one phenomenon repeatedly - ie that of 'flashover' (Appendix 16 a). Flashover occured at about 2¼ minutes after the tray-fire had been initiated. At this point the cabin temperatures soared to approximately 1,700/1,800°F at ceiling level near the fire aperture plane. In addition the oxygen level, which remained at the normal 21% prior to flashover, reduced to approximately 12% after 3 minutes 10 seconds (measured at 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 fluoride are shown as being emitted in significant concentrations, rising to some 830 ppm and 840 ppm respectively.

2. The carbon monoxide concentration appears negligible (approximately 100 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 survivable aircraft accidents with fire-related fatalities have shown significant cyanide absorption by the victims.

The limiting incapacitation time based on calculations from this type of data and applicable to three heights within the cabin - ie at the 5ft 6 inch, 3 ft 6 inch and 1ft 6inch levels , give respectively a time to theoretical incapacitation of 2 minutes 39 seconds, 3 minutes 13 seconds and 3 minutes 22 seconds (Appendix 16 Fig d). It is notable that for these tests the thermal part of the total incapacitation threat, even after flashover, was very small when compared to that due to the effects of hydrogen chloride, hydrogen fluoride, carbon monoxide and hydrogen cyanide.

Thus, even given this extreme situation of flashover within 2¼ minutes of the cabin interior being exposed to the heat flux from a large pooled-fuel fire, it would appear that incapacitation may be delayed beyond flashover in parts of the cabin away from the fire, until some 2 minutes 39 - 3 minutes 22 seconds. Furthermore, experience from real aircraft fires indicates that this situation is not always encountered - *ie* flashover is either significantly delayed or may not occur generally at all in the cabin.

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

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

In addition it is the case, from pathological examination, that the majority (c.80%) of fire fatalities occur not due to direct and excessive thermal assault, but due to smoke/gas incapacitation[4].

Tests have also been carried out at the FAA Technical Centre on the effectiveness of seat cushion 'fire-blocking' coverings. Polyurethane foam cushions covered with materials such as 'Vonar' have been tested against unprotected foam cushions, both in simulated ground fire situations and also internal cabin fires with air-conditioning air-flow, to simulate in-flight fires. These tests indicated an increase in the time to incapacitation of about 60 seconds as a result of reduced cabin temperatures (Appendix 16 Fig e). It should be noted, however, that fire-blocking layers merely delay the onset of combustion of these cushions in a full-scale ground fire situation.

One aspect of the 'in-flight' tests is of interest. Flashover did not occur during the time that 'air-conditioning' air-flow was being used, but when it was shut-off at approximately 3½ minutes, flashover occurred very quickly thereafter, within 30 seconds. It is also notable that well before this time, and indeed from the start of the fire, the concentrations of hydrogen fluoride and hydrogen chloride became critical, in spite of the air-flow operating. However, during this period the oxygen concentration remained at 21%.

The final fire test of the C133 series was carried out on the 30 July 1987 and produced some interesting new data. In this test some 105 seats were installed in the cabin. All seats were of the new 'fire-blocked' type. The fire, which in earlier tests was extinguished after some 5 minutes, was allowed to continue for some 15 minutes. The hydrogen cyanide sampling was located at a higher level in the cabin than in all previous tests - *ie* at a height of 5½ feet above the floor. For the first time, some 200 ppm of hydrogen cyanide was detected in the time before flashover occurred (latter took place 4 minutes from the initiation of the fire). In addition, some 700 ppm of hydrogen bromide was also detected before flashover. This emission was attributed to the epoxy-fibreglass material of the wall, overhead stowage 'bins' and ceiling panels. Hydrogen fluoride and hydrogen chloride were also 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 materials certification, FAR 25.853, was adopted in May 1972 and specifies that all large usage material must be self-extinguishing in a vertical orientation when subjected to a 'Bunsen-burner' flame. Whilst such a test may be useful for demonstrating protection against a small flame in a cabin, it clearly does not indicate the results of exposure to a large external (*eg* pooled-fuel) fire.

As a result of their awareness of the clear deficiency of this certification 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 issued on 30 December 1974. This notice invited 'public' participation in developing standards governing the toxic gas emission characteristics of compartment interior materials when subjected to fire.
>
> Also, Notice of Proposed Rule-Making (NPRM) No 75-3 was issued on 12 February 1975. This notice invited comments on proposed amendments to FAR parts 25 and 121 concerning the introduction of limitations on smoke emission characteristics of compartment interior materials when subjected to fire.

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

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

After its investigations into cabin materials technology, this committee issued recommendations concerning further research and development of materials, investigation of the problems of smoke and 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 from such recommendations. The flashover phenomenon, which was apparent during these tests, sustained the flammability approach to materials certification, but it appears to have done so at the expense of any serious consideration of smoke and toxic/irritant gas emissions. The associated justification for this was that:-

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

(2) The severe hazard from toxic emissions occurs as a result of flashover in fires involving interior materials. The level of toxic gases measured before flashover or when flashover did not occur, were below levels estimated to prevent occupant survival."

Both of these conclusions are severely undermined by the last C133 fire test on 30 July 1987, when some 200 ppm of hydrogen cyanide 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/sq cm.

The current regulatory response to this problem has thus been to continue to approach it solely through material flammability criteria, excluding any certification requirements for smoke or toxic/irritant gas emissions.

In this context, a discussion document issued by the FAA in July 1986 requesting further comments on their 'Improved Flammability Standards for Materials Used in Interiors of Transport Category Airplane Cabins' is of interest. In response to requests from two commenters from the materials industry for assurance that no rule-making with respect to smoke and toxicity was anticipated in the foreseeable future, the FAA replied ; "Based on the information currently available, the FAA has no plans to establish standards for either smoke or toxicity; however this does not preclude taking such action in the future if, as noted above, further research shows such standards are warranted and human tolerance levels can be adequately defined." The FAA thus amended FAR parts 25 and 121 to include the OSU test, on 20 August 1986.

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

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

Research work[5] completed as early as 1973 into smoke emission from aircraft interior materials indicated that:-

> "To date the major concern of those engaged in the development of fire-retardant materials has been the reduction of the ignition tendency and flame propagation. Thus, it has been possible to meet code and regulatory requirements regarding flame-spread but in the opinion of the author the total hazard resulting from incomplete combustion has been increased".

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

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

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

Whilst this type of testing represents a considerable improvement in materials certification, the radiant heat flux used to combust the material sample is still low (2.5 watts/sq cm) compared with the radiant heat from a real pooled fuel fire which can rise to 14-20 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 cyanide and carbon monoxide etc, the 'acid' gases such as hydrogen chloride, hydrogen fluoride, sulphur dioxide etc. attack the eyes, causing intense irritation and lachrimation (discharge of tears). Considerable research has been carried out into the effects on vision of smoke emissions from burning cabin materials[7], revealing that:-

> "The predominant factor affecting visibility is not the obscuration of vision by particles of smoke, but the irritating effects of combustion gases,

predominantly hydrogen chloride and sulphur dioxide. 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 strongly related to the irritating effects of combustion gases generated from flaming materials in a crash-fire situation".

Further research work carried out in Japan[8] also highlighted the marked effects of irritating gases on vision:-

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

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

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

Notwithstanding such research evidence, the regulatory authorities had for some time been progressing towards a requirement for low level lighting within aircraft cabins with the intention that evacuating passengers would be able to follow the lights to escape more 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 particularly the short landing/fire accident to a Boeing 727 aircraft at Salt Lakes 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 initiated research into passenger smoke protection.

A simple hood was developed made from 'Kapton' polymide, a high-temperature resistant translucent material which could protect the head against temperatures of 800°C. This simple device had no air supply, filter or carbon dioxide absorbent and merely provided a reservoir of air within the hood sufficient for some 1½-2 minutes breathing under heat/exercise conditions.

The first model, which featured a 'draw-string' neck seal, was quickly 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 reflect radiant heat. In the following 4 years, considerable testing was carried out on these hoods[9] and included:-

neck seal leakage evaluation (including exposure to carbon monoxide and smoke);
breathing capacity and carbon dioxide build-up under exercise conditions;
visibility measurements;
acoustic measurements;
effects of variations in safety briefings on use of hoods by naive subjects;
evacuation tests using naive subjects in dense non-toxic smoke conditions.

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

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

On February 27/28th 1968, more extensive evacuation tests were carried out at the Aeronautical Centre, Oklahoma. An FAA Boeing 720 aircraft was fitted with a passenger seating capacity of 124 with 4 stewardesses supplied by Braniff. A total of six evacuation tests were carried out, both with and without smoke. The associated report concluded:-

> "There are indications that the use of smokehoods during an emergency evacuation of a typical air carrier jet aircraft causes a small increase (approximately 8%) in the overall time required for naive passengers to evacuate".

The results of this test and the other research were judged satisfactory by the FAA and on the 11th January 1969 NPRM 69-2 was published in the Federal Register, with the intention of amending FAR part 121 to require that protective smokehoods be carried for all occupants on aircraft operating under these regulations:-

> "These hoods would be available for use by their occupants to facilitate airplane evacuation when fire or smoke is present after a crash-landing or other emergency".

Whilst there was much support for this proposed change, some sections of the aviation community were unconvinced. On the 11th August 1970, NPRM 69-2 was withdrawn by the FAA, with the principal reason given that the hood might cause a delay in evacuation.

In late 1971 a comprehensive report on smokehoods was reviewed by the US National Research Council. They rejected the viewpoint that carbon dioxide accumulation in the hood and the accompanying hyperventilation would cause passengers to remove the hood, but suggested the addition of a carbon dioxide absorber and oxygen supply to the hood to extend usage. The feasibility of using a small chemical oxygen source was investigated.

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

> "Survival and escape of passengers in a transport cabin fire may be impaired or prevented by smoke and toxic gasses. Advancements in protective breathing devices and limited progress in the minimization of cabin fire hazards prompted the SAFER (Special Aviation Fire and Explosion Reduction) Committee Technical Group on Compartment Interior Materials to recommend a re-assessment of protective breathing devices for usage by passengers aboard Part 25 Aircraft".

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

In 1983, as a result of their investigation into the in-flight fire and emergency landing accident to an Air Canada DC9 at Cincinnati on the 2 June, in which 23 of the 41 passengers died before they could evacuate the cabin (and survivors breathed through hand towels), the National Transportation Safety Board (NTSB) issued Safety Recommendation A-83-76 on the 31 October 1983. This recommended that the FAA:-

> "Expedite the research at the Civil Aero Medical Institute necessary to develop the technology, equipment standards, and procedures to provide passengers with respiratory protection from toxic atmospheres during in-flight emergencies aboard transport category airplanes".

It is also noteworthy that in July 1982 a very comprehensive report, sponsored by the FAA, was issued on the problems of aircraft fire[10]. This report included a very detailed cost/benefit analysis of a wide variety of different approaches to combat fire on aircraft. It concluded that smokehoods were by far the most cost-beneficial approach for survivability and would achieve the highest survivability factor, 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 March 1986, it was confirmed that the 'rebreather-bag' approach was unlikely to prove satisfactory for passenger smoke protection. It was also established that CAMI had not, at that stage, carried out any assessment of modern breathable-gas or filter type hoods.

It was therefore confirmed that the AAIB would continue to fund and direct a research/test programme to explore the potential of breathable gas and filter hoods. Work on this programme had begun in January 1986.

1.16.3.1 *Breathable gas smokehoods*

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

Using test protocol 1 (Appendix 18 a), it was found that none of the 5 hoods achieved a fully satisfactory standard, with three of the hoods requiring an increased oxygen capacity and at least one other hood needing improved carbon dioxide absorption. These results were not altogether surprising since each of the hoods tested had been developed prior to the CAA draft specification, which was used as the basis for these tests.

In the spring of 1987, 2 of the latest standard of passenger type hoods were tested, together with a cabin crew hood of the same type used in the earlier tests to provide comparative data. These tests were carried out in the laboratories of the Scientific Division of British Coal at Edinburgh, using an 'Auer' lung simulator. (Appendix 18 b)

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

In the first two protocols, both passenger hoods substantially out performed the cabin crew hood which weighed 3 lbs, compared to the 1 lb weight of each passenger hood.

The first passenger smokehood surpassed the CAA Draft Specification 20 minutes endurance with ease, achieving 28 minutes (with the final 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 period was extended to 25 minutes in a later test this type of hood achieved an endurance of 31 minutes before the inhaled carbon dioxide concentration exceeded 5%.

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

The tests at Porton Down indicated that elasticated septal neck seals alone were capable of providing adequate sealing against the external atmosphere. It was considered that the addition of an 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-protection could be regarded as a viable approach to survival in aircraft fires, since there was a widespread belief that there is insufficient oxygen in fire atmospheres. However, the young boy and man survived the fire at Manchester, others have survived for protracted times in other aircraft ground fires and there have been many instances of passengers surviving in-flight fire/smoke situations - *eg* the Canadian DC9 at Cincinatti in June 1983 (para. 1.17.7), where most survivors breathed through wet hand-towels issued by a stewardess.

In addition, the large amount of data from the C133 Fire Test Programme at the FAA Technical Centre, Atlantic City, indicated that the available oxygen concentration in the cabin did not reduce appreciably until temperatures exceeded human tolerance levels. Similar evidence was apparent from the earlier NAFEC cabin fire tests carried out in 1965. Thus, whilst this vital question is still open to the consideration of further data, based on this assessment carried out early in 1986 there appeared reasonable grounds to proceed with a scientific evaluation of filter-protection in order that the other important questions of particulate-induced blockage, 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 this question, which began to emerge as the research data was examined, appeared to be that although fires are variable, the prime reasons for incapacitation, which appeared generally accepted, were those associated with hydrogen cyanide and carbon monoxide toxic gas absorption and the related problems of attack by irritant gases such as hydrogen chloride, hydrogen fluoride, nitrogen oxides, sulphur dioxide and acrolein.

With regard to carbon monoxide, there is a body of opinion that this particular gas is slow to reach incapacitating concentrations in fires and that much of the pathological evidence of high carboxyhaemoglobin levels in fire-fatalities derives from post-incapacitation absorption, before respiration ultimately ceases. It is contended that hydrogen cyanide, which can cause rapid incapacitation at very low concentrations of approximately 200 ppm, is the more potent toxic gas. This was an important consideration, since although carbon monoxide can be countered by catalysts such as Hopcalite[2*], this requirement increases the weight and depth of any filter.

Since however, the aim of the AAIB tests was to evaluate the best protection that filters could provide, a firm decision was made that any filters to be tested within the AAIB smokehood test programme would be required to combat carbon monoxide.

Following a search of available data the following Challenge Atmosphere and 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 included in Passenger Smokehood Acceptance Criteria, issued by the AAIB on 5th March 1986 to interested manufacturers within the UK and abroad, which included requirements for the following parameters:-

filter performance, including carbon dioxide limitations (5%);
inhaled gas temperature limitations (45°C, wet);

[2*] Hopcalite A heterogeneous catalyst, prepared from a mixture of Manganese Dioxide (MnO_2) and Copper Oxide (CuO), which converts Carbon Monoxide (CO) to Carbon Dioxide (CO_2).

flame and molten drop resistance;
robustness;
weight (1 lb);
compactness;
donning time target (8 seconds) for both breathable gas and filter-type hoods.

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 burning a wide cross-section of cabin materials and kerosene in order to 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 atmosphere in a large 34 cubic metre chamber, lined with polypropylene. By June of 1986 the atmosphere could be generated on an acceptably repeatable 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, and sulphur dioxide was achieved, although hydrogen chloride levels were still variable.

The range of cabin materials used to generate the atmosphere were as 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'/Polyvinylfluoride film used to cover aluminium alloy side panels on the Boeing 737) were not included within the above list of materials due to current health concerns regarding the combustion of fluorinated compounds. Separate tests were conducted later at the Scientific Division of British Coal at Edinburgh using hydrogen fluoride gas atmospheres.

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

A full Gas Chromatography Mass Spectrographic (GCMS) analysis of the complex organic compounds in each of the atmospheres was also 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 presence of up to 850 ppm of ammonia within these atmospheres, acrolein levels up to 40 ppm and in addition particulate densities up to 5 milligrammes/litre.

The only gas which was difficult to generate to the required levels via natural combustion of the materials was nitrogen dioxide and because of this, cylinders of this gas were used to boost the atmosphere to the required levels artificially. In retrospect, some boosting of the hydrogen chloride levels would also have been advantageous, although supplementary tests were carried out where high hydrogen chloride levels had not been achieved in earlier test-runs.

Lung simulation and filter breakthrough analysis

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

An extensively modified 'Auer' lung simulator was used so that human breathing could be fully simulated. In addition, a system was devised so that the inspired gases entrained through a filter during each inhalation could be sampled, so that accurate analysis was achieved. The lung was set to inhale 30 litres/minute at a breathing frequency of 20 cycles/minute, with the exhalate fully saturated with water vapour at 37°C and containing 4.5% carbon dioxide.

Carbon monoxide, carbon dioxide, oxygen, nitrogen oxides, inhaled gas temperature and filter resistance were monitored continuously, whereas hydrogen cyanide, hydrogen chloride, sulphur dioxide, acrolein etc were absorbed in impinger-solutions so that their associated average concentrations could be measured over the test duration 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 intended approach was to test in the region of 40°C and 100°C, this was in fact quickly modified. High temperature runs were directed towards a 5 minute test averaging approximately 100°C. Medium temperature runs were initiated later in the natural temperature decay and averaged approximately 65°C for 5 minutes. Runs were also carried out to check carbon monoxide penetration at low 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 approximately 65°C during these runs.

Filter performance tests were conducted against the Challenge Atmosphere 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 30 minutes endurance.

A total of 5 weeks intensive testing of six different filter types was carried out, before the facility was closed down on the 16 October 1986. Seventy test-runs had been completed, using a total of approximately ¼ ton of materials.

In addition, at the laboratory of the Scientific Division of British Coal at Edinburgh, testing was carried out to check the performance of filters against hydrogen fluoride atmospheres to assess the 'sorption' capacity, followed by testing against 1% carbon monoxide to check for any deterioration in carbon monoxide catalyst efficiency resulting from hydrogen fluoride exposure. Tests were also conducted against an hydrogen fluoride/carbon monoxide mixture, followed by carbon monoxide exposure.

Results summary:

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

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

While certain designs of filter can maintain the inhaled gas temperature just within acceptable limits even when exposed to atmospheres at 100°C, it was demonstrated that the inclusion of a simple metal heat exchanger behind the filter can satisfactorily reduce inhaled gas temperatures.(Appendix 18 d)

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

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

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

3. Flame tests on all hoods using the British Standards Institute Flame 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 transmission capability 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 transmission characteristics restored to within 10% of their 'as-received' values after simple 'finger-wiping'. The one exception was a hood made from pure 'Kapton' material which was affected by the challenge atmosphere, creating a 'tacky' surface on the exterior. This could not be restored by wiping, and left the hood with a reduction in light transmission of some 30-35%. PFA[3*]-coated Kapton was not affected in this way and performed satisfactorily. No other detrimental effects were found due to exposure to the atmospheres.

Flame testing demonstrated that hood materials are available which can successfully resist an impingeing flame of 915-920°C maximum temperature for some 6 seconds. In addition smokehood materials can satisfactorily resist the effects of flaming droplets of nylon.

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

1.16.4 *Internal water spray systems*

The potential for water to extinguish many types of fire has long been appreciated. However, although fire authorities have known for some time that the way in which water is applied is of importance it is commonly believed that relatively large volumes of water are required and that its use on certain fires, involving fuel oils for example, is undesirable if not counter productive.

Water typically extinguishes a fire by absorbing the heat generated and depriving the fire of oxygen. The heat absorption rate is largely governed by the surface area of water exposed to the fire environment and therefore the larger the surface area of the water the greater the effect. The exposed area is increased by reducing the droplet size in a spray application but below a certain mass the droplets lack sufficient momentum to penetrate the turbulent gases to reach the seat of the fire. There is, therefore, an optimum droplet size to meet the compromise between maximum exposed surface area and minimum droplet mass.

Consideration of the use of water spray systems in aircraft is not new and was the subject of an evaluation by the FAA[10] in the early 1980's. Such systems appeared at that time to have significant potential but the cost of installation and the weight of onboard water necessary to effectively supply the spray nozzles were issues which, it was felt, required further reseach and development to reduce the operational penalties.

For some years before the accident to G-BGJL water spray nozzles had been developed for use on manifold systems distributed about large earth moving vehicles, which had proved prone to fire and difficult to evacuate. An installation had then been developed for road transport passenger vehicles and thought given

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[3*] PFA Perfluoroalkoxyethylene, an ethylene polymer

to developing the system for aircraft passenger cabin protection. The Manchester accident accelerated this development and a number of trials[11] were conducted with systems installed in a VC 10 passenger cabin furnished with limited seat rows and cabin materials. Two separate but complimentary philosophies have been demonstrated:-

1) an 'onboard' system, primarily intended to protect the cabin and passengers until the first fire appliance arrives, comprising a single line of misting nozzles down the centre line of the cabin roof. These were to be fed from an onboard water supply at a total flow rate of approximately 13 gallons/minute into a cabin 15 ft diameter by 60 ft long. This water could be drawn from the aircraft's domestic system or from a dedicated supply - about 30-40 gallons being required in a Boeing 737 sized aircraft to give 2-3 minutes application. It was intended that the system would only operate with the aircraft on the ground and be activated as soon as there was risk of fire starting in, or penetrating the fuselage.

2) a 'tender' system having an array of sprays inside the cabin and other critical zones to be supplied with water from a fire appliance alongside the aircraft. (In the case of an airfield accident the first fire appliance should arrive in not more than 3 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 the passenger cabin, using trays of kerosene producing fire transfer to rows of seats, and fires initiated with trays of kerosene outside of a door sized aperture igniting seat rows adjacent to the door by radiant heat transfer.

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

The 'tender' system extinguished the cabin fires in approximately 3 seconds, dramatically dropping the cabin temperature and improving visibility by 'washing' much of the particulate out of the atmosphere.

Further trials are planned to demonstrate the systems within a fully furnished aircraft. Although the tests carried out to date have not explored the issues of installation, reliabilty and system integration, they have nevertheless demonstrated that the concept has great potential both to limit fire development before the first fire appliance arrives, and then to allow firefighting personnel to tackle internal cabin fire directly - something which airfield fire services are currently denied during the period of passenger evacuation.

In further, separate, developments in this area, nozzle designs used within the petro-chemical industry have been adapted to produce very small droplets, with attendant increase in surface area, which are transported to the seat of the fire on their own column of moving air. This nozzle has, to date, only been tested on hose-end applications but has shown great potential when used to extinguish pans of burning crude oil. In controlled tests this nozzle significantly out-performed more conventional fire hose nozzles on a 'standard building fire'. A major advantage, in addition to the extinguishing potential is the relatively low pressures of water required to achieve a 'throw' comparable with conventional hoses, resulting in greatly reduced hose-end reaction forces. It is hoped that future tests will explore the application of this nozzle and delivery system 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 become the most widely used jet engine in the world. It has undergone many developments to increase its performance, resulting in a range of engines with differing rated thrusts. Information provided by the manufacturer shows that the JT8D-15 engine, as fitted to G-BGJL, exhibits the highest combustor can metal temperatures of the entire engine model range.

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

In addition to those instances when explosive rupture of the CCOC actually occurred, it must be recognised that 'burn-throughs' of the CCOC (*ie* penetration by the combustion flame but not resulting in explosive casing rupture) represent a different outcome from a similar initiating failure mechanism and should be included for consideration. There were 16 recorded cases of burn-through of the CCOC prior to the accident to G-BGJL, of which 4 were attributed to combustor can failure, 5 were due to can shift (locating pin failure) and the remainder due to fuel nozzle or fuel system failure.

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

Regarding the three cases of CCOC explosive rupture due to can failure which occurred in 1979, 1984 and 1985, Pratt and Whitney advised all JT8D operators of the 1979 incident in a letter, dated 31 January 1980. This letter described the circumstances of the incident to a JT8D-9A:-

"In July 1979, the combustion case of a JT8D-9A engine ruptured during climb out after take-off. The case rupture initiated at the 8 o'clock position and the resultant blowout pressure caused the edges to peel back in both the clockwise and counterclockwise directions resulting in a hole which extended circumferentially from 5 o'clock to 11 o'clock. The fan case and engine nacelle were also ruptured along this same plane. A 1 inch by 2 inch hole was found in the aircraft vertical fin, evidently caused by debris liberated from the case rupture. The No 7 combustion chamber was expelled through the hole in the combustion case. Although the chamber was not recovered, our investigation into this incident has led us to conclude the incident was initiated by the complete fracture of one of the chamber seam welds joining two liner sections. Resultant misalignment of the chamber segments caused combustion within the chamber to impinge on the combustion case wall, softening the case to the point of rupture." (*ie* a very similar mechanism to that known to have occurred on G-BGJL, albeit where the 360° fracture occurred in the No 3 liner material, not in the seam weld itself).

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

"2-3 Liner Seam Weld Cracking: This condition was first observed after introduction of reduced smoke combustion chambers and is peculiar to that configuration. It has occurred in all JT8D models. There have been 9 reported instances of 360° cracks in the 2-3 liner seam weld with part times ranging from 1,810 hrs to 7,510 hrs. Twenty additional instances of 360° cracking have also been reported. Part times for these cases could not be determined. Because of the 'piloting' effect of the air scoop and crossover tubes, 360° cracking in 2-3 liner seam weld is usually seen only at engine dissassembly. However, if allowed to continue in service for a sufficient period of time in the 360° cracked condition, vibration and gas loads could cause the chamber to seperate, sag and allow fuel spray deflection."

"3-4, 4-5 and 5-6 Liner Seam Weld Cracking: Circumferential cracks in these liner seam welds have been reported in reduced smoke liners in all JT8D engine models. These cracks typically vary from 1 inch to 6 inches in length and are normally detected during hot section inspections. This condition has been repaired in the shop by fusion welding the cracked areas or by replacing the entire liner. Recently, however, we have received several reports documenting 360° cracking of the 4-5 or 5-6 liner seam welds. Although part times were not available, times since last shop visit ranged from 3,200 hrs to 7,000 hrs. Chamber separation in these seam welds is potentially more serious than in the 2-3 liner area because these liners do not have the benefit of the piloting features of the air scoop and crossover tubes. Once the crack has progressed 360°, combustion chamber sag within a short period of time is possible. One of these incidents caused softening and bulging of the outer combustion chamber case due to resultant fuel spray deflection."

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

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

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

(b) Investigation of high time combustion chambers for possible degradation of material properties such as hardness and fatigue life.

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

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

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

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

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

The target date for the completion of the above programme was July 1980, at which time Pratt and Whitney expected to provide additional information directed towards controlling liner seam weld cracking. The letter concluded; "Pending completion of the programme, we recommend that the following currently available shop maintenance procedures be utilised to reduce the potential for combustion chamber liner seperation due to circumferential seam weld cracks."

A Solution heat treat the combustion chamber liner assemblies prior to weld repair. Refer to the Engine Manual, Section 72-42-1, Repair for the SHT procedure. SHT is beneficial in fatigue life restoration of the Hastelloy X material, and has the additional advantage of cleaning the part prior to welding if done in an inert atmosphere.

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

C Replace bulged and oxidised liners and replace liners which have 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 December 1980. This letter stated that the cause of the circumferential cracking was identified as thermal fatigue and that the 360° circumferential progression generally occurred in weld-repaired liners which have "lower fatigue strength than non-weld-repaired liners". The letter further stated that tests had shown the value of fusion weld overlay and SHT on fatigue life and that rig tests were being undertaken on weld-repaired cans in order to develop an improved technique. Four recommendations were made:-

(a) To conduct a periodic inspection of combustion cans for seam weld cracks.
(Recognising the difference in operating patterns, maintenance procedures and part times Pratt and Whitney could only recommend that each individual operator establish his own inspection frequency, but quoted one operator who had successfully overcome a can separation problem by inspecting his combustion section at 6,000 hours time since 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 have been extensively weld repaired.

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

Finally, a telegraphic 'All Operators Wire' dated 7 February 1985 was despatched from Pratt and Whitney "to inform (operators) of two recent incidents involving the Combustion Chamber Outer Case". The first incident described a JT8D-15 engine which experienced a CCOC rupture during the take-off roll. The take-off was abandoned without further problems. The telex went on to describe how the No 7 can was considered to have cracked sufficiently to allow combustion gases to impinge on the inner face of the CCOC and recommended "strict adherence to engine manual repairs and close monitoring of engine response especially during transient conditions". Specifically, "reports of slow starting or acceleration should be suspected as a potential cause of severely distressed or misaligned combustion chambers". The second incident described a primary failure of the CCOC on a JT8D-9A engine.

1.17.1.2 *Pratt and Whitney operators conferences*

Pratt and Whitney JT8D Operators Conferences, held in 1980 and 1985 addressed the can cracking problem and the notes prepared for these generally reflected the situation described in the letters issued in those years. It was noted that the 1980 conference depicted the type of cracking which could lead to 360° can separation in the area of the No 2 through No 9 liner seam welds. The cracks observed on the No 9 can of G-BGJL were not in the seam weld but adjacent to it.

The 1985 conference also gave much information on cracking in the seam weld location and said "most reports of problems related to chambers concern high time parts which have been weld repaired 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 5192 which 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 liner seam weld). It also addressed igniter guide wear and buckling of the number 11 liner. The Bulletin stated that these modifications would provide a can with "improved durability" although it was aimed primarily at the problem of seam weld cracking of the 2/3 liner joint which, because it occurs under the air-scoop, requires radiographic inspection to detect. British Airways JT8D-15 engines were all delivered with this modification incorporated during engine build.

A further Service Bulletin, No 5461 was issued in April 1983 and was applicable to all JT8D-15/I5A engines fitted with SB 5192 standard combustor cans. This SB introduced a modification to these cans whereby a ceramic coating could be applied to the interior to provide an insulation barrier and reduce metal temperatures by 50°F-100°F. The compliance category was 8 - "Accomplish based upon experience with prior configuration". Although it appears the modification was not widely adopted, it was noted that it did provide the information that "burning and cracking has been observed in some combustion chambers at the 2nd to 5th liners after 3,000 to 5,000 hours of operation". Pratt and Whitney do not apply this modification to new cans leaving their factory.

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 for strip inspection and overhaul of the engine as a whole. Whilst hard-lifed items on the engine may require engine strip to replace them (at which time, of course, the particular module would be inspected/overhauled as necessary) the operator is expected to arrange a maintenance programme with the relevant Airworthiness Authority.

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

Following negotiations with the CAA, British Airways embarked on an engine sampling programme in which engines were removed and strip-inspected at various times to monitor deterioration - the aim being to establish fixed overhaul lives for the major parts of the engine. Commencing at 5,000 hours Time Since New (TSN) various engines were sample inspected, following which it was agreed that each engine would run between 10,000 - 12,000 hours TSN before an LMI was carried out - this would include a full 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 engine P702868 would have been overhauled for the second time at 16,000 hours on this maintenance schedule, although British Airways target was to establish a 20,000 hours/13,000 cycles HMI interval, subject to a satisfactory 16,000 hour sample. The HMI would also include a combustion section overhaul.

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

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

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

> "Fully inspect combustion chambers in accordance with Overhaul Manual (including x-ray of No 3 Liner seam weld)"
> -note this refers to the 2/3 liner weld under the air-scoop and was 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 fusion weld 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 accident are given below:-

Inspection 01 1B General

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

Inspection 01 Subtask 72-41-22-044

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

Inspection 01 Subtask 72-41-14-046

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

Inspection 02 Subtask 72-41-26-000

"(1) (e) Examine developed film for circumferential cracking in 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 0.030 inch wide may be weld repaired. See Fig 803. Cracks in excess of this limit will necessitate replacement of liner assembly. For combustion chambers with cracks more than 2.500 inches in length 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 (Fusion Weld 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 2.500 inches in length, stress relief is recommended but optional based on operator's experience".

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

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

1.17.2.3 *Trouble-shooting and trim runs*

Information on day-to-day engine fault diagnosis is contained in the trouble-shooting sections of the Pratt and Whitney Maintenance Manual. At the request of British Airways, the section was also reprinted in the Boeing Maintenance Manual. The section covering 'slow acceleration' as it existed at the time of the accident is 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 the problem of combustion can cracking, but refers to an earlier problem experienced with wear/failure of the can mounting pin. All British Airways engines were equipped with cans featuring SB 5192 with greater wear resistance in the mounting lug area.

No mention of combustor can defects was made in the 'Thrust Lever Misalignment' (throttle stagger) section of the Boeing Maintenance Manual and there was no trouble shooting guidance given for low ground idle symptoms, nor was any mention made of possible inter-relationships between some of the symptoms.

The Boeing Maintenance Manual describes the procedure to be adopted for performing a Part-Power Trim Run. It is essentially to ground run the engine with a test-set of reference instruments connected and to record the various engine parameters for checking against data tables in the manual. Adjustments are then made to the fuel control unit as required so that the engine performance corresponds with these data tables.

The first step is to check N_2 idle speed and adjust as necesary (it is recommended that the ground idle be adjusted to the upper limit of the tolerance band). A part-power trim stop is engaged on the engine and the pilot's throttle levers advanced until the thrust lever on the FCU contacts the stop. This provides both a datum against which to judge the engine's performance, and also the means to check for incorrect rigging of the throttle lever cables (one possible cause of throttle stagger).

Since adjustment of the 'Idle' trim screw has some effect on the engine at higher settings, a second adjustment, refered to as the 'Mil' trim screw is used to adjust the fuel flow at the part-power setting. Having checked the parameters against the manual figures, the engine is returned to idle for 5 minutes, when the idle N_2 is checked again.

The manual procedure then continues:-

> "Idle adjustment of as much as 0.5% N_2 (8 clicks) is permitted after final setting of part-power trim without a recheck of part-power trim provided final adjustment is made in the increase RPM direction".

Both Boeing and Pratt and Whitney have stated that they do not sanction adjustment of the fuel control unit outside of a part power trim run.

British Airways routinely performed trim runs when installing a replacement engine or FCU. They did them on some occasions when low ground idle, slow acceleration or throttle stagger were reported by flight crews. It is known that some airlines regarded routine trim runs as unnecessary if the replacement engine or FCU had been calibrated on the test bench and would rely on the first flight to verify performance. Equally so, minor idle speed adjustments would also be carried out without a trim run. Questioned by an operator at the 1984 Hamilton-Standard Operators Conference on their opinion regarding the latter practice, Pratt and Whitney accepted that it was widely done. They added that the part-power trim procedure was largely intended to correct throttle stagger snags and that, where the airline is satisfied with the initial engine output following a trim run and satisfactory experience, they could see no objection to minor adjustments being made as long as they are logged and monitored. Pratt and Whitney demonstrated, however, that their customer training courses, which were attended by a large number of British Airways technicians and engineers, emphasised the importance of correct engine trim in accordance with the manual.

1.17.2.4 *Post accident regulatory action*

The basic mechanism and sequence of failure of the No 9 can was appreciated at an early stage after the accident. Accordingly, the CAA, in consultation with Pratt and Whitney, the FAA, British Airways and other UK and foreign operators of the JT8D, issued an emergency Airworthiness Directive (AD) No 011-08-85 on 27 August 1985. This called for an isotope (radiographic) inspection of JT8D engines, or disassembly, to permit visual examination of the combustion section to detect and measure the extent of combustor can cracking.

The AD has undergone several subsequent revisions to both the approved inspection methods and the initial and repeat inspection intervals in response to operator feedback. A broadly similar FAA AD has also been issued along with an Alert Service Bulletin from Pratt and Whitney, No 5639.

These mandatory documents were drawn-up from a considerable mass of data and information by the Airworthiness Authorities and it is to be hoped that they will prevent a similar accident occurring to a JT8D engine. It is also understood that the CAA have re-examined similar British engine designs to see whether the same problem could arise.

1.17.3 *Malfunctions during take-off*

The operator's Operations Manual - Flying, in use at the time of the accident, contained the following instructions and advice on the actions to be taken in the event of a malfunction before V_1.

> "Reject the take-off for engine failure, fire, take-off configuration warning or if the Captain calls Stop. Upon recognition of failure or warning, either pilot may call "Stop". The handling pilot should maintain directional control and apply MAXIMUM wheel braking consistent with the airplane's position on the runway (overriding Autobrake on Series 2 Aircraft). The non-handling pilot should immediately disconnect autothrottle, select idle thrust, lift the reverse thrust levers (to activate the automatic speed brake facility) and apply GA (Go Around) reverse thrust. He should then check/select the speed brakes fully up. Whilst the handling pilot brings the airplane to a stop (taxiing clear of the runway if conditions permit), the non-handling pilot must monitor the engine instruments and observe the GA thrust limitations. If a fire exists, consideration should be given to turning the aircraft into wind before bringing it to a complete stop. Once the airplane has stopped,

the first officer should carry out any emergency procedure as instructed by the Captain. (This applies regardless 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 vital actions are complete and the airplane is decelerating. In this event, the Captain should call "I have control" and the first officer should take the reverse thrust levers, monitoring/adjusting the power as required".

(This section has subsequently been amended so that the handling pilot brings the aircraft to a stop on the runway and the revised evacuation drill is commenced when the aircraft has slowed to a taxi speed in anticipation of a possible evacuation. The captain's option of taking control from the first officer after the vital actions are completed is retained.)

The Abnormal Procedures section of the Flight Crew Orders advised that:-

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

The Boeing recommended rejected take-off procedure differed from the operator's in use at the time of the accident in that it called for the pilot to stop the aircraft on the runway and evaluate the problem, before deciding whether conditions permitted taxiing clear of the runway.

1.17.4 Passenger evacuation checklists

The Passenger Evacuation (Land) checklist contained in the Operations Manual and the Quick Reference Handbook in use at the time was based on the aircraft manufacturer's suggested format with detailed differences, and was designed specifically to cover all areas of ground operation from start up and push back, as well as take-off and landing incidents. The non-memory evacuation drill consisted of 15 items, of which item 14 (item 13 on Boeing drill) was the initiation of the evacuation. The crew reported that they found such a lengthy drill inappropriate to this emergency.

As a result of this accident a simplified memory evacuation checklist has 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 17 paragraph 7 of the Air Navigation Order (ANO). Sub paragraph (a) refers. (Cabin attendants referred to in the ANO are synonymous with cabin crew.)

"When an aircraft registered in the United Kingdom carries 20 or more passengers on a flight for the purposes of public transport, the crew of the aircraft shall include cabin attendants carried for the purposes of performing in the interest of safety of passengers duties to be assigned by the operator or the person in command of the aircraft but who shall not act as members of the flight crew".

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

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

1.17.5.2 *Disposition of cabin crew*

The Boeing 737 Air Cabin Crew Safety Equipment and Procedure Manual recovered from the aircraft contained a diagram which illustrated the cabin crew seating positions. The Senior Cabin Crew Member (SCCM) occupies the forward inboard, No 1, crew seat. The forward outboard seat is designated No 4, and the rear inboard and outboard seats Nos 2 and 3 respectively.(Appendix 3 Fig a) The cabin crew are often referred to using the number of the station they were allocated for the flight. The next most senior or experienced member of the cabin crew was usually given the choice of which crew station they would like to occupy. For a variety of reasons, the number 4 position in the forward cabin appears to have been a popular choice. All cabin crew are trained in emergency procedures to the approved standard for each cabin crew station. Other operators have indicated that the SCCM, and the next most senior or experienced crew member would be positioned at either end of the cabin for take-off and landing.

The door opening responsibilities assumed that the minimum complement of two cabin crew would be carried, and they were responsible for opening the left main doors initially. When four cabin crew were carried, it involved the individuals crossing over to get to their individual doors.

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

1.17.5.3 Cabin crew training

The issue of an Air Operators Certificate by the CAA to an operator engaged in public transport activities requires that the operator arranges a suitable course of training for newly employed cabin crew. A very large proportion of such a course will consist mainly of Safety Equipment and Procedures (SEP). The individual is then required to undergo a refresher check at suitable intervals, normally once a year.

The cabin crew on G-BGJL had all undergone a course of lectures and 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 renewed by undergoing a 2 day refresher course and both certificates were valid for Boeing 737 and Tristar aircraft. The certificates of competency raised for the Nos 2 and 3 stewardesses, who were occupying the rear cabin, were issued after they had both completed the same initial entry course on 1 March 1985. These were also valid for Boeing 737 and Tristar aircraft. The Nos 2 and 3 stewardesses underwent assessment flights under the supervision of a purser on 21 August, and 8 July 1985 respectively. The assessments in both cases were "above-standard to excellent", the SEP knowledge being graded as "above-standard".

The smokehoods contained in the cabin were originally envisaged as being for use in dealing with cabin fires; three were positioned in the racks above row 18, and two stowed in the forward vestibule. Cabin crew were trained in their use, but not in removal from their container. During tests carried out after the accident, the fastest removal and donning of a smokehood was 40 seconds by 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 and Procedures' for the Boeing 737 included direction in numerous areas associated with the initiation and control of an emergency evacuation.

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

> "Cabin crew should always bear in mind that an aircraft emergency can occur without the flight crew being immediately aware of the situation, *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 emergency procedure only after an order from the captain. However, in cases which are clearly catastrophic, individual crew members should be prepared to act immediately on their own initiative.

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

In Part 3, the Manual further stated:-

"The captain or, in his absence, the next most senior crew member, will order an evacuation indicating, if conditions so require, the exits that should be used. Only in cases which are clearly catastrophic should individual crew members be prepared to act immediately on their own initiative".

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

"In the event of an emergency evacuation the doors are operated in 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 continuous movement without hesitation, to its fullest extent. A greater force is required to open the doors in these circumstances - so swing out and push hard. Automatic deployment of the slide occurs during door opening.

5 If a slide fails to inflate pull the manual inflation handle completely clear of the slide pack.
When the slide is ejected from its container the manual inflation handle marked 'Pull' will become visible".

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

"Smokehood - if dense smoke is being generated, fit a smokehood before entering the fire area. Portable oxygen bottles must not be used as breathing apparatus when fire fighting."

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

1.17.6 *Minimum exits*

The aircraft was equipped with exits in accordance with FAR Part 25 which, in section 25.807 'Passenger Emergency Exits' specified, for a passenger seating capacity of 130, that the aircraft should have two 'Type l' and one 'Type lll' emergency exits on each side of the fuselage.

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

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

Section 25.809 (c) states "the means of opening emergency exits must be simple and obvious and may not require exceptional effort".

FAR Part 25 does not specify any minimum access widths to overwing exits. British Civil Airworthiness Requirements, Chapter D 4-3 'Compartment Design and Safety Provisions' states in paragraph 4.2.5 'Access', "Easy means of access to the exits shall be provided to facilitate use at all times, including darkness; exceptional agility shall not be required of persons using the exits. To this end the following shall be complied with:-

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

(b) The main passenger aisle at any point between the seats will not be less than, for aeroplanes having a maximum seating capacity of more than 19 persons, 15 inches (381 mm) wide up to a height above the floor of 25 inches (635 mm) and 20 inches (508 mm) wide above that height".

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

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

(i) For aeroplanes that have a passenger seating of 20 or more the projected opening of the exit provided shall not be obstructed by seats, berths or other protrusions (including seat backs in any position) for a distance from the exit not less than the width of 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 accidents was carried out in order to compare findings with this accident and also to examine associated evidence from in-flight cabin-fire situations.

1.17.7.1 *Respiratory effects on passengers*

a) AN FAA report[12] refers to the effects of smoke on the evacuation of the United Airlines DC-8 at Stapleton Field, Denver on the 11 July 1961 stating the following:-

> "During evacuation, the principal environmental hazard was smoke. 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 cabin and out of the open door. For this reason, the concentration of smoke was heaviest in the aft cabin.
>
> Although occasional tongues of flame were blown in through the right window exits, destructive invasion of the cabin by fire occurred only after 98 passengers had escaped and 16 others had been incapacitated by smoke.
>
> Just prior to opening of the galley door, the passengers had promptly left their seats and began to queue-up in the aisle. From all accounts, this was done in an orderly and relatively calm manner; little shoving or shouting occurred and many persons took time to collect their personal belongings. As this line was forming, dense black smoke began filtering into the cabin, making breathing difficult and obscuring vision. Judging from their statements, many passengers - who up to then had reacted calmly - became frightened for the first time."
>
> "Most witnesses estimated that the evacuation was completed within 3-5 minutes after the aircraft came to a halt".

b) The same report refers to the accident to the United Airlines Boeing 727 which landed short of runway 34L at Salt Lake City Airport on 11 November 1965, initiating a localised fuel-fed fire within the aft/underside of the fuselage as the aircraft slid down the runway after both main undercarriage legs had sheared:-

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

Other passengers recalled that after a few initial shouts and cries the cabin suddenly became quiet with the only sounds coming from the flames and the muffled efforts of passengers struggling towards the exits. This silence seemed especially eerie, some recalled, because they had always previously imagined such scenes of human panic to be accompanied by screaming".

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

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

By the time the fire crew arrived, 6 minutes after the forced-landing, the fire had burnt through the aft upper fuselage. Four unconscious passengers were removed by the firemen, but only one survived. Subsequent pathological examination found that all passengers had died due to asphyxiation. The flight engineer died due to impact injuries. Seventy-eight per cent of the 122 fatalities had 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 L1011 aircraft, registration HZ-AHK, had departed Riyadh Airport for a continuation flight to Jeddah with 14 crew and 287 passengers. Seven minutes after take-off the crew were alerted, by an audio warning and visually by smoke entering the aft cabin, that they had a fire in the aft cargo compartment.

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

e) The NTSB produced a report[13] on the accident which occurred to an Air Canada DC-9-32, registration C-FTLU, on 2 June 1983 which suffered a fire behind an aft toilet partition whilst en-route from Dallas to Montreal. The aircraft was diverted into Greater Cincinnati International Airport. The aircraft landed 17 minutes after the smoke was first noticed issuing from the toilet. Of the 5 crew and 41 passengers, 23 failed to evacuate. This report stated:-

> "During descent, the cabin filled with black, acrid smoke from the ceiling down to about knee level. Passenger and flight attendant testimony and statements indicated that all of the surviving passengers had covered their faces with either wet towels distributed by the flight attendants or articles of clothing. They all attempted to breathe as shallowly as possible, and all reported that the smoke hurt their noses, throats, and chests and caused their "eyes to water". By the time the airplane landed, they could not see 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 oxygen to him from the portable bottle."

> "The smoke in the cabin was reportedly so thick that most of the passengers had to get to the exits by using the seat backs to feel their way along the aisle. None of the passengers noticed if the emergency lights were illuminated. Several passengers said that when they either bent forward or got on their hands and knees, they were able to breathe and see a little better, but it was not much of an improvement. One of the passengers who used an overwing emergency window exit said that she was able to locate it when she saw a very dim glow of light coming through the aperture. Another stated that she was able to locate the overwing emergency exit window when she felt a slight draught on the back of her knees".

Of the 23 passengers who failed to evacuate it was reported that 10 were found still in their seats. Toxicological examination found levels of 20-63% carboxyhaemoglobin and 80 - 512 micrograms/100 ml of cyanide in the victims.

1.17.7.2 Hair-ignition

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

"When the plane came to a stop all lights went out. The back of 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 opened the aft pressure door. Immediately two men ran through the door onto the stairs. At this time my hair caught fire. I put it out with my hand and my hat fell off."

This stewardess and the two men sheltered in the ventral area of the tail section until rescued 25 minutes later by firemen. During this time the stewardess breathed through her jacket. They were assisted by some air entering the partially open stairwell external door.

This evidence on hair-ignition appears similar to observations from the male survivor from seat 8D at Manchester who has referred to 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-flight emergency smoke situation are apparent from the following extract from the NTSB DC-9 Report[12]:-

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

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

The aircraft landed on runway 01 at 1836.24 hrs - *ie* 21½ minutes after the first indication of a fire/smoke problem associated with the 'C3' aft cargo compartment. It was turned off the runway and eventually stopped at 1839.03 hrs. No external evidence of fire was seen by the following fire vehicles at this time.

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

The engines shut down at 1842.18 hrs - *ie* some 3 minutes 15 seconds after the aircraft had stopped (5 minutes 54 seconds after touchdown or approximately 27½ 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 the underside of the aircraft, just forward of the wings. Also within 1 minute, smoke issued from the top of the fuselage just forward of the number 2 (centre) engine followed by flames. The report concluded that a flash-fire had occurred in the cabin shortly after the engines had been shut down and the associated air conditioning air-flow ceased. All 301 occupants perished due to fire and smoke inhalation effects but there is insufficient pathological data to identify the exact cause of death.

1.17.8 Aerosol cans

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

Research into the hazards posed by aerosols has shown that such cans invariably rupture (as a result of gas overpressure) if the temperature of the can and its contents exceeds approximately 70°C, releasing the gas in a minor explosion. The extreme turbulence associated with this explosive release of the butane propellent promotes very efficient mixing of the gas with the air. If this turbulent, rapidly expanding gas mixture ignites, which would inevitably occur in a cabin fire environment, the flame front will propagate extremely rapidly, producing a very sharp fronted, but relatively sustained pressure rise. (During a test detonation of an aerosol can located in an aircraft forward toilet, the overpressure was sufficient to blow out the toilet door, allowing the compartment pressure to vent into the cabin. Despite the cabin itself being vented by open rear doors and overwing exits, the resulting overpressure in the main cabin blew the flight deck door out of its aperture and forward several feet into the flight 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 speed into the aircraft structure or furnishings.

2. ANALYSIS

2.1 Introduction

Many of the factors which affected this accident should have biased events towards a favourable outcome. The cabin was initially intact, the aircraft remained mobile and controllable and no one had been injured during the abandoned take-off. The volume of fuel involved, although capable of producing an extremely serious fire, was relatively small compared with the volume typically carried at take-off, the accident occurred on a well equipped major airport with fire cover considerably in excess of that required for the size of aircraft and the fire service was in attendance within 30 seconds of 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 development of the fire and the evacuation, were extremely complex, involving numerous interlocking factors, many of which critically affected survival.

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

2.2 General circumstances

The explosive failure of the CCOC and the damage to the adjoining tank access panel were clearly related events. Witness marks on the access panel fragments exactly matched the shape of the domed head of the separated No 9 combustor can and the fan case fragment, and a smear of panel material was identified on the dome indicating beyond all doubt that it was this which struck and shattered the panel. It is clearly evident that the dome was ejected through the disrupted engine casing as a result of the extremely rapid escape of high pressure combustion air through the ruptured CCOC. The release of fuel from the damaged wing tank directly into combustion gases from the ruptured combustion chamber, and its inevitable ignition, changed the nature of the event from a purely engine related incident into a catastrophic accident.

2.3 Crew performance

2.3.1 Flight deck crew.

The flight deck crew were properly licenced, trained, experienced and rested to undertake the flight. They were aware of the technical log entries for the left engine and had monitored its performance during start-up, taxi, and the initial part of the take-off run. Throughout this period the engine appeared normal and, by the time the event occurred, it had been dismissed from their minds. The commander's assessment of the 'thud' as a tyre burst or fuselage bird strike was therefore quite reasonable; he responded to the cues which were available to him, which at that time consisted solely of the noise, a 'thud'. His response was rapid and decisive ordering "stop" in less than 1 second and he and the co-pilot speedily implemented the abandoned take-off drill. Although it might be argued that the falling left engine parameters should have provided additional cues which might have altered their perception of the event, any such indications would have been masked by the falling parameters on both engines accompanying the abandon take-off. During reverse thrust application, there would have been some indications of thrust imbalance, but the level of reverse thrust used was minimal and applied for a very short time, during which neither crew member would have had cause to monitor the instruments closely.

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

For the first 9 seconds after the 'thud', events proceeded as expected, reinforcing in the commander's mind his assessment of the problem, and he had every expectation that they would be able to complete the abandoned take-off and turn off without difficulty. When he had satisfied himself that the immediate problems associated with the abandoned take-off were contained, with the aircraft decelerating through 85 kt ground speed, he transmitted his abandon call to ATC. As he began this transmission the number 1 engine fire warning occurred and he modified his call adding,"it looks as though we've got a fire on number 1." This fire warning was somewhat fortuitous, the system having been designed to respond to fires contained within, not external to, the engine cowlings, large pieces of which seperated as the engine failure occurred.

This was the first indication to the flight deck crew that the problem could be other than a tyre burst or bird strike. It is evident that this new and conflicting information could not easily have been reconciled with either, except perhaps as a result of secondary damage, and the crew's ability to analyse its impact was clearly limited by their already high workload. As a result, they proceeded with the existing abandoned take-off plan whilst they considered how to deal with the new information. While the fire bell was still ringing on the flight deck, as the aircraft decelerated through 50 kt ground speed ATC transmitted, "right there's a lot of fire, they're on their way now." The commander responded quickly seeking guidance from the tower controller on the need for passenger evacuation.

During this period, the actual handling of the aircraft was being carried out by the co-pilot following the original abandoned take-off plan, whilst the commander was dealing with the significant management task. However, with a nosewheel steering tiller on the commander's side only, it was necessary for him to take control of the aircraft at some stage if he intended to turn off. It is quite apparent that by the time the briefing and other tasks were completed and he was in a position to re-assess the actual abandon take-off process, the commander was already committed to turning off.

All these events took place rapidly; the replay of the CVR provided a striking indication of the commander's workload during that period of almost continuous communication, not only with the tower but with briefing the cabin crew and responding to their confirmation request. (Appendix 1)

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

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

With the benefit of hindsight, the decision to turn to the right off the runway can be seen to have had a severely adverse effect on the fire. The operator's Operations Manual-Flying, referring to engine malfunctions during take-off, advised taxiing clear of the runway if conditions permitted and added that, if a fire existed, consideration should be given to turning into wind before stopping. However, as already explained, the way that the limited information became available to the crew, who were already engaged in a high speed abandoned take-off with concomitant very high workload, left no capacity for analysing the true nature of the emergency. Furthermore the wind, which earlier had been variable in direction and on take off was quoted as 250°/7 kt, would have been of little, if any, operational significance as far as aircraft handling was concerned. There is no doubt that this crew, and indeed the aviation community at large, were quite unaware of the critical influence of light winds on a fire, and they did as most other crews would have done faced with a similar predicament. The crew would have been conditioned to clear the single runway to the right at the usual turn off at Manchester, where only light aircraft were permitted to use the area to their left.

The commander wanted to alert the cabin crew to the need for a passenger evacuation as soon as the aircraft had stopped, so he broadcast 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 confirmation from the commander 8 seconds before the aircraft stopped and then made a number of evacuation calls himself over the PA.

It should be noted that if an evacuation instruction is made before the aircraft stops it could precipitate an evacuation, with cabin doors being opened, before the aircraft comes to a halt. At speed this could result in slides being damaged and , in any event could lead to inappropriate doors being opened. Unless there are overiding reasons to the contrary doors should not be opened until the aircraft has stopped.

The fire drill was carried out for the left engine immediately the aircraft stopped and the right engine shut down, because evacuation was to take place on that side. The crew then started on the non-memory 'Passenger Evacuation (Land) Drill' which proved unrealistically long 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 possibility of slide damage or personnel injury. Do not delay evacuation if any possibility of smoke or fire exists".

Clearly in this case it was necessary to shutdown the remaining engine and smoke/fire did exist, leaving the crew without an appropriate effective drill. Some items were actioned but the crew decided to evacuate via the right side sliding window as burning fuel flowed forward on the left of the aircraft. The operator's procedure required the flight deck crew to leave the aircraft promptly and supervise the evacuation from outside. The operator considered it undesireable to use the flight deck crew as integral members of the internal passenger evacuation team, as on some occasions they may be unavailable, having been incapacitated. However, the aircraft manufacturer's recommended procedure is for the flight deck crew to enter the passenger cabin after completing the cockpit drills and render all possible assistance to the evacuation from inside. Indeed this is the practice adopted, apparently successfully, during the evacuation certification tests.

The flight deck crew responded to the 'thud' in a prompt manner in accordance with their experience and training. Their intial assessment of the problem and their subsequent actions were entirely reasonable based on the cues available to them. The decision to turn off was a critical factor in the destructive power of the fire. However, in the context of the knowledge, training and operating practices current at the time of the accident, it is considered that this decision should not be criticised.

It is vital that in future operators and ATC services recognise that all abandoned take-offs and emergency landings should end with a full stop on the runway. Only then can a full evaluation of the situation be undertaken by the crew with the assistance of ATC and the airfield fire service as necessary. ATC will have to be prepared to accept any resulting disturbance to aircraft movements, particularly at single runway airfields. Similarly all operators must recognise the potential of even light winds to enhance the destructive power of a fire, and modify their procedures and training to ensure that aircraft are not stopped with a fire upwind of the fuselage, if at all practicable.

2.3.2 *Cabin crew*

Each member of the cabin crew was properly trained and qualified to operate at any station within the cabin. However, apart from the purser, the only cabin crew member who was reasonably experienced, having completed a season's flying on aircraft which included the Boeing 737, was the number 4 stewardess positioned in the forward cabin with the purser. Of the two stewardesses at the rear of the cabin only one had limited experience of flying as a crew member the previous year, and then on a different type of aircraft.

The forward cabin crew seats were on the left side of the aircraft in the forward entrance vestibule, from where the view into the cabin was restricted by a galley bulkhead. This made it difficult to see what was happening in the cabin particularly on the left side, although the purser did become aware that passengers were becoming agitated. Although in this particular case the restricted vision probably did not affect the outcome of the accident, the inability of the forward crew members to monitor conditions in the cabin from their take-off and landing position was unsatisfactory and could, in other circumstances, have been more serious.

There was no delay in the response of the forward cabin crew members to the evacuation order. Indeed, it was the rapid operation of the R1 door, with particular acceleration of the door through the aperture, which exposed the design fault associated with the release lanyard, leading to the premature release of the slide box which caused the door to jam in the aperture. Such jamming of the forward doors was repeated on other similar aircraft and, on at least one occasion a rear door suffered the same problem during tests which followed the accident, when an aggressive opening technique was used. The aircraft manufacturer had no record of any similar occurrence during 20 years of experience of certification testing of the the door with various slide designs, or in any actual emergency evacuations.

The purser quickly decided not to devote further time to the jammed door and excercised caution in bringing into operation the L1 door as an alternative escape route. He showed initiative in identifying the cause of the R1 door obstruction and the means of freeing it, all under conditions of great pressure. It is probably a good indication of his sense of urgency that he felt it necessary to pull the chutes' manual inflation handles, despite the fact that they were already deploying automatically.

It is notable that although the No 4 stewardess initially had to keep passengers out of the galley whilst the purser was dealing with the doors, once he had opened the L1 door a 'log-jam' of passengers formed in the narrow aisle between the galley bulkheads, which she had to free by pulling passengers clear. From the survivors statements the jam occurred as passengers moved forward down the aisle, whilst being pushed from behind, and jostled for position at the bulkheads with other passengers who had moved forwards over the seats. It is apparent from the statements of the cabin crew that survivors tended to flow in groups to either one door or the other - probably because the aisle between the galley bulkheads effectively throttled the flow, restricting the exit rate to less than the potential capacity of the two forward doors.

The forward cabin crew members reacted commendably and with courage, remaining on board until they were on the point of being overcome by smoke themselves and were being urged by firemen to get out. A number of survivors clearly owe their lives to the direct actions of the purser and the No 4 stewardess.

The No 2 and No 3 stewardesses were placed in an extraordinarily difficult position. The extent of the external fire and its effects would have been known to them at an early stage, as would the discomfort and alarm of the passengers in the rear of the aircraft, particularly on the left hand side. Little is known of their actions. The first, and only activity evident at the rear of the aircraft was the opening of the R2 door just before the aircraft stopped. This occurred very shortly after the commander's evacuation instruction and could have been a very rapid response to that command, or a direct response to the deteriorating conditions in the rear cabin. A number of witnesses saw a hostess, probably the No 3, standing in the R2 doorway before it was hidden by the smoke.

As a general rule doors should not be opened before the aircraft stops, however, in this case there was an urgent need to make exits available with passengers suffering from the radiant heat through the windows before the aircraft left the runway. At the time that the door was opened there would have been no indication of fire on the right side of the aircraft. Unfortunately this door was immediately engulfed in smoke when the aircraft stopped and undoubtedly some smoke and subsequently possibly some fire entered the passenger cabin via this route. Even if it had been judged desirable to reclose this door from inside the aircraft, the presence of external smoke and fire would have made it impossible. Although it would not have appeared inviting from inside the aircraft this exit may have briefly provided a viable escape route, certainly the stewardess appeared to have had an opportunity to escape. She stayed on board the aircraft and perished; nobody escaped through the R2 door.

From the total of 22 rows of seats in the cabin, there were only 5 survivors from the seats aft of row 16, from where 29 passengers and the 2 stewardesses perished. The rearmost, and sole survivor in row 20, remembered a stewardess in the aisle next to him, apparently trapped in a melee of passengers. This was probably the No 2 stewardess whose evacuation task in other circumstances would have been to open the L2 door.

Such evidence that there was indicated that the No 2 and No 3 stewardesses carried out their duties to the best of their ability until they succumbed to the rapidly deteriorating conditions in the rear cabin. However, as the two least experienced members of the cabin crew they were confronted with a very critical situation which developed rapidly and independently of the conditions in the forward passenger cabin. Although it is unlikely to have significantly influenced the outcome in this instance, in general it would seem prudent for the most experienced crew members to be positioned at either end of the cabin in an aircraft the size of a Boeing 737, or evenly distributed throughout the cabin of larger types.

Some of the emergency equipment for use by the cabin crew, including two loud-hailers, was in overhead bins in the passenger cabin, not at the cabin crew stations. In an emergency evacuation the cabin crew may find it impossible to reach this equipment as passengers moved towards the exits.

2.4 The left engine

2.4.1 Sequence of failure

A 360° crack developed around the circumference of can No 9 in the area of the 3/4 liner joint. The aft portion of the can, then located only by the sliding fit in the transition duct, rotated relative to the dome and, as the overlapping fracture faces made contact, some rubbing wear occurred. Further movement of the aft portion of the can occurred both in a rearwards and rotational sense.

The dome portion of the can, experiencing air loads on its forward face and having lost the element of support provided by the aft section of the can, started to cant outboard by bending the mounting lug and pin. Resistance to this motion was initially provided by the fit of the fuel nozzle nut in the centre of the dome swirl vanes but considerable wear of these parts occurred allowing progressive deflection of the dome.

Eventually the dome became canted about 11° from its normal axis, hot combustion gases started to consume the aft portion of the can and to heat the inner surface of the CCOC which eventually bulged, split and ruptured explosively. The instantaneous release of pressure in the combustion section generated high supersonic airflows which led to the fracture of the dome locating pin and the expulsion of the forward portion of the can. The bypass duct failed due to a combination of being struck by the edges of the split CCOC and overpressure or impact from the escaping No 9 can dome.

It was not possible to identify the time interval between the full development of the 360° crack and the rupture of the CCOC. It is even possible that deflection of the dome started before the crack had run the full 360°. The wear on the fuel nozzle nut, however, showed that failure of the CCOC was not coincident with deflection of the dome. The rotation of the separated aft portion of the combustor can also must have occurred over a period of time, sufficient to have permitted fretting marks to be left on the can dome.

2.4.2 Failure of the No 9 Can

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

Thermal fatigue cracking of combustor cans is a relatively commonplace phenomenon and was acknowledged as such in the Pratt and Whitney Engine

Manual which also reassured operators that cracks were "usually of a stress relieving nature and, as such, are not serious in that the rate of growth decreases as the crack lengthens". Analysis of the temperature distribution around the 3/4 liner joint of the post-modification 5192 can also concluded that a certain amount of early cracking could be expected, particularly in areas subject to 'hot-spots'. There are many variables which can affect the maximum temperature of such hot spots which, whilst present on a significant number of the cans tested, did not necessarily result in visible cracking in all cases. Theoretical analysis of stresses induced by some of the steepest thermal gradients served to emphasise the critical nature of the effects of temperature on the fatigue life of the material, in which a relatively small increase in temperature dramatically reduces the fatigue life.

The above analysis illustrates how a wide spread of fatigue damage occurring after various times-in-service could be expected, with those cans experiencing relatively small increases in operating temperatures showing disproportionately longer cracks. Inspection of the radiographic records of British Airways first-run cans prior to repair reflects this wide scatter but it is interesting to note that the length of cracking in the 3/4 liner area of can No 9 from engine P702868 was at the limit of British Airways first run experience, indicating that some factor, or combination of factors, was causing greater distress in this can than the others.

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

Visual examination of similar crack patterns in cans from other operators showed that such an area of branchy cracking usually displayed 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 widespread cracking or material loss although one area, close to the male transfer port, did exhibit a short crack parallel to the main circumferential crack in liner 3. Whilst the small crack would have been apparent to the BEOL inspector/welder it is not possible to judge the visual appearance of this area and therefore to state categorically that it presented itself as an obvious area of thermal distress.

It must be concluded that it was the length of cracking in can No 9 which was the most obvious evidence of its poor fatigue performance when it was inspected prior to overhaul. It is also self-evident that the subsequent repair failed to impart sufficient life recovery to enable it to remain in service until its next scheduled inspection.

2.4.3 *British Airtours ' Maintenance and Repair Procedures*

British Airways Engineering Dept. controlled British Airtours engine maintenance and repair, BEOL implementing the overhaul policy. As noted in Paragraph 1.17.2.1 the engine manufacturer did not specify any fixed times for strip inspection and overhaul of the engine as a whole. They advised that operators should negotiate with their airworthiness authority using the method of sample inspection to substantiate the optimum inspection intervals, or even to operate the engine 'on-condition'. Guidelines were, however, presented as a basis for such negotiations.

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

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

British Airways/Airtours were, by worldwide standards, a relatively new operator of the JT8D engine. They had, however, many years of experience on the Pratt & Whitney JT3D engine, which also employed combustor cans manufactured from Hastelloy X material. Although the JT3D cans are considerably larger in size, the repair limits and procedures for circumferential cracks were substantially the same, and they could thus be considered experienced in the inspection and repair of such components.

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

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

Whether or not the presence of this hot spot, measuring roughly 10-15 mm in diameter in liner 3 of can No 9, fell within the Pratt and Whitney description of "severe local distortion and/or oxidation" remains unclear, although the evidence of can No 1 indicated that BEOL were prepared to repair more severe damage than this by multiple pass welding to restore material to the damaged areas. The inspector who examined the can set upon removal from engine P702946 recorded "considerable burning and cracking of the 3rd liner" in five of them, but it is evident that the damage was thought to be repairable by direct fusion weld. Ultimately, assessment of such condition could be considered subjective, since the word "severe" implies that some local oxidation and distortion is acceptable for weld repair. Indeed, it appears that very few cans would ever be direct weld-repairable if no local oxidation and distortion were allowed, since hot spots of varying severity were present on a large number of cans inspected at random.

As noted in paragraph 2.4.2., can No 9 exhibited an abnormally long circumferential crack in the 3/4 liner area but no length limit for weld repair had existed in the Inspection sections of the Engine Manual since some time before British Airways/Airtours had become operators of the JT8D engine. It became apparent that a 3 inch crack length limit had been included in the Engine Manual until 1977, when it was deleted by Pratt and Whitney, following requests from a number of operators. Pratt and Whitney were unable to recall why the length limit had been included originally but have stated that, "an engineering review had indicated that cracks up to and including a full 360° could be safely weld repaired using the proper Engine Manual procedures", as justification for its removal. British Airways stated they were unaware of the pre-existence of a limit, deletion of which occurred some three years before they commenced JT8D operations. It was also discovered that many operators were unilaterally imposing repair limits more stringent than those in the Engine Manual. A post-accident survey of 13 operators and overhaul agencies who performed weld repair of circumferential cracks found that only British Airways and one other had no limit on the length of circumferential cracking permissible for weld repair. The rest had imposed or retained crack length limits at or around 3 inches. Some other operators had a policy of no direct weld repair of circumferential cracks, opting instead for automatic patch or liner replacement techniques.

This would indicate that many operators were adopting what the manufacturer calls "Burner Management" programmes, that is they had found from experience that reliable and economic operation was achieved through selective application of the basic repair limits and procedures. It should be noted that, prior to the accident to G-BGJL, British Airways had not had a chance to inspect their combustor cans after second run and therefore to judge how effective their repair procedures were.

The process of "Burner Management" also apparently extended to deletion of some of the Engine Manual repair requirements and recommendations. BEOL had performed neither SHT or Post Weld Stress Relief (PWSR) on the can set fitted to G-BGJL. Since SHT was a requirement in the Manual, BEOL needed to raise a Manual Revision Authority (MRA) and hence gain approval from the CAA to delete this process. Although attempts were made initially to accommodate SHT in the can repair procedures, difficulties were encountered with its implementation and BEOL engineering took the decision to delete it. Accordingly, an MRA was raised and approved by the CAA. The full process was, however, re-instated in 1985, prior to the accident to G-BGJL. PWSR remained an optional but recommended procedure and did not require such approval.

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

2.4.4 *The effectiveness of Direct Fusion Weld Repair of circumferential cracks*

This method has always been a feature of JT8D and JT3D Engine Manual repair schemes. It must therefore follow that it has been employed with success by many (but not necessarily all) operators. It was extremely difficult to compare the experience of other operators directly with that of Britih Airways in this rergard because of the very limited ammount of data available. Data supplied by British Airways based on their post-accident fleet inspection for can re-cracking indicates strongly that they were achieving little recovery of can fatigue life by direct fusion weld repair.

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

Pratt and Whitney had, on several occasions through all-operator communications and conferences warned that weld-repaired cans did not have the same fatigue life as new cans or those repaired by material replacement techniques. This is confirmed both by examination of the can No 9 fracture and by consideration of the nature of this type of thermal fatigue. The fatigue initiation occurs at microscopic sites around the circumference of the can which in time link together to form one or more major (visible) cracks. Since direct fusion weld repair can only address visible cracks, the embryonic sites remain untreated.In order to tackle this problem, SHT was recommended by the manufacturer on the grounds that it would retard the growth of such embryonic cracks. Since the major effect of SHT as specified in the Engine Manual would be to restore ductility to the age - hardened material of a used can, it was argued that this would have a beneficial effect on crack growth rate. An additional benefit would be that the 'weldability' of the material would be enhanced, with reduced post-weld cracking occurring and, when performed in a reducing atmosphere, some removal of oxidation occurred. These latter benefits are certainly valid and beneficial to the welding process, although the former claim that SHT has a significant effect on fatigue crack growth rate is disputed. A Pratt and Whitney report dated 12 May 1986 concluded that "Solution heat treatment of AMS 5536 (Hastelloy X) at 1900°F-2050°F can restore original material properties and be used to extend the useful service life of JT8D combustors, sometimes by as much as one-third". However, an independent programme of analysis and testing of specimens also conducted after the accident to G-BGJL concluded that SHT using the then-currently specified temperatures would have no beneficial effects on fatigue crack propagation rates. This same programme also concluded that Post-Weld Stress relief seemed "unnecessary in view of the high running temperature of the cans" *ie* a similar effect would be achieved during the first period of service of the cans.

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

It is possible that the combination of the omission of these processes together with the (presumed) repair of the hot-spot may have shortened the life of can No 9 to some extent. However, it is difficult to envisage how, even without these factors, this can at least could have been safe to return to service with a direct fusion weld repair to the abnormally large crack in liner 3. It should be noted that it only achieved some 46% of the target 10,000 hours Time Between Overhaul.

Since it is beyond dispute that the residual life of a weld-repaired can is an unknown quantity it follows that a separate re-sampling programme should have been advocated for cans after repair. It is possible to draw the conclusion from the subsequently revealed differences between operators' repair policies (burner management programmes) that they had achieved the required results through individual service experience of poor can condition. British Airways would have had an opportunity to re-examine their repair policy had they seen the fleet-wide results after second run and certainly if the No 9 can had resulted in the more benign failure mode of a burn-through or even been detected as a 360° failure - either of which it could easily have been. It was tragic misfortune that they should learn that they had a can cracking problem in such a way.

2.4.5 *British Airways reaction to previously reported incidents of combustor can failure*

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

The engine manufacturer was clearly concerned about these incidents but felt that the problem lay in improperly repaired and/or high time parts and hence did not warrant Service Bulletin or Airworthiness Directive action. It must also be said that, presumably, neither did the regulatory authorities. The All-Operator Letters and Wires issued were advisory communications between manufacturer and operators. They did, however, contain information which, in hindsight, might have prevented the accident to G-BGJL, viz:-

(a) Slow engine acceleration could be symptomatic of a disrupted can.

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

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

British Airways, in receipt of this information had to decide, therefore, what action they would take as a result. An airline the size of British Airways would deal with many such advisory communications through their engineering department and decide whether the information needed to be passed to the maintenance or workshop staff, together with any additional analysis which could assist. A line maintenance technician, for example, would expect to receive more information on fault diagnosis that the simplistic statement contained in (a) above.

British Airways Engineering cited various reasons why they did not consider that they were likely to suffer from combustor can failures:-

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

(2) They had a hard-time LMI/HMI inspection programme which was more conservative than some other operators. They were aware of at least one major US operator who had run his new JT8D engines to 16,000 hours and beyond without a scheduled inspection of the combustor cans.

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

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

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

It has become evident from the complete absence of dialogue between British Airways and Pratt and Whitney on the subject of combustor can potential failures that, on one hand, the manufacturer believed that his messages were being understood and acted upon and on the other, that the airline interpreted these messages as largely inapplicable to them at that time. Whilst the Pratt and Whitney literature and discussions gave the impression that can failures were largely a high-time problem, British Airways did not seek definitions of 'high-time' and 'extensive weld repairs' or confirmation that modification 5192 standard cans were less prone to serious cracking problems. Although it is difficult to speculate on precisely what reply they would have received at the time, it would have been prudent to have sought clarification on some of the more generalised statements.

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

2.4.6 *British Airways reaction to pilot reports in the technical log of G-BGJL*

The phenomenon of slow engine acceleration on British Airways Boeing 737 fleet had been a source of some irritation to the airline almost since delivery of the first aircraft. An analysis of the pilot reports in the technical log for the first 7 months of 1985, across the fleet of 43 aircraft, showed some 60 reports of slow acceleration and 85 reports of throttle stagger. The rectification action had been, variously, to perform trim runs, drain/clear the PS4 line, check rigging, change the FCU, adjust the FCU idle, etc. At no time was a disrupted can suspected or found. Although retrospective analysis of the technical logs revealed a large number of reports, it was noted that the random frequency of the reports was such that it did not trigger the repetitive defect alerting procedure adopted by British Airways. This procedure was designed to identify problems which recurred within a short period of time. The nature of the slow acceleration/throttle stagger reports was such that they occurred over an extended period of time and did not appear to cause significant delays. They came to be regarded as an irritating but non-critical fact-of-life in JT8D operation and were dealt with at line maintenance level. The knowledge that some other operators were also suffering 'wandering' ground idle and consequent variable acceleration times served to re-inforce this impression. It should be noted that the line maintenance technicians were not aware of the content of the Pratt and Whitney letters because British Airways Engineering had elected not to advise the maintenance staff of their contents. For the reasons stated in the previous section, they did not consider that British Airways had, or were likely to suffer from, a can cracking problem.

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

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

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

With respect to (a) above, the JT8D engine FCU has a droop governer limiter, ie there is no fixed idle speed. The engine will adopt an idle speed appropriate to a set fuel flow but which can vary widely with ambient temperatures and pressures and engine bleed and accessory loads. There is thus the possibility that some pilot reports of slow acceleration and/or low idle were due to unfamiliarity with the operating characteristics of the JT8D engine.

It should be noted at this point that a significantly reduced idle speed is likely to result in disproportionately increased acceleration times from idle. This is because the acceleration schedule is depressed at low speeds, which the FCU can interpret as still being within the start cycle range. Once the engine has accelerated beyond this range, a more rapid rate is scheduled. An engine with 'gas path distress', such as a badly disrupted can, would lose combustion efficiency with a corresponding reduction in idle RPMs and slow acceleration.

However, none of the Pratt and Whitney letters nor published data spoke of low idle speeds or throttle stagger as a symptom of a disrupted combustor can and the 'Troubleshooting' section of the Boeing Maintenance Manual did not refer to the possible inter-relationship of some of the symptoms. There was no troubleshooting guidance at all for low ground idle defects, yet it is clear that British Airways believed the low ground idle figure reported by the pilot on 21 August to be responsible for the slow acceleration and reacted accordingly.

It is regrettable that British Airways had not raised the whole question of the persistent fleetwide pilot reports for slow acceleration, low idle, and throttle stagger with the manufacturer prior to the accident to G-BGJL. Even though a Pratt and Whitney engineer was resident at the British Airways main engineering base, this problem was never relayed back to the engine manufacturer's design or operations staff. Information subsequently forthcoming from Boeing and Pratt and Whitney and closer monitoring by British Airways has helped to considerably reduce the number of pilot reports. These discussions have also shown that some maintenance crews were not analysing the reasons why certain rectification actions were being performed. Although it would appear that draining the PS4 water drain trap was a commonly accepted action to take with slow acceleration pilot reports, there is no technical reason why it should have been effective. However, at the 1984 Hamilton Standard Operators Conference one operator indicated that they had achieved success using this approach.

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

The rationale behind the one turn adjustment of the ground idle screw is also puzzling, since the pilot's report indicated a drop of about 8% idle N_2 and the one turn adjustment would theoretically recover only some 2%. Hence it would seem to be an ill-considered attempt at rectification. Equally so, the actual adjustment was performed prior to starting the engine, thereby denying the technicians the opportunity of confirming the figures reported by the pilot and led them to think that their theoretically ineffective troubleshooting had resolved the problem.

In making such criticism of the troubleshooting, however, it is necessary to examine the other options open to the line technicians faced with three separate, but apparently inter-related symptoms. It is now clear that they believed that the problems lay in the low idle RPM and intended to address this - for which no troubleshooting was provided in the Maintenance Manual. A retrospective analysis of the effectiveness of troubleshooting for combinations of one or more of these symptoms across the British Airways Boeing 737 fleet, indicates that the most common and effective rectification procedure was a trim run. It should be remembered that the basic purpose of a part-power trim run is to check and adjust as necessary the engine power output and idle speeds. If the idle speed is found to be low, the procedure is to adjust it until it falls within limits. For low idle and slow acceleration defects it is essentially a technique of adjustment rather than a diagnostic process.

The factor which rendered troubleshooting difficult in the days leading up to the accident was that the symptoms appeared and disappeared apparently at random. In establishing that the rectification carried out on the 21 August was insufficient to account for the dramatic recovery in idle speed, acceleration and throttle stagger, attention has been focussed on the one-turn adjustment of the idle screw. As discussed in the following section, the amount of idle speed recovery was approximately 13% - quite disproportionate to the amount of idle speed adjustment made. It is thus true to say that the Manchester technicians were not simply grossly over-fuelling the engine to compensate for the low idle figure. Consideration of the engine characteristics by engineers from Pratt and Whitney and the Royal Aerospace Establishment has, however led to the suggestion that, if the problems on 21st August were being generated by a distressed No 9 can, then a mechanism could be envisaged whereby a small step change in idle fuel flow could result in a large change in idle RPM. It is hypothesised that if distress in the can was causing the symptoms (and circumstantially it would appear to be the case) the major reason would be that the can was failing to 'light' (*ie* sustain combustion). It is possible, therefore, that a relatively small step adjustment in engine trim could change the characteristics sufficiently to cause the can to light and recover most of the lost combustion efficiency. It is also true that the can might re-light on its own accord - this could have been occurring with the report of slow acceleration and throttle stagger of the 20 August. It is impossible to state exactly how long the can had run in a badly disrupted state but it is felt that it was unlikely to have run for more than a few flights with a 360° separation and consequent severe damage.

In summary, it must be emphasised that much of the above is not only speculative but has also been arrived at following lengthy consideration of the engine design and characteristics by professional engineers and specialists. A line maintenance technician should not be expected to have to apply such detailed reasoning to his troubleshooting nor, probably, would he have the time in practice. Whatever the inadequacies of the troubleshooting employed at Manchester it is difficult to state that implicit following of the existing Maintenance Manual guidelines, and in particular performance of a part-power trim run, would have revealed the defect in can No 9.

Finally, since the accident, the manufacturer has recomended to British Airways that the engine be accelerated from idle to 70% N_2 five times followed by a 5 minute stabilisation period each time they perform a part-power trim check of the idle speed. The maintenance manual originally only called for a 5 minute idle stabilisation period following start up.

2.4.7 *Information on engine performance extracted from the flight data and quick-access recorders*

Important evidence was obtained from the FDR and Quick Access Recorder (QAR). The latter could have been used by the airline to analyse and trend certain engine data on a routine basis, but British Airways were not doing so prior to the G-BGJL accident. There was no mandatory requirement for them to use the data for trending. In fact, the pre-delivery operator survey, conducted by British Airways, seemed to indicate a general lack of enthusiasm for the system by those canvassed. The recorder specified by British Airways for the batch of Boeing 737 aircraft which included G-BGJL lacked two important recorded parameters, LP shaft speed and EGT, which limited its usefulness. Using the engine manufacturer's method for analysing the data available from G-BGJL, the airline would not have been alerted to take further investigative action. However, a plot of corrected engine fuel flow versus N_2 for the idle condition (Appendix 5 Fig i) was made to see whether this could identify a defect in the engine. This would not normally be done by the airline.

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

Referring to Appendix 5 Fig i, a steady fall in the left Engine idle N_2 can be seen occurring from sectors flown on 21 August until the ground run. Only point (6) fails to show a corresponding decrease in fuel flow. The post-idle adjustment ground run point (4) then shows a jump of nearly 13% idle N_2 at which time the two engines are within 1% of each other. Points (3) and (2) show a further decay but point (1), the accident take-off, shows a sudden recovery to about 2% differential between the two engines.

The amount of recovery following the idle adjustment is quite disproportionate to the actual adjustment made. Equally so, most points apart from point (6), lie fairly close to the reference line and do not exhibit constant fuel flow with decrease in N_2, which might be expected if a loss of combustor efficiency was the cause of the idle N_2 drop.

The fuel flow parameter, particularly at low flow conditions is open to considerable inaccuracy, and must therefore be treated with caution. It is equally true to say, however, that this analysis does not provide any evidence that the No 9 combustor can was causing disturbance of engine parameters or that such a defect would have been revealed by a part-power trim run. The fluctuating nature of the N_2 parameter appears only circumstantially to be associated with such gas path distress, and the degree of the RPM drop on 21st August is greater than theory would predict for loss of one ninth of the combustion system efficiency. If it is argued that the fluctuations were due to can distress, then it could have been random movement of the can and/or 'lighting' of the flame which was causing the erratic behaviour. Testing of the engine indicating instrumentation did not reveal any defect which could have affected the readings.

In stating that ECM would not have detected the incipient failure of can No 9, it should not be inferred from this that it is not a valuable and worthwhile tool to assist with reliable and economic engine operation. With correct and rapid trend analysis it is capable of detecting deterioration within the engine and its accessories before more serious problems result and, indeed, examples of can distress being predicted by ECM trends have been demonstrated. It would, however be incorrect to say that even full ECM programmes will safely predict incipient can problems such that direct engineering improvements and additional inspection programmes are unnecessary. This accident has demonstrated that the erratic and fluctuating performance of a disrupted can makes fault diagnosis extremely difficult, even though hindsight can sometimes explain and rationalise the behaviour.

2.5 Wing tank penetration

Although only the compressor and turbine sections of an engine are conventionally regarded as high energy zones, with attendant potential for uncontained failure, the energy imparted to the combustor can dome in this instance was sufficient to shatter the wing tank access panel. However, the indications are that if the dome had struck the adjoining wing skin rather than the access panel, which has an impact strength approximately one quarter that of the lower skin, penetration of the tank would not have occurred. The wing skin and access panel were not designed to any impact criteria and nor where they required to be.

In the light of this accident it is considered advisable that, in future, the access panels used in wing fuel tanks, in particular those vulnerable to impact by engine or wheel/tyre debris, should have impact strengths comparable to that of the lower skin forming the tank floor, and that panels on existing aircraft which do not meet this criteria are modified. It is further considered that both engine and airframe manufacturers, and the airworthiness authorities, should at the design stage take greater account of the potential energy contained within the high pressure sections of all gas turbine engines and, where necessary, incorporate impact strength into the design requirements for potentially affected structure.

2.6 The fire

2.6.1 The external fire

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

An analysis of fire damage on the wreckage identified two quite distinct and separate damage patterns, which were clearly caused by the two phases of the fire: its initial 'dynamic' phase whilst the aircraft was still at speed on the runway, and the later 'static' phase after the aircraft had slowed and turned off. The characteristics of these damage regions provided a valuable insight into the essential features of each mechanism.

2.6.1.1 The dynamic fire

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

i) a region of lower skin burn-through over the outboard section of the left tailplane;
ii) oily-soot streamlining over the central area of the left tailplane leading edge;
iii) paint bubbling and light heating over the lower fuselage on the left side aft of the rear door (Appendix 8 Fig a).

This pattern of damage was consistent with a large plume of fire and partially burnt fuel residues trailing aft from a region behind the left engine. A general analysis of the features associated with this fire, drawing on known aerodynamic, thermodynamic and physical behaviour characteristics of the elements involved, has enabled the nature of the fire plume to be determined. From this knowledge, its impact upon the fuselage can be assessed.

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

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

(2) Much of the fuel bouncing up from the tarmac was entrained into the intensely turbulent vortex behind the deployed reverser buckets. Within this turbulent wake, efficient mixing of the fuel and air occurred, resulting in a hot, stable flame which burned within, and was controlled by, the turbulent wake boundary.

(3) Some of the fuel splashing off the ground was caught by the bottom lip of the lower reverser bucket and carried around the inside (*ie* forward) surfaces of the buckets, rather in the manner of tap-water being deflected by a spoon. This fuel emerged at the upper lip of the buckets and was immediately entrained back in the slipstream, forming a sheet of fuel droplets just above the wake upper boundary. Some of this fuel was entrained into the wake where it added to the fire, but most remained unburnt and is visible in the first photograph of the fire sequence (Appendix 4 Photo a) as a white 'vapour' plume, trailing above the fire plume proper.

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

From a consideration of the aerodynamic factors involved, the turbulent wake behind the reverser buckets would be expected to take the form of a roughly elliptical cylinder, with the major cross-sectional axis lying in the 7 o'clock/1 o'clock plane (viewed from behind), in line with the axis of the canted reverser bucket doors. This assessment of the wake's shape is supported by the physical evidence; the fire plume burning inside the wake trailed directly rearwards and passed beneath the left tailplane, where it produced the intense, localised damage on its under-surface. The unburnt fuel and partially burnt residues forming the 'vapour' plume produced the oily soot streamlines on the tailplane leading edge, slightly inboard of the fire damage.

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

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

(2) With the combustion sectioned burst completely open, much of the air mass passing through the (windmilling) engine would have spilled out of the open casing, in preference to passing through the more restricted turbine section of the engine. Even if the engine had been intact, but idling at the same RPM as that recorded on the FDR for the damaged engine, the efflux velocities would still not have been sufficient to have had any significant influence on the plume.

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

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

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

The effect of the plume on the fuselage could not be determined directly because of the destruction of evidence caused by the continuing fire. However, the absence of any significant radiant heat damage on the aft fuselage, in combination with the cylindrical form of the fire plume, suggests that the radiant heat damage in the area of fuselage penetration would have been similarly light. This assessment is re-enforced by a calculated estimate of the radiant heat flux at the fuselage surface adjacent to the core of the fire plume, which suggests that it would, at most, have produced some slight pre-heating, but would not by itself have threatened the integrity of the fuselage skins. When the estimated convective cooling due to the slipstream is taken into account, the indications are that the fuselage would have been largely unaffected by the heat from the dynamic fire plume. However, this convective cooling would not have reduced the heat flux transmitted through the window transparencies and it is possible that material immediately inboard of the windows could have felt heat fluxes in the order of 1 to 2 BTU/Ft^2sec,

2.6.1.2 *The static fire*

As the aircraft decelerated, the turbulent wake which had entrained much of the fuel and sustained the dynamic fire plume decayed, and the fire transitioned into a quasi-static fire burning above the increasingly large pool of fuel trailing behind the aircraft. As the aircraft turned into link Delta, the relative wind changed from a slight crosswind component from the right to a larger but still slight crosswind component from the left, placing the cabin downwind of the fire for the first time. The series of witness photographs show that whilst the aircraft continued moving, the resultant velocity vector trailed aft sufficiently to prevent the pool-fire plume from being swept over the cabin section of the fuselage. However, as it slowed to a halt, the resultant vector swung progressively forward until, as the aircraft came to rest, smoke completely enveloped the rear fuselage, including the R2 door which had been opened just as the aircraft started to turn off. From that stage onwards the fire was driven directly against the fuselage where it was concentrated in the region between the wing trailing edge and the fin leading edge by the blocking effects of the tail and wing surfaces. (Appendix 8 Figs f-g)

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

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

Although the wind was only some 5-7 kt - a strength so slight that it would have been a relatively insignificant factor in terms of aircraft handling - there is a powerful body of evidence which clearly shows that the influence of the wind on this accident was paramount. Not only did it drive the static fire plume against and beneath the hull, making a more rapid penetration of the aluminium alloy fuselage skins inevitable, it created an aerodynamic pressure field around the fuselage which, once doors and exits had been opened on the side opposite to the fire, induced the products of the external fire into and down the length of the cabin interior. In turn, some interior materials ignited leading to the development of a fire inside the cabin.

2.6.2 *The internal fire*

2.6.2.1 *Penetration of the hull*

Analysis of the wreckage has shown that the fire initially penetrated the skins on the left side in the vicinity of seat rows 17 to 19, below the level of the cabin floor. Having breached the outer skin, the only barrier which prevented the fire gaining access to the cavity formed between the outer skin and the cargo bay side-liner panels, which communicated directly with the cabin interior above via floor level air-conditioning grills (Appendix 8 Fig h), was a 1 inch thick fibreglass wool accoustic insulation blanket contained in a thin plastic bag. Although fibreglass insulation material of this type is temperature resistant, the indications are that it provides very little protection against penetration by fires of the type which occurred at Manchester[14]: in the flame turbulence associated with such fires, the material is eroded and quickly breaks down. Consequently, once the fire had penetrated the fuselage skin, it would have quickly gained potential access to the cabin. (Note: The normal outflow of conditioning air would not have been present at that time because the R2 door had already been opened, venting any residual cabin pressure and short circuiting the normal outflow paths.)

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

The pattern of floor collapse on G-BGJL was consistent with sub-floor fire transfer having taken place, with fire entering in the region of skin penetration on the left side and then moving across in the floor cavity, branching fore and aft of the cargo door area to follow the least restricted path into the cabin on the right side. This fire transfer mechanism can only have been active whilst the cabin as a whole was intact (ie whilst there existed an appropriate pressure gradient into the cabin interior - prior to significant roof penetration), and before floor collapse occurred. The resulting damage would have reduced significantly the fuselage strength in the area of the aft hold.

Estimates of the time of initial fire penetration of the fuselage skin, using published data[15] for large pooled fuel fires, indicate that rear fuselage skin penetration should be expected within a period of 13 to 22 seconds from the time when the fire is established enough for significant flame coverage to occur. Depending upon the assumptions made about the 'pre-burn' effect of the aircraft taxiing as it turned cross wind whilst trailing a pool fire with it, and the extent to which the dynamic fire would have 'pre-conditioned' the pool fire, the estimates of penetration time in the specific case of G-BGJL range from 13 to 22 seconds at the upper end of the scale down to a minimum period spanning the range 5 seconds before to 5 seconds after the aircraft came to a halt.

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

Using the external skin penetration estimates as a guide, but allowing for the additional time necessary for the fire to penetrate the aluminium cabin side liners and the thicker fibreglass wool insulation layer above cabin floor level, the indications are that the cabin side wall would have been penetrated within 1 minute of the aircraft stopping. This mechanism would have allowed the fire direct access to the cabin.

At some stage the combined weakening of the rear fuselage, due to the lower hull and cabin floor damage, allowed the tail section to collapse to the ground and fire to enter the cabin through the disrupted cabin floor. It was not possible to produce an accurate theoretical estimate of when collapse occurred.

Some witnesses spoke of the fire penetrating the windows very early. However, the weight of evidence from previous research into window fire penetration[13] suggests that the type of window fitted to G-BGJL should typically withstand a pooled fuel fire for at least 40 seconds, and possibly would present a barrier to the fire for 60 to 90 seconds, or more. It may be significant that, when under attack by fire, windows of that type give an illusion of penetration, including a spider-web cracking pattern on the outer panel with a focus or apparent hole in the centre, and the panels give off smoke. It is possible that this, together with the entry of fire and smoke through the floor level grills and cabin side-walls, led those witnesses to believe that the windows had been breached. On balance, it is considered more likely that window failure occurred later, probably after the cabin side wall had itself failed.

It is likely that some flame transients would have entered at the open R2 door but the damage to the door aperture and surrounding skins was not consistent with this being a major point of fire entry.

2.6.2.2 *Entry of external fire*

During the critical period when survivors were still in the process of evacuation, conditions in the cabin would have been controlled by the combined influence of the wind and the various openings in the fuselage. Later, as the internal fire became fully established and the roof started to burn through, the influence of the wind would have diminished somewhat.

The effect of a crosswind blowing over a fuselage is principally to create a region of high aerodynamic pressure on the upwind side of the hull, and a low pressure region on the downwind side, relative to the ambient pressure (Appendix 8 Fig i). Consequently, once the fuselage is opened to the outside atmosphere, whether as a result of penetration by the fire or because of doors and escape hatches being opened, there will be flows set up through the cabin interior dependent upon the pressure differential between the various apertures in the hull. (It is of extreme importance to appreciate that the wind strength necessary for this pressure-field mechanism to operate in practice has been shown to be very low[17] - as little as 1 or 2 kt is sufficient.(Appendix 8 Fig j) These flows are crucial, because they have the capability to draw fire and toxic combustion products from the external fire into and down the length of the cabin, with disastrous consequences for those still inside.

Because the R2 door had been opened as the aircraft began turning off the runway and the R1 door was cracked as the aircraft came to a halt, there existed from the outset one large aperture, and one much smaller aperture, into the low pressure regions downwind of the fuselage. Although there may have existed a slight pressure differential between the R1 and R2 doors (caused by the angle of wind against the fuselage and by the aerodymanic 'end effect', due to the proximity of the R1 door to the nose) which may initially have drawn smoke and possibly some fire into the R2 door, once the fire penetrated the fuselage skins on the high pressure (upwind) side of the hull, a dominant pressure gradient would have been set up between the fire aperture and the open rear door which would have drawn the fire into the interior via the conditioning air grills. This fire would have predominantly passed across the rear cabin, exiting through the R2 door, and to a lesser extent down the cabin towards the R1 door. This entrainment of fire, combined with the proximity of fire to the rear right door, would have rapidly produced fatal conditions in the rear cabin. However, the direct 'through-path' for fire products at the rear of the cabin, towards the R2 door, would have minimised any tendency for them to migrate forward and, during the period when the R1 door remained partially closed, the forward cabin would have remained relatively immune from the effects of the fire at the back of the aircraft.

The jamming of the R1 door is cause for concern. However, having created a delay in the start of the evacuation at the front of the aircraft it may have had some secondary beneficial effect in the context of this specific accident as it forced the crew to fully open the L1 door first. This limited the size of aperture which was opened into a low pressure zone at the front of the aircraft, minimising the adverse internal pressure gradient which would otherwise have drawn fire forward into the cabin, creating instead a beneficial pressure gradient. This helped to keep the fire confined to the rear of the aircraft and minimised the adverse depression created in the forward cabin when the R1 door was eventually opened fully. This effect will have served to benefit the passengers waiting to exit at the front of the aircraft. However, if the door had not jammed, an earlier commencement of the evacuation would probably have benefitted the passengers at both front and rear. Once the R1 door and the overwing exit were opened fully, there would have been an immediate loss of any positive pressure gradient and fire products would have filled the cabin.

2.6.2.3 *Cabin fire*

The establishment of an internal fire in the rear of the cabin, as distinct from the entrainment of external fire through the interior, probably occurred relatively early - certainly whilst a majority of the passengers were still on board. The progress of the internal fire remains largely obscure because of the substantial destruction of evidence which it caused as it progressed, and there is no reliable evidence from which a timescale might be developed. However, several features of the internal fire were identified as having important implications for survival. Contrary to conventional wisdom, a full flashover in the cabin did not occur, although clearly a number of brief flash fires did occur as vapours in the ceiling space ignited. This is important because much of the literature in the field of aircraft fire safety, particularly that relating to improved cabin materials, implies that flashover will inevitably occur. This assumption is not supported by the evidence of this fire's behaviour, and is discussed further in para 2.6.4..

Prior to the roof being penetrated, the fire burnt in the upper cabin and roof space. After roof penetration, the fire was vented to atmosphere and thereafter burnt as a series of localised fires within the cabin. No overall pattern of fire development could be seen, nor was any single propagation mechanism evident, although within some areas the fire appears to have used the plastic surface film on the side liner panels as a 'wick', allowing the fire to progress from one group of seats to another some distance away without affecting the intervening furnishings. Generally, the more damaged regions of seating appear to be associated with the collapse of burning overhead lockers. The very localised areas of extremely severe fire damage were possibly the result of burning duty-free spirits, or the discharge of oxygen from the therapeutic oxygen cyclinders carried in the (collapsed) overhead lockers.

This accident has confirmed the very steep rates of change of both temperature and soot (smoke) as a function of height in the cabin, commented upon consistently in the research literature. This stratification was clearly evident as a grading of the burning and sooting on panel surfaces in the forward galley area (Appendix 19), and probably explains the survival of those few passengers who collapsed during the initial evacuation. This has significance in the discussion, later in this analysis, of floor marking and lighting schemes.

2.6.2.4 *Additional hazards*

There was evidence in the wreckage that certain very localised zones within the cabin had burnt with exceptional ferocity. No positive evidence could be found to indicate the cause of this damage, but the burn characteristics were indicative of the presence of flammable agents, several of which are known to have been present in the cabin; duty-free spirits, therapeutic oxygen, and aerosol sprays. Because of the inevitable disturbance of the cabin interior during the emergency phase, it has not been possible to correlate these areas of intensive fire damage with the locations of flammable items during the period of the fire.

It is not clear precisely how duty-free spirits affected the fire, but it is likely that some did contribute. Alcohol spirits, if released onto absorbant material, would have had the potential to produce a local enhancement of the fire for a significant period. Those spirits stored in baggage on the cabin floor are unlikely to have contributed actively to the fire until quite late, probably too late to have affected survival. However, because of the temperature stratification which is a feature of all cabin fires, any spirits placed in the overhead lockers would have been subject to very high temperatures early in the fire and their hazard potential would have been correspondingly greater. The early involvment of such materials would add significantly to the transfer of fire from the ceiling region down onto seats, carpets and other materials in the lower levels of the cabin.

All therapeutic (portable) oxygen cylinders became overheated in the fire and either ruptured or vented (via the over-pressure relief mechanism incorporated into the pressure gauge), discharging the whole of their contents into the fire. The effects of these discharges cannot be precisely established from the evidence, but they are likely to have produced sudden, very severe but short lived enhancements of the fire. They are unlikely to have caused significant (explosive) pressure-fronts unless, by enriching an oxygen deficient atmosphere, this led to the flash ignition of flammable decomposition products. Nevertheless they were extremely hazardous and unpredictable elements which could have caused severe casualties amongst rescue personnel.

The stowage of therapeutic oxygen cylinders in the overhead lockers on G-BGJL was doubly hazardous. The ceiling temperatures in an internal fire will reach high levels very rapidly, but because of the steep temperature gradient the lower part of the cabin is likely be at habitable temperatures long after extreme temperatures are reached at ceiling level. Consequently, there is a risk of overheating oxygen cylinders venting or rupturing and releasing oxygen into the fire whilst survivors are still in the cabin. It is therefore recommended that the stowage of oxygen (and any vessel holding flammable material) is confined to fire proofed containers at floor level.

Although the extent to which aerosols played a part in this fire cannot be determined, there is little doubt that they made some contribution. The damage potential of typical domestic aerosols has only recently come to light and their implications as 'dangerous cargo' are still being studied by the UK CAA. However, there is no doubt that these items are extremely hazardous if they are involved in an aircraft cabin fire.

It is considered that the carriage of aerosols in hand baggage presents an unnecessary risk, and it is recommended that these materials are subject to the same controls as other flammable gas cylinders (*eg* camping gas cylinders).

2.6.3 Relevance of this accident to post-crash aircraft fires in general

The early penetration of fire into the cabin appears to conflict markedly with the air transport industry's expectations (at that time) of survival in a 'typical' pooled-fuel fire. Although there existed no formal yardstick of survival in a fire of this type, the general expectation appears to have been that, with an initially intact fuselage, a period of between 1 and 3 minutes would be available for evacuation before the external fire was in a position to directly threaten the occupants. The 90 second evacuation criterion, whilst it was never put forward by the airworthiness authorities as a measure of the expected survival time in a fire, has nevertheless, through widespread misinterpretation of its intent, contributed significantly to this belief.

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

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

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

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

(3) The fire principally responsible for cabin penetration was a 'typical static pooled fuel fire', involving modest quantities of fuel.

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

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

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

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

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

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

2.6.4 *The effectiveness of the current fire hardening strategy in limiting fire damage*

Research into aircraft fire hardening has been under way for many years, but is only now starting to bear fruit in terms of the introduction of advanced materials into service. G-BGJL was typical of the majority of commercial aircraft in service at the time of the accident in that it was of conventional construction and was fitted out with standard cabin furnishing materials, which, although conforming to the appropriate regulatory requirements, were not specifically fire hardened in the currently accepted meaning of the term. It is not possible to quantify the advantages (or otherwise) which specific fire hardening materials and techniques may have had at Manchester, had they been used on G-BGJL. Nevertheless, all possible effort must be made to use the knowledge gained from the investigation of this accident to reduce both the risk of fire occurring, and the threat to life posed by aircraft ground fires in general. Consideration must therefore be given as to whether or not the routes currently being taken to reduce fire risks are actually addressing those problems in most need of urgent solutions.

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

The results of research into fire hardening are often quoted in terms of how effective the material is at either delaying flashover or preventing it altogether. This method of describing the benefits of new materials provides a useful measure of fire performance because the primary factor influencing flashover is the rate of heat and smoke generation by burning interior materials; these same properties also control the environmental conditions in the cabin prior to flashover. A further reason for using the 'time to flashover' is that flashover is a very clearly defined point when conditions inside the cabin change from being (arguably) survivable to being (generally) non-survivable, allowing materials to be compared one against another. Using this method of rating implies that flashover is inevitable. However, there are powerful reasons to question whether flashover occurs at all often in real aircraft fires, as opposed to test fires.

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

Prior to this accident, the principal thrust of the fire survival program has been in the area of fire hardening of cabin materials, to slow down the fire development in the cabin, thereby reducing the rate of temperature rise and extending the time interval before flashover occurs. These avenues of endeavour are entirely proper and valid. However, as an aim in itself, preventing flashover, whilst laudable, is somewhat reduced in its relative importance if, in practice, flashover is unlikely to occur. It is considered that the widespread assumption that flashover will occur has produced an imbalance in the way the problems of fire protection are currently being tackled by the regulatory authorities worldwide. So far as the majority of the occupants of the cabin are concerned, there are other avenues which need to be pursued with equal or greater urgency - aimed at preventing or delaying the penetration of external fire into the cabin interior, mitigating the effects of toxic (and irritant) fumes and smoke and improving exit paths.

In contrast to the extensive research into fire hardening interiors, research into fire hardening of the hull itself has been much more limited. Mainly, this work has been directed towards obtaining data on fuselage skin penetration times and improving the fire resistance of windows and their fixing systems. Whilst it is understood that manufacturers and airworthiness authorities have devoted time and effort to the effects of fire on the fuselage structure, there is little evidence that fuselage penetration by an external fire, or the subsequent transmission of that fire through the internal structure, has been addressed with anything like the vigour applied to the fire hardening of interior materials. The question therefore arises as to whether the balance of effort between work on fire hardening interiors and improving the fire resistance of the hull itself is appropriate, particularly in the light of the Manchester experience.

Aircraft fires fall broadly into three principal categories:-

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

Typically, these involve fuel or hydraulic oil. The problems which they generate and the fire mechanisms involved are quite different from those under consideration here, and therefore further discussion of this type of fire is not relevant.

(2) Fuselage fires inside the pressure hull.

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

Cabin fires are normally small and, generally, are successfully controlled by cabin crew using the on board hand-held extinguishing equipment. However, if the fire cannot be dealt with rapidly, perhaps because of a lack of access, they have the potential to cause heavy loss of life, as witnessed in the Saudia L1011 accident in 1980. It is in this category of fire that the current efforts to fire harden interior materials can, arguably, offer the greatest potential to save lives. However, it must be borne in mind that fatalities in these types of fire invariably result from the inhalation of toxic fire products rather than from the fire itself. Therefore, in order to be really effective, these materials must not only be fire resistant, but must produce much lower emissions of toxic material - even in a smouldering, as distinct from an open flaming type of fire. In this respect, progress has been disappointing. The indications are that for the forseeable future fires involving cabin materials will continue to produce highly toxic fumes, even if flame spread characteristics are much improved. The corollory to this is that whilst the current effort to reduce flammability will open the door to survival in terms of the aircraft itself and the crew, passengers, without effective smoke protection, will not be in a position to reap a similar benefit.

Despite the evident problems concerning toxic fire products, it is clear that the current efforts to fire harden interior furnishing materials and cargo hold liners are, so far as they go, entirely appropriate for this category of fire, and should receive continued encouragement.

(3) Pooled fuel fires

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

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

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

If the fuselage is ruptured by impact or other forces in a region adjoining the fire, the first link in the defensive chain is broken, and any means of strengthening the secondary links will be of potential value. In these circumstances therefore, fire hardening of the interior materials will play an important role by retarding the development of active burning within the cabin. In the case of an intact fuselage however, fire hardening the interior, although still necessary, is of secondary importance compared with the need to maintain the integrity of the hull, not only in terms of fire penetration, but also the maintenance of structural stability. At Manchester, skin penetration occurred whilst there were substantial numbers of passengers still in the process of evacuating.

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

As a part of the short term approach, the experience gained in the building, maritime and industrial fields should be critically examined to see whether techniques used in these areas could be used, or developed to make them suitable for use, in aircraft. The application of intumescent coatings[4*] to structural members in buildings, and to critical parts of ships and submarines, is an example of a technique which may have application to the fire hardening of aircraft. Even though these materials might previously have been rejected as an exterior finish for the fuselage, it may be possible to use them in other ways, *eg* to fire harden the inner (*ie* hidden) surfaces of the cabin side-liner panels and floor panels, providing an effective secondary fire barrier.

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

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

To summarise, there currently appears to be something of a mismatch between the effort being expended on limiting the flammability of interior materials and that aimed at inhibiting the fire's progress through the hull to the interior of the cabin in the first place. Although no suggestion is being made that an improvement in interior materials is not necessary, it is considered essential that balance is restored by increased effort to address the problems of:-

i) hull penetration;
ii) the internal communication of fire through the structure;
iii) premature structural collapse.

[4*] Intumescent coatings — Paint-like coatings which swell and thicken when heated to form a semi-rigid, fire proof insulating layer.

2.6.5 *Aircraft positioning relative to the wind*

Although the effects of wind on fire generally were well known, there was a widespread belief that only strong winds are significant. There is overwhelming evidence that this is not so: in the context of a typical pooled fuel fire, wind velocities as low as 1 or 2 kt can critically influence the fire's damage potential.

These influences not only control the severity of the fire's attack on the hull, but they also control how the fire propagates through the aircraft interior[14].

Aircraft operating procedures generally in use at the time of the accident made little active allowance for wind in the event of a fire, beyond a generalised directive to stop on the runway if the wind was likely to have an adverse effect. Certainly British Airtours did not include any active consideration of the wind (in terms of its effect on a fire) in their simulator training, nor was active consideration given to these aspects in any other area of their operation. In this respect, Airtours was typical of most operators. This does not reflect a lack of care or judgment on the part of British Airtours (or the other operators), rather a lack of understanding of aircraft fire behaviour. Indeed, it confirms that knowledge within the fire research community about the importance of wind had not (and to a large extent still has not) been assimilated by the aviation community at large. The investigation of this fire has given a new perspective to that knowledge, which has been freely available for many years, and has focussed attention on the need to encourage ways of reducing the wind's destructive power. In practical terms, this means developing operational techniques which ensure that aircraft orientation relative to the wind does not compromise the safety of those on board, and, if at all possible, creates beneficial relative winds which enhance prospects for survival.

The importance of the wind, in terms of both the external and internal fire development, was recognised during full scale fire research carried out as early as the nineteen sixties, and its influence has been repeatedly noted and commented upon within the fire research community ever since then - often as an explanation for variability in the test data. Consequently, there has been a tendency to view the wind as a problem; a barrier preventing a precise understanding of aircraft fires. However, although the wind undoubtedly does make the mathematical analysis of fires impossibly complex, its prime influence in practical terms is not so complicated - it sets the trend of behaviour of a fire and, usually, magnifies its destructive potential.

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

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

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

In Appendix 8 Fig k, the fire is shown on the upwind side of the cabin. The occupants' perception of where the threat lies will encourage them to open those doors furthest removed longitudinally from the fire, and on the opposite side to the fire, *ie* into low pressure regions. Even if no door is opened directly onto the fire, the fire will be driven by the wind against the fuselage and, in the case of a conventional narrow body aircraft such as the 737, penetration of the cabin is likely to occur almost before the evacuation has got properly under way. (Even in the case of the larger wide body types, penetration by the fire is likely to occur before evacuation is complete.) A 'fire aperture' will almost certainly form, therefore, on the upwind (high pressure) side of the hull, and the resulting pressure differential between the upwind fire aperture and the opened doors downwind will drive the fire the length of the cabin, greatly reducing the chances of survival. Those passengers who might succeed in evacuating the cabin will find themselves in the hazardous region downwind of the fire - a far from ideal position to be in. In this scenario, which is broadly representative of Manchester, it can be seen that all of the factors are working adversely, *ie* more rapid fire penetration, door availability limited to those giving rise to an adverse pressure gradient leading to rapid fire involvement of the cabin, and poor external escape paths - all of which are controlled by the relative wind direction.

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

Therefore, rather than viewing the wind solely as a negative factor, there is a powerful argument to be made for actively striving to harness the wind's potential to bias the fire's behaviour in a positive, or helpful, direction. In practice the task of correct positioning does present formidable problems because of the implied need to analyse the wind direction, the fire location, the availability of suitable manoeuvring areas and the risk of introducing unacceptable delays in evacuation - all whilst a fire-related accident (or incident) is in progress. Clearly such additional tasks could well raise the crew workload above a level which they could safely manage, possibly leading to a loss of control or some other more immediate hazard.

Because of the many operational difficulties involved, it has hitherto been viewed as impractical to actively seek to position aircraft with the fire on the downwind side, and the only move towards this aim has been one of damage limitation, *ie* stopping on runway heading to minimise the cross-wind. This, together with the widespread belief that such a requirement is only necessary in strong wind conditions, has led to the wind being virtually ignored from the point of view of practical emergency procedures training. Consequently, aircrew have a low awareness of the wind unless it is of sufficient strength to affect the performance or handling characteristics of their aircraft.

This accident has tragically illustrated the significance of the wind. Furthermore, because crosswind components as low as 1 or 2 kt are critical, simply stopping on runway heading, or even 'into wind', is not sufficient to guarantee that, in typically variable conditions, an adverse crosswind component will not be present. Therefore, it is essential to reconsider ways in which crew might be assisted in the difficult task of positioning their aircraft so as to ensure that any crosswind puts the fire downwind of the fuselage.

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

As an aid to the crew, direct visual cues should be enhanced wherever possible. For example, windsocks located in the threshold areas could provide a rapid and easily assimilated picture of the actual wind conditions in areas where an aircraft is likely to stop in the event of a fire (as distinct from the wind at the anemometer location). It is also considered that there is a need for research into devising practical methods of alerting crews to fire (and possibly other external damage) outside their field of direct view, perhaps by use of cameras or mirrors.

2.7 Evacuation and survival

Perhaps the most striking feature of this accident was the fact that although the aircraft never became airborne and was brought to a halt in a position which allowed an extremely rapid fire-service attack on the external fire, it resulted in 55 deaths. The major question is why the passengers did not get off the aircraft sufficiently quickly.

2.7.1 Opening of and access to exits

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

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

Without any appreciation of how the hatch would open, they were unprepared for it to fall inboard, pivoting about its lower edge and trapping the occupant of 10 F. It was only with difficulty and the help of a male passenger that the hatch (weighing 48 lbs) was finally lifted into the cabin and placed on seat 11D. To avoid the hatch becoming a further obstacle to evacuating passengers it would appear beneficial to throw it out of the aperture rather than retain it in the cabin. Although it is possible to invent a scenario where reclosure of the exit is desireable, in practical terms, it is likely to prove impossible. This exit was opened about 45 seconds after the aircraft stopped. Passengers started to evacuate from the right overwing exit after the L1 door was open but before the R1 door was fully opened and slide deployed. Two passengers (12A,19B) referred to becoming tangled with a white strap, the lifeline. However, one passenger reported catching hold of it as she collapsed, to recover consciousness with her head outside the exit.

Although it is generally accepted as undesireable to have infants/children with separate child lap straps seated on adult laps in the seat row adjacent to an overwing exit, in this case the occupants of seats 10C and 10D evacuated quickly with their charges. No survivors made reference to the child lap straps.

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

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

> "Easy means of access to the exits shall be provided to facilitate use at all times, including darkness; exceptional agility shall not be required of persons using the exits.
>
> Access shall be provided from the main aisle to Type III and Type IV exits and such exits shall not be obstructed by seats, berths or other protrusions to an extent which would reduce the effectiveness of the exit."

It must be kept in mind that whilst such obstacles might well be accommodated by passengers evacuating in clear air conditions, they can have a severely detrimental effect in dense smoke of the type which existed in the cabin at Manchester.

Indeed the minimal 1 - 2 inch increase in seat pitch at rows 9 - 10, the only concession to provide access to the overwing exit, is not only of little, if any, significance in providing additional space in which to manoeuvre between the seats, but also fails to provide identification of the route to the exit from the aisle for passengers engulfed in dense smoke and feeling their way along the seat rows.

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

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

This, in a typical modern high density seat layout with seats down to 17 inches in width, as at Manchester, provides a minimal clear zone for the projected aperture. This permits seat armrests or any cabin furnishing obstruction as close as 17 inches to the exit within the projected aperture.

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

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

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

Although there is little doubt that had the R1 door opened at his first attempt, the purser would not have opened the L1 door, having both front doors available should have enhanced the evacuation rate from the forward end of the aisle. However, the existence of the twin forward bulkheads with only a gap of some 22½ inches between them effectively restricted passenger flow to single-file. The effects of this restriction were only too apparent for the many passengers who successfully made their way forwards over the seats only to be confronted by the bulkheads. The potential egress rate of both forward doors was therefore never realised and a consequent delay was thus directly imposed on those waiting to exit via the forward end of the cabin.

2.7.2 *Effects of toxic/irritant gases and smoke*

It is significant that, of the 51 passengers who successfully evacuated from the two forward doors, some 23 escaped before the thick smoke had reached them - *ie* 45%. Of the remaining 28 who became engulfed in smoke, the stewardess had to pull two female passengers on to her slide at the L1 door, after they had collapsed. Two male passengers collapsed near the forward aisle before recovering later and getting out and a third was recovered alive but unconscious after some 33 minutes.

Shortly after the right overwing exit was opened and passengers began evacuation onto the wing, the centre section area was rapidly engulfed in thick black smoke, which had flowed into the aft cabin as the aircraft stopped. This smoke was drawn out of the right overwing exit due to this aperture being on the 'downwind' side of the fuselage. Delays rapidly built up at this exit due to the restricted egress, which caused a fatal crowding of passengers around the centre section, who were rapidly engulfed in the choking irritant/toxic gases and smoke.

Many passengers who suddenly felt their respiration severely affected by the atmosphere decided to climb over seat backs in order to get to the exit. This was forced upon them by other passengers collapsing in the aisle as they became debilitated and then incapacitated by the toxic gases. Some 46% of those survivors who successfully evacuated from the right overwing exit stated that they had gone over the seats. Many passengers in the forward cabin did likewise as the smoke quickly flowed forward from the centre section.

As was the case with evacuees queuing at the forward galley restriction, a number of survivors who evacuated out of the right overwing exit nevertheless collapsed temporarily due to smoke and toxic/irritant gas inhalation before recovering sufficiently to get out. One passenger stated that the doorway was blocked with peoples' bodies lying half in and half out of the aircraft. The male passenger from seat 16C died during evacuation after becoming lodged in this right overwing exit. It was not possible to positively identify the mechanism by which he became trapped. However, the failure of the seat 10F hinge-baulk, which allowed the seat back to fold fully forwards, probably under a weight of bodies, may have trapped his legs against the seat cushion. In addition it is probable that he had become weakened by the dense smoke atmosphere and would have been unable to extricate himself. The majority of the bodies (approximately 38) were eventually recovered from the area around row 10 (*ie* rows 8-12).

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

2.7.3 *Additional effects of the dense smoke atmosphere*

As well as the choking and debilitating effects of the smoke many survivors spoke of their inability to see. This problem is not solely a function of the extreme density of the smoke, since research has shown that it is also due to chemical effects on the eyes. At Manchester a number of survivors' eyes were seen by rescue personnel to be "frosted over", consistent with the anticipated effects of the high concentrations of acid gases in such atmospheres. Against this background of research and survivor evidence it is difficult to substantiate the rationale behind current regulatory moves towards the introduction of low-level 'escape-path' lighting to assist evacuations from smoke filled cabins. Under such circumstances the net safety-gains from such a requirement are likely to be minimal unless the passengers' eyes are protected.

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

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

The combined physical and psychological effects of the dense black smoke atmosphere on evacuees at Manchester created fear and panic in a manner strikingly similar to that reported in many previous fire accidents.

2.7.4 *Thermal effects of the combustion atmosphere*

The survival of the 14 year old boy recovered from his position lying over the body of the male passenger from seat 16C, is significant. His rescue by a fireman about 5½ minutes after the aircraft stopped, with only superficial burns to his hands, is indicative that the temperatures within the cabin were not totally unsurvivable at that stage. This observation is reinforced by the survival for 6 days of the male passenger from seat 8B who was found in the forward aisle, between rows 2-3, some 33 minutes after the aircraft stopped, and whose death was due primarily to lung damage and associated pneumonia rather than external burns.

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

Such evidence is in sharp contrast to the fire test results from the FAA Technical Centre at Atlantic City which have shown 'flashover' to occur within 2¼ minutes of fire penetration into a furnished cabin, with attendant temperatures of 1800°F and a critical reduction in oxygen levels. It is considered that the major difference between that test model and many real accidents is the enhanced ventilation which occurs due to multi-door openings, cabin ruptures, roof burn throughs and external wind/fire-convection (chimney) effects within the cabin. These cause 'purging' of the flammable combustion gases and smoke particulate, thereby delaying or suppressing flashover.

However, the flashover scenario depicted by such tests, an extreme situation, can occur, particularly where cabin ventilation is minimal. This appeared to be the case in the Lockheed L1011 accident at Riyadh after the engines were shut down and the air conditioning ceased, with no doors open.

Only between 6 and 9 of the fatalities at Manchester resulted primarily from excessive thermal exposure, the remaining 45 died as a result of incapacitation from carbon monoxide and hydrogen cyanide (*ie* some 83%). It is interesting to note that this result compares closely with fatalities from other aircraft fire accidents and domestic fires where around 80%, on average, die due to smoke/gas inhalation, as opposed to burns.

The evidence from survivors is entirely consistent with the results of the pathological examinations and indicated that passengers were not in general being 'burned to death', but that the majority were being rapidly incapacitated as a result of a few breaths of the dense toxic/irritant gas atmosphere.

2.7.5 *The interelationship between delay and debilitation*

Some of the survivors who were seated close to the forward exits escaped without experiencing the smoke and without too much difficulty. However, the majority of the survivors were affected by the atmosphere and many were temporarily overcome within the cabin, having suffered evacuation delays for various reasons. Those who succumbed fatally to the atmosphere within the cabin are unable to relate what prevented their timely escape but it is reasonable to conclude that most, if not all, experienced similar, but more acute evacuation effects and resulting debilitation/incapacitation effects.

The 25 second delay in opening a forward door, followed by further delays due to the small gap between the forward bulkheads and access problems associated with the overwing exit, had a catastrophic effect on the survivability for some on board G-BGJL.

Any delay in a critical evacuation - *ie* one where the cabin is threatened by fire/smoke invasion - is potentially very serious due to the attendant debilitation/incapacitation of the evacuating passengers. The onset of debilitation increases the delay, which in turn increases the inhalation of toxics leading to incapacitation/collapse of increasing numbers of passengers, rapidly escalating the problem of egress. This closed loop process can thus lead to stagnation of the evacuation.

Whilst such delays can be minimised by improved design and reliability of exits/slides and a more 'evacuation orientated' approach to cabin seating densities and configuration, in real accidents delays will occur for a variety of both unforeseen and predictable reasons - *eg* exit doors can jam due to impact-induced distortion, slides may be affected by strong winds or fire, etc.

Another situation when evacuation cannot be started immediately is when fire/smoke penetrates the cabin before the aircraft stops, as in the case of the accident to the Boeing 727 at Salt Lake City in 1965.

The most critical examples of this type of imposed delay are, of course, in-flight smoke situations where the cabin is invaded by combustion products and passengers cannot evacuate, but may only try to move away from the area of threat.

As delays will always be a threat, for any one or a combination of many reasons, passengers must be protected from the debilitating effects of such atmospheres, being kept conscious and mobile until such time as they can successfully evacuate.

2.7.6 *Evacuation certification requirements*

The Boeing 737-200 was required to demonstrate an emergency evacuation to the requirements of FAR part 25.803, which applies to all public transport aircraft with seating capacities greater than 44. (Appendix 7)

As stated in paragraph 1.6.8. the UK type certification of the 737-200 took place at Luton airport on 26 November 1970, when 130 passengers and 5 crew evacuated in only 75 seconds, some 15 seconds within the specified 90 second requirement. During this test, only the left forward, aft and overwing exits were used - in accordance with the requirement that only the emergency exits and emergency evacuation equipment on one side of the fuselage be used.

Such certification tests do not explore the effects on evacuation times when the exits at one end of a cabin are unavailable and therefore do not examine:-

i) The effect of twin bulkheads throttling the passenger flow. *eg* the forward galley bulkheads in G-BGJL;
ii) Increased mean aisle distances to available exits;
iii) Increased importance of the overwing escape routes.

These are clearly major deficiencies.

The regulatory authorities have stated that such tests are not intended to represent a realistic evacuation, but are merely regarded as a 'yardstick' test - *ie* to compare the evacuation potential of one aircraft with another.

FAR 25.803 nevertheless requires amongst other things that the demonstration must be conducted under the following conditions:-

1) It must be conducted either during the dark of night or during daylight with the dark of night simulated, utilising only the emergency lighting system.

5) A representative passenger load of persons in normal health must be used as follows:-

   (i) at least 30% must be female.
   (ii) approximately 5% must be over 60 years of age with a proportionate number of females.
   (iii) At least 5% but no more than 10% must be children under 12 years of age, prorated through that age group.

The above requirements conflict with the view that this test was intended as purely a yardstick comparison and raise questions as to precisely what such a test is intended to demonstrate. The main reason for evacuating an aircraft quickly is that associated with a potential fire/smoke threat to the passengers. The 90 second requirement cannot guarantee that all passengers will have evacuated the cabin before it has been penetrated by fire or smoke. Indeed, as soon as smoke invades the cabin this '90 second' criterion ceases to have any relevance, *ie* because this type of certification does not, by intent, address itself to the effects of smoke and toxic/irritant gases upon evacuating passengers with the attendant breathing difficulty, loss of vision, induced panic and therefore 'irrational' (non-ordered) behaviour - *eg* egress over seat-backs.

Because of this certification perspective, evacuating passengers in the test are in an ordered 'queuing' situation. The statements from passengers in this accident indicate that such ordered behaviour did not prevail. Furthermore it is important to appreciate that this type of evacuation certification test has strongly influenced the type of subsidiary testing carried out within the industry to establish evacuation rates from aisles, past obstacles (e.g. bulkheads or seats), towards and through exits. Although such tests are invariably conducted in clear air conditions, the results are used to influence aircraft design when critical evacuations can occur in conditions of thick smoke with associated lack of visibility and disorientation. Quite apart from other considerations, this does not explore the obvious problem of how passengers are expected to recognise where their exit is located and the fact that some obstacles encountered during an evacuation are readily accommodated in visual conditions, but might stagnate the flow of evacuees in smoke.

2.7.7 Evacuation logic

The 90 second requirement does indicate, however, that given a closely ordered evacuation the egress time can be minimised. The key question is how behaviour in a real, critical evacuation can be influenced to bias it towards optimum ordered egress. The starting point here must be to recognise the obvious prime requirement to maintain the evacuating passengers in a conscious, mobile state - for as soon as even a few begin to collapse and block aisles and exits, the egress problems escalate. Secondly, as indicated in the survivor statements, the onset of breathing problems provides a strong stimulus to escape by whatever means. It is therefore clear that the assurance of continued respiration for evacuating passengers would bias behaviour towards improved order.

With passengers maintained in a conscious, mobile and more ordered state, the next requirement is that of guidance towards exits. A notable feature of the passenger statements was that whilst they were in the aisle, they were moved along by the column of other evacuating passengers. A major problem with this type of transportation is that if one passenger falls, a critical blockage quickly results. The chances of such occurrences must be reduced if debilitation and incapacitation are not factors.

It is apparent that protection of both the eyes and the respiratory system from the effects of the fire atmosphere will contribute greatly towards achieving the kind of ordered evacuation which the 90 second test has shown minimises egress time, and which the regulatory authorities are seeking to achieve.

2.7.8 *The effectiveness of the current fire hardening strategy related to the evacuation environment*

Some 50% of the passenger seats, which were of the standard non fire-blocked type, survived the fire at Manchester. By contrast, the cabin wall panelling, and overhead stowage-compartments and ceiling panels were completely consumed.

Furthermore, it is evident from the statements of those survivors from the aft cabin that dense black toxic/irritant smoke rapidly filled that area without any observations of widespread fire in the cabin. Only 2 of the survivors who escaped from the right overwing exit recall seeing any fire in the aft cabin prior to their egress. The point which emerges from such testimony is that the seats do not appear to have played a significant part in the production of the heavy smoke which suddenly engulfed the aft cabin immediately after the aircraft stopped, and yet this smoke was very potent in its debilitating effects. It is thus probable that the smoke was largely from the external fuel fire, with significant amounts entering through the open R2 door, and the air conditioning grills located at floor level from the fire which had penetrated the outer skin adjacent to the aft cargo compartment.

Such evidence indicates that whilst the advent of fire-blocked seats is a positive step towards improved fire resistance in aircraft cabins, it is only one part of the overall problem of aircraft materials and associated pooled-fuel fires. It must also be emphasised that although the term 'fire-blocker' is used, when such seats are exposed to the heat flux from a major fuel fire, the blocking layer of material merely delays the combustion of the seat materials, typically by some 50 seconds. If during this delay the cabin overhead lockers, ceiling and wall panels are burning (due to higher temperatures at ceiling level), passengers will still be exposed to the associated combustion gases in addition to dense particulate smoke.

Such fire-blocked seats are the main outcome thus far of the 'fire-hardening' strategy, which has been the main approach to the problem of aircraft fire. This approach, which is almost solely based on the ignition, flame-spread, and heat release characteristics of materials, to the exclusion of any regulatory requirements for smoke or toxic/irritant gas emission criteria, cannot, even in the longer term, effect a complete solution to the problem.

Indeed, an example of the inadequacy of the flammability approach employed in materials certification thus far has been the range of flame-retardant materials developed by chlorination of previous materials which, when burnt in a real fire, generate even more smoke and toxic gas than their non fire-hardened equivalents. The two main findings of the C133 fire test programme[3] at the FAA Technical

Centre upon which the rationale for the current flammability approach to materials certification rests are:

"i) There is a correlation between flammability characteristics and toxic emissions.

ii) The severe hazard from toxic emissions occurs as a result of flashover in fires involving interior materials. The levels of toxic gases measured before flashover, or when flashover did not occur, were below levels estimated to prevent occupant survival. After flashover occupant survival is virtually impossible, regardless of the level of toxic emission."

In the light of the most recent C133 fire test, which took place at Atlantic City in 1987, conclusion ii) appears incorrect. A concentration of some 200 ppm of hydrogen cyanide was detected before flashover, -sufficient to induce rapid incapacitation and death. In addition this finding would appear to undermine statement i).

Statement ii) also overlooks the evidence from previous fire related accidents such as the Denver DC8, Salt Lake City Boeing 727, Varig Boeing 707, Cincinnati DC9 and others. Such a view is also in complete conflict with the results of the pathology and the evidence from survivors at Manchester. The clear message from all these accidents has been that the smoke and toxic/irritant gases which engulf the cabin, producing debilitation/incapacitation effects, were being generated without flashover having taken place.

It is therefore concluded that the FAA was correct in its attempts to add smoke and toxic gas emission criteria to their existing materials certification requirements in 1974/5. Although their latest ' Improved Flammability Test Standards for Cabin Interior Materials' as required by FAR amendments, FAR parts 25-61 and 121-189; and CAA Airworthiness Notice No 61 (16 March 1987), represent an improved flammability certification test, they nevertheless fall short of addressing the total problem of smoke and toxic gas emission.

The radiant heat flux from the OSU radiant apparatus, used for the revised certification, is 3.5 watts/square cm. Whilst this level of radiant heat flux is a vast improvement on the simple bunsen burner flame test, when it is compared against a typical heat flux from a pooled-fuel fire of 20 watts/square cm, it may be seen that it does not approach the realistic conditions encountered in such situations.

In view of the foregoing it may be seen that materials which meet this latest test standard, based purely on flammability and heat release criteria, will nevertheless still continue to burn when subjected to the high radiant heat flux from a kerosene pooled-fuel fire and will, consequently, produce smoke and toxic irritant gases. Since this test does not check such emissions, the associated gases, their concentrations and effects will be subject to no limitation.

Against this background, the second discussion document issued by the FAA in July 1986, which requested further comments relating to their ' Improved Flammability Standards for Materials Used in Interiors of Transport Airplane Cabins', is notable. In reponse to requests for assurance that no further rule making with respect to smoke and toxicity was anticipated in the forseeable future, the FAA replied:-

> "Based on the information currently available, the FAA has no plans to establish standards for either smoke or toxicity."

The position of the regulatory bodies, as it appears in the requirements concerning these issues, contrasts with that of many manufacturers, including Boeing, McDonnell Douglas, and European Airbus Industries, whose materials specifications do include, in addition to flammability criteria, smoke and toxicity limitations. However, the associated radiant heat flux used within such specifications is still low at 2.5 watts/square cm. The Airbus Industries ATS 1000 specification is regarded by British Airways as the best specification presently available world wide, and they have operated to it for the last 5 years.

Even if substantially improved materials were available which could withstand the heat flux from a kerosene pooled-fuel fire, the cost of retro-fitting current aircraft worldwide would ensure that the majority of aircraft flying would not be so equipped before the turn of the century. Furthermore, even if a stage were reached where substantially improved materials were generally in use, the problem would not have been completely solved; *eg* where a kerosene fuel fire break-through had occurred into a cabin, either due to burn through (as at Manchester) or due to cabin rupture, passengers would still be engulfed in dense kerosene smoke, albeit with less toxic/irritant effects, but nevertheless capable of disabling evacuees, as occurred at Denver in 1961. It should be borne in mind that passenger baggage in cargo compartments would also generate these toxic/irritant gases. Thus, whilst it is desirable that materials improvements are accelerated with consequent expansion of the escape-time window, before temperatures exceed human tolerance, the 'fire-hardening' approach is complex and essentially a long term strategy because of the inherent difficulties associated with materials development, evaluation and cost of the introduction of new materials into service.

One of the major problems caused by the current over-emphasis of the 'fire-hardening' approach to the problem of aircraft fire, has been its depressive effect on other means of combating this problem. Other solutions which appear to be more direct and may be applicable in the near to medium term are available. These other solutions include passenger smoke protection, water spray and related fire suppressant systems.

This accident highlights the fact that passengers are required to self evacuate, essentially unaided as quickly as possible when the cabin environment is becoming very hostile. Clearly the passengers must be provided with a survivable environment for as long as it takes to escape. This can be done by providing each passenger with his own mobile environment and/or by influencing the cabin environment as a whole. Whatever the approach, the strategy must provide for both the in-flight and ground fire situations.

2.7.9 *The case for passenger smokehood protection*

Passenger smokehood protection has been advocated repeatedly by various highly respected aviation bodies over the last 20 years, usually in the wake of a major aircraft accident which had, once again, illustrated the major effect of smoke and toxic/irritant gas incapacitation upon survivability.

The FAA proposed a requirement for passenger smokehood protection on passenger transport aircraft in the associated NPRM issued on 11 January 1969. This was withdrawn on 11 August 1970 due to technical objections raised by the aviation industry.

The US National Research Council then issued a comprehensive report on smokehoods, recommending further smokehood development.

In June 1980, the FAA Technical Centre at Atlantic City, requested the FAA, CAMI to re-examine passenger smokehood protection. This request was prompted by findings from the SAFER Committee Technical Group which had highlighted the survival suppression effects of smoke and toxic gases on evacuating passengers, and the limited progress which had been achieved in the reduction of cabin fire hazards.

In 1983, as a result of their investigation into the in-flight fire and emergency landing accident to the Air Canada DC9 at Cincinnati on 2 June 1983, in which 23 of the 41 passengers died before they could evacuate the cabin, and survivors had breathed through hand towels, the NTSB issued Safety Recommendation A-83-76 on 31 October 1983. This recommended the FAA to accelerate research into passenger smoke protection at CAMI.

A comprehensive FAA report [10], published in July 1982, examined all the applicable approaches which could be utilised to combat aircraft fires and their effects. This report also included a very detailed cost benefit analysis of these concepts. This analysis indicated that passenger smokehoods were by far the most cost-effective approach and would achieve the greatest improvement in survivability, with the lowest cost per death prevented. It estimated that passenger smokehoods would cost $140,326 per death prevented, compared to $1,154,720 per death prevented for a zoned water spray concept, which would give almost the same improvement in survivability. (Appendix 17) This report also concluded that passenger smokehood protection could be implemented in the near term.

The passenger smokehood approach to survivability in aircraft fire situations has the following benefits:-

1. It is the most cost-effective solution to the problem of passenger survivability in aircraft fires, according to the above FAA report.

2. It can be implemented in the near term.

3. It will protect passengers respiratory systems and thereby maintain consciousness and mobility, without which passengers are not able to successfully evacuate aircraft in critical smoke/toxic gas conditions.

4. Smokehoods would reduce the level of 'panic' during a critical evacuation, which is triggered frequently by the sudden envelopment of passengers in dense black smoke and toxic/irritant gasses. This should bias the situation towards improved order, and there is little doubt that the closely ordered evacuation is the most efficient way to achieve minimum egress times, as demonstrated in the '90 second' evacuation certification test.

5. Smokehoods would protect the eyes from the irritant gas effects which cause blinding due to lachrymation and soot deposition. This would enable passengers to make full use of the proposed low level escape-path lighting, the benefits of which will be severely limited without such eye-protection.

6. The provision of smokehoods for cabin crew has already been agreed by the FAA and CAA. Such smoke protection is primarily intended to protect cabin crew whilst they are attempting to extinguish a cabin fire. There can be no guarantee that such attempts will always be successful, particularly where the fire source is remote, *ie* behind panelling or within a cargo compartment. In such situations where the fire cannot be extinguished, the provision of smokehood protection for crew members only is illogical and may introduce competitive behaviour, with critical disorder on board the aircraft. The additional provision of

passenger smokehoods is thus clearly required under such conditions, if disorder is to be avoided.

2.7.10 *The AAIB passenger smokehood trials:*

These trials were originally directed towards the evaluation of smokehoods for passenger protection in a ground fire situation, such as occurred at Manchester. A target endurance of 5 minutes protection was thus chosen to afford sufficient time to evacuate in critical conditions. Tests were carried out on smokehoods which were already in quantity production and on prototype smokehoods, some of which had been in development before this accident. One smokehood was designed and developed in response to the AAIB tests.

The performance demonstrated by some of these lightweight hoods during tests in 1986 indicated that the original 5 minutes protection target could readily be exceeded. It was apparent that such protection could be extended to combat in-flight incapacitation of passengers, where fire had occurred in the air.

Nevertheless, the postulation of a 20 minute endurance for passenger smokehood protection in the first CAA draft specification issued in July 1986 represented a formidable challenge to the manufacturers. The scale of this new proposal was particularly striking when compared to that proposed (and later required) by the CAA and FAA for cabin crew smokehood protection - *ie* that of 15 minutes protection, from units which weighed some 3-4 lbs, compared to the 1 lb target weight for passenger smokehoods. The reason given for the disparity in protection endurance was that the passengers would require an extra 5 minutes protection for the purposes of ground evacuation, whereas the cabin crew would not require this additional protection, since they would be positioned at the exits. The evidence from the surviving cabin crew at Manchester, and indeed other accidents, indicates quite clearly that cabin crew do require protection under such conditions.

The results of the AAIB trials programme have demonstrated that breathable gas smokehoods designed for passenger use, can achieve (and in the case of one particular type greatly exceed) the 20 minute endurance required by the CAA Draft 'Type 1' specification, even at the current stage of development. Indeed, two such smokehoods completely out-performed an existing cabin crew hood, manufactured to French specifications and which weighed 3 lbs. This clearly demonstrates the potential available within such lightweight smoke protection, developed since the Manchester accident.

In addition, two filter-type smokehoods demonstrated that they could successfully filter-out smoke particulate and toxic/irritant gases such as hydrogen cyanide, carbon monoxide, hydrogen fluoride, hydrogen chloride, nitrogen dioxide, sulphur dioxide, ammonia, acrolein in addition to benzene, toluene, styrene, acetaldehyde etc. Inhaled gas temperatures can be maintained within acceptable limits. Even without carbon dioxide absorbers, the concentration of carbon dioxide can be maintained within reasonable limits, if the challenge concentration does not rise above 4%. An interesting finding from the AAIB tests on filters is that frequently a small increase in oxygen concentration (approximately 1%) occurred downstream of the filter, due to removal of the other gases. With regard to the concentration of oxygen and carbon dioxide in aircraft fires, it is notable that the C133 results from the FAA Technical Centre indicate that the oxygen remained at 21% while temperatures were still survivable, and the carbon dioxide concentration was negligible.

Filters have achieved an endurance of up to 10 minutes during exposure to the AAIB challenge atmosphere. This additional endurance capacity, above that required for ground evacuation, may be considered with respect to in-flight protection. The anticipated workload for the in-flight case would result in a respiration rate substantially lower than the 30 litres/minute used in these filter tests, due to passengers being in an essentially sedentary state. If a respiratory rate of 10 litres/minute is assumed to apply in-flight, then this would increase the effective endurance of such a filter by a factor of 3. The overall endurance of filtered protection would thus be equivalent to 15 minutes (in-flight) + 5 minutes (ground evacuation).

In addition, the CAA have indicated in their latest draft specification, that they would accept the assumption of an average in-flight challenge concentration of smoke and gases of 25% of that applicable to the ground fire situation. This factor would also extend the potential endurance of filter protection, which is generally limited by smoke particulate densities, as opposed to gas filtration limitations. Indeed the AAIB tests demonstrated that filters, based on the Hopcalite catalyst, can successfully block carbon monoxide for periods of up to 30 minutes.

These tests have thus demonstrated that low weight smokehoods can be made available for passenger protection, with endurances of 20 minutes.

In addition, recent developments by some of these smokehood manufacturers, using potassium 'superoxide' units, has produced cabin crew hoods with greatly increased breathing capacity and endurance. Development work has also started with the aim of producing lightweight units of this type, for passenger use.

Whilst smokehoods cannot protect some of the passengers threatened by direct thermal assault, thermal injuries are responsible typically for about 20% of fatalities only; the remaining 80% stand to reap great benefit from the use of smokehoods, and their provision on all public transport passenger flights is urgently recommended.

2.7.11 *Water spray systems*

Work on water mist systems to date indicates that they may have the potential to rapidly and dramatically improve the environment within the whole passenger cabin by reducing the temperature and 'scrubbing' the particulate and soluble gases from the atmosphere. However, water sprays are not initially envisaged for use in the in-flight fire case and even if they become so, until their efficiency in dealing with the toxic and irritant gases has been fully examined there is a need for a twin strategy.

2.7.12 *The 'Twin strategy' of passenger smokehoods/cabin water spray*

The AAIB passenger smokehood trials have demonstrated that the technology is currently available to provide passenger smoke protection.

Cabin water spray systems have been examined by the FAA in the past, and are currently being re-assessed by the CAA. There is little doubt that such systems would provide a very effective means of delaying/preventing fire ingress into an aircraft cabin or suppressing/extinguishing a cabin fire, increasing the time available for passengers to evacuate. However, the relative cost of retrofitting current aircraft in service raises questions concerning how long it would take, even given a regulatory decision to adopt such an approach, for aircraft generally to be so equipped.

In addition, at present such systems are proposed for ground use only. Passengers would still require smokehood protection against an in-flight smoke situation, until such time as the aircraft could carry out an emergency landing.

It is clearly important that the possibility of using such water spray systems in-flight is examined. Whilst the problems of water interaction with the aircraft's electrical systems (which increasingly play a major role in flying-control systems) may be overcome, a major question remains over the ability of such systems to guarantee rapid extinguishing of an in-flight fire. Such a fire may be remote from the cabin, within an electrical equipment bay, cargo compartment or behind panelling. In addition, if such systems are adopted, they will be severely restricted in the quantities of water available. It would thus appear prudent to also provide passenger smokehood protection, to give an added measure of safety for use where an in-flight fire is not immediately suppressed.

Furthermore, the additional cost of such smokehood protection would be very modest, in comparison with that associated with the water spray system.

It is thus considered that the early adoption of passenger smokehood protection, followed by the introduction of such cabin water spray systems, would combine to form a 'twin-strategy' which would greatly increase survivability in aircraft fires, be they in-flight or on the ground.

2.8 Firefighting and Rescue

In the course of the following analysis, it might appear that criticism is being levelled at rescue personnel; this is not the intention. It is fully recognised that it is one thing to analyse events in the cold light of hindsight, but quite another to have to deal with such events in practice. It is quite clear that the individuals involved did their utmost under extremely hazardous, rapidly changing and stressful conditions. In particular, the individual efforts to effect an early entry into the forward cabin and to help people trapped in the overwing area were extremely courageous and contributed directly to the saving of lives. However, it is only from an objective look at such real emergencies that techniques and equipment can be improved.

2.8.1 Initial response

The response of the MIAFS was commendably fast, resulting in the first firefighting vehicle arriving at the scene approximately 25 seconds after the aircraft stopped, rapidly followed by the other available appliances. This was a much faster reponse than could reasonably be assumed for the purpose of emergency planning (the regulations allow up to 3 minutes for the attendance of the first vehicle at an airport incident/accident).

The immediate deployment to recover the second 'jumbo' major foam tender (J2) from the hanger, where it was undergoing re-painting, made this vehicle available in time to contribute significantly to the firefighting effort. Some aspects of the RFF service deployment were less helpful however, notably the deployment of the fire station ambulance to rendezvous with the GMC Fire Service. This vehicle's absence deprived the scene of a medical 'command post', which could have provided a focal point for those involved with helping survivors, thereby reducing the confusion which developed over where they should be assembled. In addition, the ambulance went to the wrong RVP and so did not fulfill the escort task either. The emergency orders current at the time required the ambulance to attend the scene of the incident/accident, the airport police providing the escort.

The response of the GMC Fire Service was also commendably fast, but their efforts were frustrated by a series of communications blunders which, on the day, resulted in the Airport Police escort going to the West RVP while they waited at the North RVP. The resulting 3 minute delay in the attendance of the GMC water tenders occurred at a time when the officer in charge at the scene had recalled his breathing apparatus team from the cabin because of concern over diminishing water supplies. However, although this delay may potentially have cost lives, on this occasion it probably did not significantly compromise the rescue effort. The rapidly deteriorating conditions in the cabin were, by that stage, already limiting access anyway, and would by then have probably caused fatal injury to those passengers still on board. Nevertheless, the possibility that the delay directly contributed to loss of life cannot be discounted entirely and the communications breakdown which caused it is a matter for serious concern.

2.8.2 *Fighting the external fire*

The conventional firefighting and rescue techniques adopted by RFF agencies in the UK (and elsewhere) relied upon the speed of response of the RIVs to provide 'first aid cover', pending arrival of the larger foam tenders. The tasks of the RIVs were to provide a quick knockdown of incipient or early stage fire, and to protect exit paths if passengers were already evacuating. Upon their arrival, at least one of the major foam tenders would normally adopt the position on the nose so as to be in a position to deploy foam along the length of the fuselage on the side affected, or likely to be affected, by the fire. The remaining vehicles would be deployed in tackling the fire in whatever manner was most appropriate in the particular circumstances, with the major emphasis being laid on the protection of passengers and the maintenance of escape paths, rather than extinguishment of the fire as such.

The crew of the first RIV to arrive (RIV2) appear to have quickly identified the left engine area as the source of the fire, and positioned themselves well, both to attack the main pooled-fuel fire in that area and to cover the left side exits. Having knocked back the fire in the left engine area, this vehicle was repositioned to address more effectively the fire which could then be seen attacking the rear fuselage. It is not clear whether the running fuel fire was extinguished fully at that time. After running out of media, the vehicle was moved clear of the aircraft so as not to impede access by others. With the exception of J1, which was later manoeuvred off the left side to deal with the resurgence of fire under the left engine, this was the only vehicle used to actively address the fire at its source; all other vehicle crews appear to have adopted a tactic of general coverage of the fuselage and exits, mainly on the right side.

Whilst it is apparent that the actions of all crews fell broadly within the bounds of conventional practice, some aspects were less than ideal. In particular RIV1 - the second vehicle to arrive - adopted the position on the nose normally taken by a major tender, forcing J1 to take up a position further off the nose. Furthermore, it was left in this position throughout the proceedings, even after its media had been exhausted, impeding J1 during its manoeuvre into a new position on the left side. Although it was not obstructed, the Protector foam tender also positioned too far away initially, and needed to be re-positioned twice during its period of active operation.

The apron fire vehicle, despite a prompt attendance, was not used in the firefighting effort - probably because it did not have a foam monitor and was therefore parked some distance away, possibly too far away for its presence to be noted by those directly involved in tackling the fire. This vehicle carried 100 kgs of Monnex powder, which is an agent specifically intended for use on '3 dimensional' fires. In all probability, this could have been used to good effect during the attempts to extinguish the intractable running fuel fire which flared up (or re-ignited) after the initial foaming operations had ceased. The absence of any training in the use of Monnex powder during the 3 months prior to the accident may have been significant, in that the personnel involved would have been less aware of its potential value than they might otherwise have been, and therefore less likely to actively seek it out.

With the above exceptions, which probably did not have a great impact on the overall outcome, the firefighting and rescue effort was about as effective as conventional techniques would allow; it is less certain whether such a 'conventional' approach is the most effective one for dealing with fires of this type.

2.8.3 *Fighting the internal fire*

RFF services in general were not, and indeed still are not, equipped to tackle internal fires effectively. This fact was distressingly apparent at Manchester where, having achieved a good measure of control over the external fire, to a large extent rescuers had to suffer the trauma of becoming impotent spectators to the deaths of those still inside.

Although entry was made into the cabin at the earliest opportunity, some 7 minutes into the fire, the internal fire was by that stage too severe to permit effective rescue or firefighting attempts to be mounted; the hazard involved was all too evident when the fireman was blown out of the door by an internal explosion and the roof was seen 'rippling'.

The cause of the explosion which blew the fireman out of the forward door could not be positively identified. However, the rupture of an aerosol-can as a result of heat induced overpressure and the explosive ignition of the propellent gas (typically butane) so released, or the rupture of a therapeutic oxygen cylinder are considered to be possible candidates. The aircraft's in-built oxygen system played no part in the fire but the discharge of the remainder of the therapeutic oxygen cylinders, clearly represented a very considerable hazard to firefighting personnel. Although their precise role in this fire could not be identified, the presence of duty-free spirits in the cabin undoubtedly presented an additional hazard for both passengers and rescue personnel.

2.8.4 *Water shortage*

The delay in obtaining water from the hydrant system occurred just before the arrival of the GMC water tenders, but because of the time required for the foam tender to re-fill from a hydrant, some 15 to 18 minutes, the problems with the hydrant probably did not have any detrimental effect on the outcome so far as the availability of water to fight the fire was concerned. However, two RFF personnel spent long periods away from the scene because of the initial abortive attempt to find water and then the time taken to fill a major appliance.

2.8.5 *Communications*

It is evident that poor communications were a major handicap throughout the period of firefighting activity. In particular, there was no means for the officer in charge to contact RFF personnel outside his immediate vicinity, preventing him from re-directing resources to provide a more unified effort should he have considered that necessary, and no means for him to obtain feedback on the progress of, or to process requests from, individual teams. This was illustrated graphically by the variety of individual instructions issued and actions taken during attempts to obtain water from the hydrants, all of which were carried out in isolation and without the individuals concerned being aware of the actions of others.

It is considered that the lack of a helmet mounted communications system is a serious handicap which limits the potential effectivenss of both the aerodrome RFF services and the local authority fire services which attend. It is considered necessary that a requirement for suitable communication systems be introduced as part of the licencing requirements for all major airports, and that these requirements include provision for communication on the same system by (at least) the officer in charge of any local authority fire service having standing arrangements to attend aircraft emergencies at such aerodromes. It is further considered necessary that the recruitment and training of airport fire officers be amended to facilitate a more command orientated approach.

The difficulty experienced by the GMC fire service in identifying the officer in charge of the MIAFS at the scene demonstrates the need for this officer to be visually distinctive. It is recommended that some form of high visibility clothing be worn by the officer in charge at any incident/accident scene.

2.8.6 *Firefighting tactics*

The belief that a 'prompt, mass application of foam' is all that is needed from RFF crews is clearly a fallacy; this fire involved less than 700 gallons of fuel, foaming began much more promptly than one could reasonably have expected and the quantities of media even met the requirements for much larger wide bodied aircraft, yet the fire burned out of control. Clearly, the whole approach to aircraft firefighting was called into question by this accident.

The present training of RFF personnel depends heavily on the development of each individual's skill, thus equipping him to assess the best tactics to adopt under widely differing conditions. This is a proper approach to adopt given the many permutations of circumstances which can arise. There is, for example, no way of allocating specific crews or vehicles to particular tasks or locations since the vehicle arrival sequence cannot be predicted and the requirements of one fire will be quite different from those of another. In all cases however, the fundamental requirement is to get the initial firefighting effort under way with a minimum of delay, and to this end, the existing approach is probably as good as one can practicably achieve. However, the initial positions and tactics adopted will of necessity be a first guess at the requirements of the task; subsequently, the firefighting effort must be flexible enough to permit re-direction of resources, whilst continuing to provide a unified and co-ordinated attack, if its full potential is to be realised.

During the period of active foaming, individual RFF personnel will be occupied with their own firefighting tasks and cannot be expected to look to the overall requirements of the operation, neither would it be desirable for them to do so since to act individually could lead to an unco-ordinated and confused firefighting effort. The co-ordination and direction of the firefighting operation is a management role, which must be the responsibility of the officer in charge. No suggestion is being made that such a role would be an easy one, particularly in view of the difficulties in achieving rapid access, or a good 'vantage point' from which to make an assessment of priorities. However, difficult though it may be, the requirement to actively manage resources is born of the need for a more effective solution to the firefighting problem.

At the present time, the lack of helmet mounted radios seriously handicaps the effective management of the firefighting resources. Arguably, the running fuel fire which caused such difficulty at Manchester might have been addressed more effectively had those directly involved in dealing with it been able to communicate more effectively.

Currently, fire crews can only fight an internal fire by making an entry into the cabin in breathing apparatus and deploying branch lines to attack the fire directly, and the policy is to commit fire crews to the inside of the aircraft at the earliest opportunity. However, committing firemen into the cabin during the period when passengers are self-evacuating could clearly lead to conflict between passengers trying to get out and firemen trying to get in. In an incident such as this one the approach should be to effectively suppress any fire which is affecting means of escape which are not in use , so as to bring them into use or effect an entry via these into the aircraft.

Immediately fire takes hold inside the cabin, the 'knock down' effect of toxic combustion products will result in a majority of those still inside, if left unprotected, rapidly losing consciousness. At this stage there will be an abrupt transition from a relatively ordered evacuation of mobile, uninjured passengers - whose interests are best served by allowing them to continue evacuating without hindrance - to a rapidly deteriorating evacuation process in which panic rules and people collapse, impeding the progress of fellow passengers and blocking exits. Once this transition has occurred, it is crucial that rescuers effect immediate entry to recover those who have lost consciousness.

Although a number of alternative methods of fighting internal fires have been examined in the past, and some, including the use of 'harpoons' or 'lances' to penetrate the hull and deliver media into the interior, have been used operationally, none has been introduced for general use on passenger aircraft fires. It must be concluded that current aerodrome firefighting policy makes no realistic provision for dealing with internal fires and, equally important, there is no licencing requirement for them to be able to do so.

Some form of automatic or semi-automatic fire fighting system, built into the passenger cabin, is essential if internal fire is to be tackled early enough to limit its development effectively. This requirement has long been acknowledged within the aircraft fire research community and a number of theoretical and practical studies have been undertaken to assess systems using both water and alternative extinguishing agents. Of the alternative agents, the halons appeared initially to offer a good performance, but were later found to have serious deficiencies when used in a cabin environment; principally the production of extremely toxic decomposition products if extinguishment was incomplete. It was also found that in winds exceeding 2 mph, halon agents tended to become dispersed to the point where they became ineffective. Work on water discharge systems has shown that spray nozzles designed to provide a controlled mist coverage have great potential to extinguish fire, reduce temperatures within the cabin and to 'scrub' the atmosphere.

It is considered important that on-board extinguishing systems, designed to limit and extinguish internal fires, should be developed as a matter of urgency. On the evidence available to date, water mist/spray systems appear to offer the most viable solution. In particular, a water based system has the potential to operate in two modes; an independent mode using existing on-board water to enable an attack to be made before, or as breakthrough occurs, and a tender-supplied mode using water from firefighting vehicles connected to valves at the aircraft's extremities. Such a dual mode operation is seen as an essential attribute if the system is to realise its full potential.

Because of the problems of survivors collapsing in and around exits, particularly the overwings, and the evident problems this creates, it is desirable that where possible, RFF personnel in breathing apparatus should be positioned by overwing and other exits at the earliest opportunity to assist those evacuating and to help keep the exits clear. This would require the airport fire service to be equipped with additional breathing apparatus and all fire fighting personnel to be trained in its use.

3. CONCLUSIONS

(a) Findings

The flight deck crew

1 The flight deck crew were properly licenced, trained, experienced and rested to undertake the flight.

2\. The flight deck crew discussed defect and rectification entries in the technical log relating to the performance of the left engine; they monitored it closely during start-up and acceleration to take-off power and were satisfied with its performance.

3 The flight deck crew responded to the 'thud', later to be identified as an engine failure, in a prompt manner in accordance with their experience and training.

4 The first indication to the flight deck crew of fire, a left engine fire warning, occurred 9 seconds after the 'thud', at a time of extremely high workload. The commander had no direct means of assessing the extent of the fire and sought advice from air traffic control on the need for passenger evacuation.

5 The decision to turn the aircraft to the right into link Delta, given the sequence and timing of the information available to the commander, in particular the initial lack of a fire warning, was understandable.

6 Turning the aircraft to the right had a critical effect on the fire, placing it upwind of the fuselage.

7 The aircraft was turning off the runway when the commander said over the public address system "evacuate on the starboard side please", intending the cabin crew to prepare in anticipation of the imminent full stop.

8 The left engine fire drill was actioned immediately the aircraft stopped and the right engine then shut down.

9 The Passenger Evacuation (Land) Drill was inappropriate for such an emergency and has since been modified. However, the evacuation was not delayed as a result.

10 The commander and co-pilot evacuated the aircraft via the flight deck right sliding window because of the fire on the left side of the aircraft.

The cabin crew

11 Each member of the cabin crew was properly trained and qualified to operate at any station within the cabin.

12 The two most experienced cabin crew members were seated in the forward cabin leaving two relatively inexperienced stewardesses at the rear. However, it is unlikely to have significantly influenced the outcome in this instance.

13 The forward cabin crew seats were positioned such that, when seated, the crew members had a restricted view of the passenger cabin.

14 On failure of the left engine the public address volume automatically switched to the lower level.

15 One of the rear stewardesses opened the right rear door as the aircraft turned off the runway, either as a rapid response to the commander's evacuation instruction or as a direct reponse to the deteriorating conditions in the aft cabin.

16 The motion of the right forward door as it was rapidly opened by the purser, exposed a design fault associated with the slide box lid release lanyard, causing the door to jam in the aperture.

17 The purser showed initiative under pressure in opening the left forward door and then returning to the right forward door and clearing the jam.

18 The forward stewardess had to pull passengers free who had become wedged in the forward aisle at the galley restriction to start the flow of evacuees.

19 The forward cabin crew members remained on board until they were on the point of being overcome by the smoke themselves. A number of survivors owe their lives to their direct actions.

20 The two stewardesses in the rear cabin were faced with an impossible situation. However, the little evidence that there was indicated that they carried out their duties to the best of their ability until they succumbed to the rapidly deteriorating conditions.

21 The cabin interphone was not used throughout the emergency.

22 Some of the emergency equipment for use by the cabin crew, including two loud hailers, was in overhead bins in the passenger cabin, not at the cabin crew stations. In an emergency evacuation the cabin crew may find it impossible to reach this equipment as passengers move towards the exits.

The left engine

23 The aircraft had a valid Certificate of Airworthiness in the Transport Category (passenger) and had been maintained in accordance with an approved schedule.

24 The left engine failure was caused by an explosive rupture of the combustion chamber outer case. The rupture immediately caused the engine to run down.

25 The instantaneous release of high pressure air from the combustion chamber outer case caused the forward (dome) part of the disrupted No 9 combustor can to fracture its locating pin and be ejected radially from the engine.

26 The combustion chamber outer case rupture was caused by localised overheating in the area adjacent to the No 9 combustor can which caused a reduction in material strength over a critical length of the casing.

27 Overheating of the combustion chamber outer case occurred due to a 360° separation of the No 9 combustor can in the 3/4 liner joint area which allowed hot combustion gases to escape from the can and impinge upon the inner surface of the combustion chamber outer case.

28 Post-separation mechanical and thermal damage prevented full analysis of the precise nature of the 360° fracture. The available evidence, however, suggested that previously cracked and repaired areas of the circumference and a further area without visible cracking at the time of repair, had cracked first from multiple origins typical of a thermal fatigue mechanism. The nature of the fracture linking these areas suggested that a mechanical mode of fatigue had been present, but still with some evidence of multiple origins.

29 Multiple embryonic thermal fatigue origins would not be detectable by normal inspection techniques employed during overhaul and repair.

30 The can had been inspected and circumferential cracking of 180 mm combined length in the 3/4 liner joint area had been repaired in November 1983 after 7,482 hours/3,371 cycles time since new. It then ran a further 4,611 hours/2,036 cycles until it failed.

31 The repair carried out in 1983 used the direct fusion weld method described in the British Airways Engine Overhaul Manual. Solution heat treatment and optional post-weld stress relief, which formed part of the repair procedure in the Pratt and Whitney Engine Manual at that time, were not carried out.

32 Omission of the above two heat treatments and a further process known as 'braze/reinforcement' was permissible in accordance with the approval granted to British Airways/British Airways Engine Overhaul Ltd by the Civil Aviation Authority.

33 Conflicting evidence was presented on the effectiveness of solution heat treatment, but on balance it is considered that it would not have had a significant effect on the fatigue life of the can. It was accepted, however, that its inclusion would have facilitated weld repair of the can.

34 The Pratt and Whitney Engine Manual did not preclude direct fusion weld repair of a circumferential crack of any length. Local areas of "severe distortion and oxidation" were not permitted to be weld repaired.

35 A 3 inch circumferential crack length limit had existed in the Engine Manual prior to 1977 at which time it was removed by Pratt and Whitney. British Airways were unaware of this pre-existing limit, starting operation of the JT8D in 1980.

36 A small area of parallel cracking, possibly associated with thermally distressed material, was present on liner 3 of can No 9 prior to repair and was addressed by fusion weld repair. The precise nature and appearance of this area at that time is not known.

37 The repair failed to impart sufficient residual life to the can to enable it to remain in service until the next scheduled inspection.

38 No abnormalities or other defects were found within the engine or its accessories which could have precipitated the early failure of No 9 can.

39 The manufacturer had advised operators that direct fusion weld repaired cans have lower fatigue lives than ones repaired using material replacement techniques but had not quantified this reduction. British Airways interpreted this as applicable to cans with a much greater time-in-service than any they operated at the time.

40 Whilst direct fusion weld repair appears to have proved a worthwhile method for many operators, some did not employ this technique for circumferential cracks. A large proportion of operators who did had self-imposed circumferential crack length limits in the region of 3 inches.

41 A fleet survey of British Airways engines resulting from the Emergency Airworthiness Directive after the accident to G-BGJL, revealed that weld repair of circumferential cracks was providing little, if any, recovery of can life. Had this accident not occurred British Airways would not have been aware of this until the next scheduled inspection of a repaired can, or if earlier, until some incident of can distress had been detected.

42 The can life reduction resulting from the possible repair of a localised hot-spot, and the ommision of one required and one optional heat treatment process, could not be quantified. However, the abnormally long circumferential cracking which existed in can No 9 prior to repair was an easily detectible and quantifiable indication that the can had suffered abnormal thermal fatigue damage during first run.

43 Since the method of direct fusion weld repair addresses only the visibly cracked areas and not embryonic fatigue damage in the remainder of the can, the residual life of a can repaired by this method remains an unknown quantity compared with the demonstrated performance of new cans.

44 Material or complete can replacement techniques theoretically represent the only satisfactory way to ensure complete life recovery in vulnerable areas. Some airlines which employ direct fusion weld repair of circumferential cracks would appear, however, to have demonstrated satisfactory performance within their pattern of operations and inspection programmes.

45 British Airways regarded the JT8D as a well proven and developed engine which they were operating well behind the lead operators. Whilst this was true, certain areas, including combustor can durability, continued to cause problems and were the subject of continuing development by the manufacturer.

46 After the accident to G-BGJL, the CAA and FAA issued mandatory directives requiring operators to perform inspections on their JT8D engines at intervals designed to detect circumferential combustor can cracking at an early stage before it could develop into a full 360° separation.

47 Inadequate exchange of information between operator and manufacturer led to under-reaction by the operator to previous similar incidents, which were notified to them through the medium of advisory communications. The content of these communications gave insufficient information to enable the operator to make accurate judgements regarding their subsequent course of action and the operator did not seek clarification.

48 The Pratt and Whitney Maintenance Manual gave no guidance for trouble shooting an engine with low idle RPM. British Airways regarded low idle as the prime reason for the slow acceleration of the No 1 engine, also reported by the crew on 21 August. None of the Pratt and Whitney communications referred to low idle as a symptom of a disrupted can.

49 The action taken by British Airways to address the low idle RPM pilot report on the 21 August involved adjustment of the engine idle trim without performing a part power trim run, contrary to the Pratt and Whitney and Boeing Maintenance Manuals.

50 It appears unlikely that a part power trim run on the 21 August would have revealed distress to the No 9 combustor can. However, application of low idle/slow acceleration trouble-shooting procedures employed by the operator over a period of time had the potential to impair accurate fault diagnosis.

51 Routine trend analysis of the flight recorder data from G-BGJL would not have provided warning of the impending failure of No 9 combustor can. Although such trend analysis, given that the necessary parameters are recorded, can indicate severe combustion can distress it cannot be relied upon to do so in every case.

52 The left engine thrust reverser deployed on selection but falling oil pressure accompanying the engine run down inhibited the system and it remained locked out after reverse thrust was de-selected.

The fire

53 The ejected dome of the No 9 combustor can and a small section of the fan case struck an underwing fuel tank access panel creating a hole which had an area of 42 square inches.

54 The wing tank access panel had an impact strength approximately one quarter that of the lower wing skin; had the dome struck the adjacent skin penetration of the tank probably would not have occurred. Neither the access panel nor the lower wing skin were designed to any impact resistance criteria, nor were they required to be.

55 The fire ignited when fuel from the punctured wing tank access panel came into contact with combustion gases escaping from the damaged engine.

56 The left engine fire detection system was serviceable and indicated to the flight deck crew an 'engine fire' 9 seconds after the combustion chamber outer case ruptured; the delay occurred because the fire was burning external to the engine nacelle.

57 The operation of the engine fire extinguisher system had no significant effect on the fire, and could not have been expected to do so.

58 The fire burnt in two separate but overlapping phases, involving fundamentally different fire mechanisms:-

i) Whilst the aircraft was moving at speed on the runway, fuel became entrained into the strong turbulent wake generated by the extended thrust reverser buckets and burnt vigorously as a 'dynamic fire plume'.

ii) As the aircraft decelerated and the turbulent wake decayed, the fire transitioned into a quasi-static fire burning above the pool of fuel trailing behind the aircraft. By the time the aircraft stopped, a fully established 'static' pooled fuel fire was burning adjacent to the left rear fuselage.

59 The application of reverse thrust did not at any stage play an active role in controlling or influencing the fire beyond the establishment of the turbulent wake referred to in (i) above.

60 Although the 'dynamic' fire plume was visually very dramatic, hull penetration was caused primarily by the 'quasi-static/static' pooled fuel fire.

61 The aft right door aperture allowed the early entry of smoke and possibly some flame transients, but was not the principal point of entry of the fire into the cabin.

62 The wind was the principal factor controlling the fire's behaviour. It carried the external pooled fuel fire against and beneath the rear fuselage, giving rise to rapid fire penetration. Subsequently the wind induced aerodynamic pressure field around the fuselage drew fire products into the hull, through the cabin interior and out through open exists on the right side of the fuselage.

63 The initial fire penetration of the fuselage occurred within 20 seconds of the aircraft stopping, when the lower skin panels on the left side adjacent to the aft cargo hold were burnt through, followed shortly afterwards by penetration of the fibreglass accoustic insulation blanket. This gave the fire access to a cavity surrounding the cargo hold, from which it entered the aft cabin via floor-level air-conditioning grills located on each side of the aircraft.

64 It is estimated that within 1 minute of the aircraft stopping, the fire penetrated the cabin sidewalls just above floor level adjacent to seats 17A to 19A, giving the fire direct access to the cabin interior.

65 It is estimated that the windows resisted penetration by the fire for at least 40 to 50 seconds after the aircraft stopped. However, visible signs of damage to the outer panels, including cracking and apparent melting, were evident much earlier.

66 The fire was entrained by the wind beneath the rear fuselage, creating a large area of fire-contact with a high rate of heat transfer into the hull, resulting in the rear fuselage and tail collapsing onto the ground. The time when collapse occurred could not be determined.

67 Initially, the internal fire burnt in the aft section of the cabin, spreading forwards as roof panels and overhead lockers ignited and collapsed down onto seats.

68 Approximately 50% of the seats suffered little or no fire damage, and many plastic safety instruction cards, magazines and other fragile items survived undamaged in the seat-back pockets and on seat cushions. In contrast, all ceiling panels and overhead lockers were destroyed and all side-liner panels above cushion level were extensively damaged by fire.

69 A marked stratification of both temperature and smoke was evident throughout the cabin; in areas not actually combusting, there was comparatively little heat or smoke below a level of approximately 18 inches above the cabin floor.

70 Several areas of very intense damage were caused by the combustion of flammable materials, possibly alcohol or aerosol sprays, or by the release of therapeutic oxygen.

71 A fully developed flashover did not occur, although a number of flash ignitions of gaseous material did. This is contrary to much of the evidence from fire research which implied that flashover was inevitable and focused attention on the fire hardening of cabin interior materials as the primary strategy in fire management.

72 Of 27 aerosol sprays recovered from the cabin, 15 had ruptured as a result of thermal overpressure, and 3 of these had been propelled at high speed into seat frames or other obstructions. The practice of routinely permitting the carriage in hand baggage of aerosol cans containing butane or other flammable gases, represents an unnecessary risk in the event of a cabin fire.

73 Nine of ten therapeutic oxygen cylinders carried in the overhead lockers had discharged their contents into the fire. It is considered that the practice of storing therapeutic oxygen cylinders in overhead lockers is undesireable in view of the high temperatures experienced by ceiling lockers at an early stage in a fire, and the attendant risk of thermal discharge occurring whilst passengers are still evacuating or when rescue personnel are inside the cabin.

74 All the 'basic ingredients' of the fire at Manchester were typical of those which could apply to any other aircraft involved in such an incident.

75 This accident has confirmed what was known to a small section of the aviation community; that a slight wind (2kt or more), of little or no operational significance from an aircraft handling and performance standpoint, is nevertheless critically important so far as aircraft orientation in a fire is concerned.

76 The accident has highlighted a general ignorance of the importance of light winds within the aviation community at large. Operational procedures in widespread use at the time of the accident made little or no allowance of practical value for such winds and provided minimal guidance to aircrew.

77 Procedures should be devised to enable aircrew to position the aircraft most beneficially against the wind in the event of a ground fire.

Firefighting tactics

78 The scale of the firefighting and rescue protection at Manchester International Airport, even without the major foam tender which was undergoing repainting, met CAP 168, Category 8 requirements. Operation of a Boeing 737, only requires protection at Category 6 level at best.

79 The speed of response of the Manchester Airport Fire Service was rapid, resulting in the commencement of firefighting approximately 25 seconds after the aircraft stopped.

80 The external fire was quickly brought under control except for a small running-fuel fire in the area immediately beneath the wing puncture, which proved difficult to extinguish fully.

81 There had been no recent training in the use of Monnex powder, carried by the apron fire vehicle for use in tackling running fuel fires, and no attempt was made to use this agent.

82 Despite the early containment of the external fire, fire-penetration of the rear fuselage led to an internal fire which the Manchester International Airport Fire Service were not equipped effectively to deal with, nor were they required to be so equipped.

83 The early recovery of J2 from the paint shop made that vehicle available at the scene in time to play a significant role in the firefighting effort.

84 Approximately 7 to 8 minutes after the aircraft stopped the water carried by the airport fire vehicles had effectively been exhausted. Initial attempts to replenish from nearby hydrants were unsuccessful because the ring main supplying the hydrants had been isolated. A later attempt to draw water from the hydrants was successful.

85 The hydrant water flow rates were such that, when operating normally, it would have taken between 15 and 18 minutes to completely replenish a major foam tender. This time is considered too long a period to permit effective re-deployment after replenishment.

86 The Greater Manchester Council fire service was in attendance at the rendezvous point within 8 minutes of the accident, but was unable to gain access to the aircraft for a further 3 minutes because there was no Police escort vehicle to meet them.

87 The absence of an escort vehicle had arisen because of recent changes in emergency procedures which had been agreed between the Manchester International Airport Fire Service and the Greater Manchester Council, but which the Airport Police had not been a party to and of which they were not aware.

88 A further (short) delay in bringing the Greater Manchester Council firefighting effort to bear on the fire occurred because their officer in charge was unable to identify the officer in charge of the Manchester International Airport Fire Service.

89 The delay in replenishment of the water, due to both the unavailability of water from the hydrant and the delay in escorting the Greater Manchester Council fire vehicles from the rendezvous point, occurred at a time when attempts to fight the internal fire by means of hand lines had been curtailed by lack of water. Although it is considered unlikely, the possibility that the lack of water at that critical time led to loss of life cannot be discounted.

90 The potential for an officer in charge of airport firefighting crews to manage resources effectively is compromised by a lack of helmet-mounted communication,

91 Entry into the cabin to tackle the fire did not take place until some 7 minutes after the aircraft stopped, by which time a severe fire was established in the cabin which could not be tackled effectively using hand-held branch lines.

92 The firefighting techniques used at Manchester fell broadly within the bounds of established practice. The efforts of the Manchester International Airport Fire Service personnel directly resulted in the saving of life.

93 Using current techniques and equipment, the unavoidable delay in entering an aircraft cabin imposed by the need to avoid conflict with evacuating passengers makes effective control of an internal fire extremely unlikely.

94 Recent tests have demonstrated that water-mist spray systems built into the fuselage, supplied either with onboard water or water from a firefighting vehicle, have great potential in limiting/extinguishing cabin fires.

95 Because of the potential for fire penetration occurring before the arrival of airport fire vehicles, the 'on-board' water capability of water-mist systems is seen as essential for the early limitation of the fire and the maintenance of a survivable temperatures throughout the evacuation period.

Fire hardening

96 There has been an imbalance of effort between the amount of research being undertaken into the fire hardening of interior materials and that directed towards fire hardening of the hull itself.

Survival/Evacuation

97 Of the 131 passengers and 6 crew on board G-BGJL, 52 passengers and 2 aft cabin crew died on the aircraft. A further male passenger, who was found still alive but unconscious in the forward aisle some 33 minutes after the aircraft stopped, died from lung damage and associated pneumonia 6 days later.

98 Only 47% of those engulfed in the dense smoke atmosphere survived and of these eight collapsed due to toxic/irritant gas and smoke inhalation during their evacuation. Two of those who collapsed were dragged onto the front left slide by the surviving hostess and a 14 year old boy was pulled out of the right overwing exit by a fireman, 5½ minutes after the aircraft stopped.

99 The primary reason for the majority of the fatalities was rapid incapacitation due to inhalation of the toxic smoke atmosphere, the effects of which were made more critical by evacuation delays. Of the 54 fatalities on board, 48 had absorbed levels of Carbon Monoxide and/or Hydrogen Cyanide in excess of that required to induce incapacitation.

100 Eighteen survivors escaped from the front/left door, which was opened by the purser approximately 25 seconds after the aircraft stopped; 27 used the right overwing exit, which was opened by adjacent passengers approximately 20 seconds later; and 35 escaped from the forward/right door, which was opened by the purser some 1 minute 10 seconds after the aircraft stopped.

101 Although 26 survivors including 1 infant and 1 child escaped through the right overwing exit unaided, for the 76 passengers from the rear of the aircraft this was the first available exit and for 100 passengers it was the nearest. The exit routes through the aft left and right doors plus the left overwing exit were unavailable due to the fire.

102 The narrow gap of 10½ inches available between row 9 and 10 seats impeded passengers' access to the right overwing exit. The pressure of passengers on the 10F seat back caused failure of the seat back hinge baulk allowing the backrest to fold forwards creating a further obstacle to egress. Twin bulkheads in the forward cabin restricted evacuation flow to the forward exits after both were open.

103 The present regulatory Evacuation Certification Requirements are inadequate in their evaluation of important potential egress restrictions and make no attempt to demonstrate evacuation times in the conditions where speed of evacuation is of prime importance - that of egress in conditions of dense smoke.

104 The current regulatory Certification Requirements for aircraft cabin materials are inadequate in their omission of any restriction on smoke and toxic/irritant gas emissions, whilst unable to give assurance that such materials shall not undergo thermal degradation or combustion when subjected to large fuel-fed fires.

105 A comprehensive test programme has shown that lightweight, easily donned smokehoods have the performance to protect evacuees, keeping them conscious and mobile in typical aircraft fire environments and, in addition, can offer significant protection against in-flight fires.

106 Water-mist systems have demonstrated the potential dramatically to improve the cabin thermal environment and to scrub particulate from fire atmospheres but their effect on the overall toxicity has not been fully examined.

(b) Cause

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 wing tank 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 forward right door malfunction and restricted access to the exits.

4 Safety recommendations

4.1 Procedures should be developed to enable the crew to position an aircraft, when a ground fire emergency exists, with the fire downwind of the fuselage. Visual indicators of local wind direction located within the manoeuvre areas would be valuable aids to the implementation of such a procedure.
(letter to CAA 14 March 1986)

4.2 Research should be undertaken into methods of providing the flight deck crew with an external view of the aircraft, enabling them to assess the nature and extent of external damage and fires.

4.3 Operators should amend their Operations Manuals, if necessary, to direct crews on any rejected take-off or emergency landing to stop on the runway and review the situation before a decision on clearing the runway is made.

4.4 Consideration should be given to the requirement to fit an evacuation alarm permitting flight deck crew to instruct cabin crew to initiate an evacuation immediately, or if the aircraft is still moving to prime for an evacuation immediately the aircraft is brought to a halt.

4.5 Emergency equipment for use by cabin crew during an emergency evacuation should be stowed at the cabin crew stations.
(letter to CAA 19 September 1985)

4.6 The Civil Aviation Authority should continue to work with other regulatory authorities to define a mandatory international code of practice for identifying the appropriate method of promulgation for manufacturers' safety information. This code should include a procedure for ensuring that, at the earliest opportunity, preliminary/advisory information should be followed up and superseded by appropriate Bulletins, Airworthiness Directives or manual ammendments.

4.7 If manufacturers are to continue to supply maintenance guidelines which require the operator and his regulatory authority to determine maintenance intervals, particularly for critical components, a re-evaluation should be undertaken of the methods employed to judge residual component lives, particularly following repair.

4.8 Direct fusion weld repair of circumferential cracks in JT8D engines combustor cans should be deleted from all approved Engine Overhaul Manuals, unless the safe life of the repaired can has been demonstrated for the anticipated overhaul/inspection period.

4.9 Operators should seek the manufacturers comments when making changes to approved technical manuals, under the terms of approval granted by the CAA.

4.10 A review of the approval of the cabin configuration as it existed on G-BGJL should be conducted, with particular reference to the following features of that configuration:-
(letter to CAA 19 September 1985)

i) The restricted view of the passenger cabin afforded the forward cabin crew when seated.
ii) The forward aisle restriction created by the floor to ceiling forward galleys.
iii) Access to the overwing exit where the presence of row 10 seats appeared to conflict with the British Civil Airworthiness Requirements. It is recommended that all row 10 seats be removed.

The approval of other configurations on Boeing 737 and other types should also be reviewed with the intention of addressing any similar problems.
(letter to CAA 19 September 1985)

4.11 A review should be conducted to examine the adequacy of existing British Civil Airworthiness Requirements relating to 'unobstructed access' to exits and these updated where necessary to take account of modern high density seating configurations.

4.12 A requirement should be introduced for passenger public address systems that can continue to function largely independently of engine or airframe system condition, and provide a high gain mode for use in emergencies.
(letter to CAA 4 December 1985)

4.13 Operators should adopt a policy of distributing the most experienced cabin crew throughout the passenger cabin.

4.14 A requirement should be introduced for an effective communication system for Rescue and Fire Fighting personnel as part of the licensing requirements for all major airports. That requirement should include provision for communication on the same system by the officer in charge of the units deployed by any local authority fire service having standing arrangements to attend such airports.

4.15 The recruitment and training of airport fire officers should be amended to facilitate a more management orientated approach.

4.16 RFF personnel in breathing apparatus should be positioned by overwing and other exits at the earliest opportunity to assist those evacuating and to help keep the exits clear. This would require the airport fire service to be equipped with additional breathing apparatus and all RFF personnel to be trained in its use.

4.17 A requirement should be introduced for some form of standardised high visibility clothing to be worn by the officer in charge of the Rescue and Fire Fighting personnel at any incident/accident scene.

4.18 A thorough review should be undertaken into techniques for extinguishing fires inside the passenger cabins of public transport aircraft, with a view to rectifying the current deficiencies in airfield firefighting capability when dealing with internal fires.

4.19 Onboard water spray/mist fire extinguishing systems having the capability of operating both from on-board water and from tender-fed water should be developed as a matter of urgency and introduced at the earliest opportunity on all commercial passenger carrying aircraft.

4.20 The balance of effort in aircraft fire research should be restored by increased effort directed towards fire hardening of the hull, the limitation of fire transmission through the structure and the prevention of structural collapse in critical areas. Short term measures should be devised for application to existing types but, in the long term, fire criteria should form a part of international airworthiness requirements.

4.21 A requirement should be introduced to ensure that existing external fuel tank access panels which are vulnerable to impact from engine or wheel/tyre failures on aircraft in service are at least as impact resistant as the surrounding structure. The potential risk of damage from debris impacts should be addressed in future by appropriate design reqirements covering debris ejection from engines and/or impact strength requirements for the airframe.

4.22 Aerosols with hydro-carbon propellants should be treated in the same way as other cylinders of flammable gas and their carriage on board aircraft controlled accordingly.

4.23 A requirement should be introduced to ensure that all portable oxygen bottles carried on board public transport aircraft are fitted with pressure relief valves and are stowed in thermally protected areas, preferably at low level.

4.24 The Civil Aviation Authority should urgently give consideration to the formulation of a requirement for the provision of smokehoods/masks to afford passengers an effective level of protection during fires which produce a toxic environment within the aircraft cabin.
(Made December 1985)

4.25 The proposed requirement for cabin crew smokehood protection be extended to include training for crew donning and use during aircraft emergency evacuations associated with a fire and/or smoke threat during the evacuation.

4.26 The applicable regulatory requirements for aircraft cabin materials certification should be amended at the earliest opportunity to include strict limitations of smoke and toxic/irritant gas emissions.

4.27 A research program should be undertaken to establish the effect of water mist/spray extinguishing systems on the toxic/irritant constituents of fire atmospheres.

4.28 The existing regulatory requirements governing the Evacuation Certification of public transport aircraft should be reviewed and amended to include:

i) A demonstration of an acceptable evacuation time when the cabin is evacuated using half the total number of exits, disposed towards one end of the cabin; that end being chosen which represents the greatest restriction to passenger egress.

ii) Simulation of a defined dense smoke atmosphere within the cabin, existent from the initiation of the evacuation until its completion.

iii) All other sub-testing associated with cabin evacuation, including passenger aisle flow, the identification of exits and aperture egress rates, upon which design and configuration certification decisions are based, be conducted in the same simulated smoke atmosphere.

4.29 The design strength of the break-forward 'baulks' fitted to the seats adjacent to overwing exits should be increased to prevent failure due to passenger pressure-loads on the backs of these seats.

4.30 Research should be undertaken to assess the viability of 'audio-attraction' and other techniques designed to attract passengers towards viable exits when speech and vision is impaired in smoke and toxic/irritant gases.

4.31 Research should be undertaken into the effects of cabin airflow on smoke/gas venting and flashover delay/suppression, with a view towards the possible benefits of changing current cabin air-conditioning design and/or associated procedures.

D F KING
Inspector of Accidents

Air Accidents Investigation Branch
Department of Transport
December 1988