AIRCRAFT ACCIDENT REPORT 3/91

Air Accidents Investigation Branch

Department of Transport

Report on the accident to Lockheed L1011-500, C-GAGI 1 nm south east of Manchester, Cheshire on 11 December 1990

This investigation was carried out in accordance with

The Civil Aviation (Investigation of Air Accidents) Regulations 1989

London : HMSO

First published 1991

ISBN 0 11 551086 9

Produced from CRC
Supplied by the Department

Printed in the UK by HMSO
Dd 294092 C7 12/91 3390/2 19593

LIST OF RECENT AIRCRAFT ACCIDENT REPORTS ISSUED BY AIR ACCIDENTS INVESTIGATION BRANCH

6/89	Concorde 102 G-BOAF over the Tasman Sea, about 140 nm east of Sydney, Australia on 12 April 1989	December 1989
1/90	Sikorsky S-61N G-BDES in the North Sea, 90 nm north-east of Aberdeen on 10 November 1988	May 1990
2/90	Boeing 747 N739PA at Lockerbie, Dumfriesshire, Scotland on 21 December 1988	September 1990
3/90	Sikorsky S-61N G-BEID 29 nm north-east of Sumburgh Shetland Isles on 13 July 1988	September 1990
4/90	Boeing 737 G-OBME near Kegworth, Leicestershire on 8 January 1989	October 1990
5/90	Bell 206 B Jetranger, G-SHBB 2 miles east south east of Biggin Hill Aerodrome, Kent on 18 December 1989	February 1991
1/91	British Aerospace ATP, G-OATP at Ronaldsway Airport Isle of Man on 23 December 1990	August 1991
2/91	Sikorsky S-61N G-BEWL at Brent Spar, East Shetland Basin on 25 July 1990	October 1991
3/91	Lockheed L1011-500, C-GAGI 1 nm south east of Manchester, Cheshire on 11 December 1990	December 1991

These Reports are available from HMSO Bookshops and Accredited Agents

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

19 November 1991

The Right Honourable Malcolm Rifkind
Secretary of State for Transport

Sir,

I have the honour to submit the Report by Mr E J Trimble, an Inspector of Air Accidents, on the circumstances of the accident to Air Canada Lockheed L1011-500 Tristar, C-GAGI, which occurred at flight level 370 1 nautical mile south east of Manchester on 11 December 1990.

I have the honour to be
Sir
Your obedient servant

K P R SMART
Chief Inspector of Air Accidents

CONTENTS

CONTENTS

Page

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	Air Accidents Investigation Branch
AD	Airworthiness Directive
APU	Auxiliary Power Unit
ARB	Air Registration Board
ATC	Air Traffic Control
BCAR(s)	British Civil Airworthiness Requirements(s)
CAA	Civil Aviation Authority
CAS	Calibrated Airspeed
CSD	Cabin Service Director
CVR	Cockpit Voice Recorder
DFDR	Digital Flight Data Recorder
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FL	Flight Level
ft/min	Feet Per Minute
FS	Fuselage Station
g	Normal Acceleration
JAL	Japan Airlines
JAR(s)	Joint Airworthiness Requirement(s)
kg	Kilogram(s)
KIAS	Knots Indicated Airspeed
kt	Knot(s)
lb	Pound(s)
M	Mach
°M	Degrees Magnetic
Mb	Millibar(s)
MMO	Mach No. - Maximum Operating
MSA	Minimum Safe Altitude
NDT	Non-Destructive Testing
NPRM	Notice of Proposed Rule - Making
NTSB	National Transportation Safety Board
PA	Public Address
psi	Pounds Per Square Inch
PSU	Passenger Service Unit
SB	Service Bulletin
S/O	Second Officer
TSB	Transportation Board of Canada
UK	United Kingdom
US(A)	United States (of America)
UTC	Coordinated Universal Time
V_{LE}	Maximum Landing Gear Extended Speed
V_{LO}	Maximum Landing Gear Operating Speed
V_{MO}	Maximum Operating Speed
VHF	Very High Frequency

Air Accidents Investigation Branch

Aircraft Accident Report No: 3/91

(EW/C1185)

Registered Owner and Operator:	Air Canada
Aircraft Type:	Lockheed L1011 TriStar
Model:	Series 500
Nationality:	Canadian
Registration:	C-GAGI
Place of accident:	1 nm south east of Manchester Latitude: 53°21'N Longitude: 002°16'W
Date and time:	11 December 1990 at 0630 hrs

All times in this report are UTC

SYNOPSIS

The accident was notified to the Air Accidents Investigation Branch (AAIB) at 1455 hrs on the 11 December 1990 and an investigation began that afternoon. The AAIB team comprised Mr E J Trimble (Investigator in Charge), Mr J D Payling (Operations), Mr C A Protheroe (Engineering) and Mr R Vance (Flight Recorders). In addition Mr L E Vance of the Transportation Safety Board of Canada (TSB) participated in the early stages of the investigation as an Accredited Representative and Dr J W Bristow of the Civil Aviation Authority (CAA) worked closely with the investigation, particularly during the initial stages which involved air safety liaison and action in conjunction with the Federal Aviation Administration (FAA), Lockheed and the United States National Transportation Safety Board (NTSB).

The aircraft was preparing to descend from flight level(FL) 370 during the final stage of a scheduled passenger flight from Montreal to London Heathrow, with 10 crew and 104 passengers (including 2 infants) onboard, when cabin depressurization suddenly occurred at a position 1 nm south east of Manchester. The first officer immediately transmitted a request for descent clearance and donned his oxygen mask as the commander disengaged the autopilot. The commander momentarily passed control of the aircraft to his first officer whilst he also donned his oxygen mask, before resuming control and initiating an emergency descent in accordance with the emergency descent checklist. As the commander closed the throttles, extended the speed brakes and accelerated to the maximum operating speed (V_{MO}) in the descent, the first officer completed his essential communications with ATC and made a PA announcement directing that oxygen masks should be put on immediately.

In the passenger cabin, subsequent to the sounds of a loud 'boom' and the rushing of air from the aft left toilet which were heard by two aft flight attendants, the passenger oxygen masks had deployed. The flight attendants sat down and donned oxygen masks. The purser then made a PA announcement in English and French reminding passengers of the actions required to initiate their oxygen supply and directing them to apply masks to sleeping infants.

After the aircraft had levelled at 10,000 feet the commander called the flight attendant-in-charge to the flight deck to inform him that oxygen was no longer required. The flight attendant informed the commander of the noise associated with the aft toilet and commander advised him not to attempt opening of the toilet door.

The aircraft subsequently landed without further incident at Heathrow Airport, where it was met by medical personnel who attended to the passengers, 3 of whom had experienced severe headache and earache.

The sudden cabin depressurization was caused by a localised rupture of the rear pressure bulkhead, behind the aft/left toilet compartment, which occurred as a result of fatigue cracking which had initiated due to the following factors:

1. The presence of a score defect on the bulkhead diaphragm aft surface which had been inadvertently introduced during the manufacturing process.

2. The localised intensification of the bulkhead pressurization stresses by a bonded doubler butt-join discontinuity, which was co-linear with the score defect.

Five Safety Recommendations were made during the course of this investigation.

1 Factual Information

1.1 History of the flight

The aircraft was operating scheduled Air Canada Flight No. 866 from Montreal Mirabel to London Heathrow. At approximately 0625 hrs, as the aircraft was approaching the area of Manchester at FL 370, the second officer made a public address (PA) broadcast to the passengers advising them that the aircraft was about to descend and that they could expect to land in about 30 minutes. He also reset the pressurization controller in preparation for the descent, causing the cabin pressure altitude to descend slowly from 7,000 feet to 6,300 feet during the following three minutes. Meanwhile the first officer had requested descent clearance from air traffic control (ATC) on the airways control frequency in use and had been instructed to change frequency to the next airways sector for descent clearance. Just after he had made this frequency change, a rapid loss of cabin pressurization occurred.

None of the three pilots heard any noise, but all were aware of a sudden change in airflow and ventilation on the flight deck. The first officer immediately transmitted a request for descent clearance on the new frequency and then donned his oxygen mask. The commander felt his ears 'pop' and, thinking that this was due to movement of the outflow valves in response to the small pre-descent increase in cabin pressure differential, he disengaged the autopilot and allowed the aircraft to descend 100 - 200 feet. He then saw the first officer put on his oxygen mask and the second officer operating the pressurization controls, so he handed control of the aircraft to the first officer, put on his own mask, and resumed control. He was aware that at some time during this sequence of events the cabin altitude warning horn sounded. He was also aware that, in response to the first officer's earlier request, clearance to descend had been passed by ATC. Accordingly, he called for the emergency descent checklist, selected cabin signs and continuous ignition 'ON', closed the throttles, extended the speed brakes and accelerated the aircraft to maximum operating speed (V_{MO}). The second officer also donned his oxygen mask and completed the loss of cabin pressure checklist, but was unable to reduce the cabin altitude rate of climb, which was showing maximum rate. The first officer stated that, after donning his oxygen mask and completing the essential communications with ATC, he pressed the PA microphone switch and made an announcement saying "ATTENTION. PUT ON YOUR OXYGEN MASKS IMMEDIATELY", repeating these words twice. The commander and second officer later recollected hearing the first officer make this announcement.

In the passenger cabin, two flight attendants at the rear of the aircraft had heard a loud 'boom' and a sound of rushing air from the left-hand rear toilet. They signalled to the cabin service director (CSD), who joined them and tried to open the toilet door, but without success. As he turned round to go forward again he saw the passenger oxygen masks begin to deploy. He, together with all the other flight attendants in the rear and mid sections of the cabin, seated themselves and put on passenger oxygen masks. One flight attendant noted that a small number of masks failed to deploy. The purser in the first class cabin felt marked ear distress and went to the flight deck to ask if there was a problem. She saw the first officer donning his oxygen mask and immediately returned to the first class cabin, where she saw the passenger oxygen masks appear. She took a mask herself, saw that all the passengers in the first class cabin were using masks and a few moments later made an announcement in English and French to all cabins reminding passengers how to initiate oxygen and to stretch extra masks to sleeping infants.

As the aircraft descended through FL310 the first officer declared an emergency to ATC, explaining that the aircraft had suffered a rapid decompression and was in emergency descent. ATC responded by advising that there were no restrictions on either height or heading. The commander later recollected that when the second officer told him that the cabin altitude had risen to 19,000 feet the aircraft was passing that same height in their descent. Analysis of the flight data recorder showed that the cabin altitude peaked at 20,600 feet, before beginning to reduce again with aircraft altitude. During the descent the airspeed peaked at 377 kt and the rate of descent reached 8,500 feet per minute for a short time. The aircraft descended to 18,000 feet in a little over 3 minutes and levelled at 10,000 feet some 5 minutes and 20 seconds after the loss of pressurization. Cabin altitude was above 18,000 feet for approximately 2 minutes and 18 seconds.

When the aircraft was level at 10,000 feet the commander used the PA to call the CSD to the flight deck. The flight attendants took this as a sign that it was safe to resume their duties. Only one flight attendant remembered hearing an announcement that oxygen was no longer required. The CSD went to the flight deck where he told the commander about the noise from the rear toilet area, and the commander advised him not to try to open the toilet door. The CSD then checked the condition of the passengers and found that three were experiencing severe headache and earache, but the remainder were suffering no physical distress.

The aircraft continued to make a normal approach and landing at Heathrow Airport, where it was met by medical attendants with wheelchairs for the most affected of the passengers.

1.2 Injuries to persons

	Crew	Passengers	Others
Fatal	-	-	-
Serious	-	-	-
Minor / None	10	102+2 infants	-

1.3 Damage to aircraft

Structural damage was limited to the rupture of a rear pressure bulkhead gore panel on the left side, immediately aft of the outboard toilet compartment. Associated non-structural damage had occurred to the toilet compartment wall panels as a result of cabin differential air pressure forces on the panels and subsequent venting of cabin air through the rupture.

1.4 Other damage

There was no other damage.

1.5 Personnel information

1.5.1	*Commander:*	Male, aged 54 years
	Licence:	Canadian Airline Transport Pilot's Licence
	Aircraft ratings:	Viscount, DC8, DC9, L1011, B747, B767
	Medical certificate:	Renewed 6 November 1990, valid to 30 June 1991
	Instrument rating:	Renewed 6 December 1990
	Last base check:	6 December 1990

Last route check: 3 January 1990

Flying experience:

Total on airline transport types:	13,053 hours
Total on L1011:	350 hours
Total last 90 days:	45 hours
Total last 24 hours:	6 hours

Duty time: 6 hours 55 minutes

1.5.2 *First Officer:* Male, aged 36 years

Licence: Canadian Airline Transport Pilot's Licence

Aircraft ratings: DC8, DC9, L1011, B727

Medical certificate: Renewed 6 March 1990, valid to 31 March 1991

Instrument rating: Renewed 24 January 1990

Last base check: 12 July 1990

Last route check: 2 October 1990

Flying experience:

Total on airline transport types:	8,460 hours
Total on L1011:	663 hours
Total last 90 days:	65 hours
Total last 24 hours:	6 hours

Duty time: 6 hours 55 minutes

1.5.3 *Second Officer:* Male, aged 56 years

Licence: Canadian Commercial Pilot/Flight Navigator's Licence

Aircraft ratings: DC8, L1011

Medical certificate: Renewed 17 August 1990, valid to 28 February 1991

Instrument rating: Renewed 22 May 1990

Last base check: 19 October 1990

Last route check: not known

Flying experience:
Total on airline transport types: 8,574 hours
Total on L1011: 4,232 hours
Total last 90 days: 133 hours
Total last 24 hours: 6 hours

Duty time: 6 hours 55 minutes

1.6 Aircraft information

1.6.1 Leading particulars

Type: Lockheed L1011-385-3 TriStar

Constructor's number: 1209

Date of Manufacture: 1981

Certificate of Registration: Registered in the name of Air Canada, 2 June 1989

Certificate of Airworthiness: Issued on the 15 May 1981 and valid

Total airframe hours: 36535.48 hours
Total flight cycles: 8308
Engines: Three Rolls Royce RB211-524 turbofan engines

Maximum weight authorised for take-off: 496,000 lb (224,982 kg)

Actual take-off weight:	405,500 lb (183,934 kg)
Estimated weight at time of accident:	328,700 lb (149,096 kg)
Estimated fuel remaining at time of accident:	33,100 lb (15,014 kg)
Centre of gravity (CG) at time of accident:	within limits
Maximum operating speed:	0.88M/375 kt (MMO/V_{MO})
Maximum landing gear operating speed and landing gear extended speed:	0.85M/300 kt (V_{LO} and V_{LE})

1.6.2 *Maintenance details*

Last "A" check:	35951.03 hrs
Last "C" check:	33671.26 hrs

Relevant maintenance and inspections of the rear pressure bulkhead area:

SB093-53-218:	Aft pressure bulkhead and FS1860 - fuel line and guard clearance inspection, accomplished at last "C" check. Visual inspection of mid lower section of aft pressure bulkhead, accomplished at last "C" check.
SB093-53A-239:	Aft pressure bulkhead - replacement of negative pressure relief valve adaptor, accomplished November 1985.
SB093-53-249:	Aft pressure bulkhead - inspection/repair of negative pressure relief valve, last accomplished at 5226 landings. (Repeat inspections due at 6000 landing intervals.)
SB093-53-258:	Aft pressure bulkhead - inspection/repair of cracks near 6 inch edge doubler at top of bulkhead; 'one-time' inspection, accomplished February 1990.

1.6.3 *Rear pressure bulkhead construction*

The rear pressure bulkhead was a thin shell structure comprising a series of 0.040 inch thick gore panels lap-jointed to form a pressure membrane, with additional doublers and anti-tear straps, producing a bulkhead of spherical profile as shown in Appendix 1, fig 1.

Constructional details are shown in fig 2. The gore panels were lap jointed alternately on the forward and aft sides of the nominal membrane surface, producing a 'handed' form of construction. A series of radial and circumferential anti-tear straps, bonded in a typical *'waffle'* pattern to the aft face of the bulkhead, subdivided each of the gore panels into ten elements of approximately rectangular shape.

Around the outer circumference of the bulkhead, adjacent to its attachment to the fuselage proper, were a series of 6 inch wide by 0.040 inch thick doublers bonded to the forward/aft surfaces of each gore panel, mirroring the constructional form of the gore panels proper, as indicated in fig 2. Additional doublers 0.020 inch thick were bonded to the 8-9 o'clock and 3-4 o'clock gore panels at cabin floor level, abutting the 6 inch wide circumferential doubler, and extending inboard to approximately the 1/3rd radius position (*ie* over the two outermost grid panels formed by the anti-tear straps). Because of the handed nature of the gore panel lap-joints, these doublers and the adjacent 6 inch wide edge doublers were on the aft face of the gore panel on the left hand side of the aircraft, and on the forward face on the right hand side.

A large diameter auxiliary power unit (APU) air duct, and various other services, passed through the bulkhead in the outer segment of the 7-8 o'clock gore panel. In this area the gore panel was reinforced by a bonded doubler and the anti-tear straps were omitted. The mid-upper regions of the 11 o'clock to 1 o'clock gore panels contained the inward vent valves. These areas were also reinforced by doublers, again without anti-tear straps.

1.6.4 *Aircraft oxygen system*

Oxygen for the flight crew was supplied from a 3,200 litre fixed oxygen cylinder on the flight deck. The cylinder was fitted with a combined ON/OFF valve and pressure reducer that reduced pressure to 50 psi - 90 psi. In the event of loss of cabin pressure, oxygen was provided automatically to diluter-demand, quick-donning, microphone-equipped crew oxygen masks.

There was automatic provision for passenger oxygen masks to drop down whenever cabin altitude exceeded 13,000 feet and for the 'NO SMOKING' and 'FASTEN SEAT BELTS' signs to illuminate. A dual control system would open passenger oxygen mask flaps and energize all the associated chemical oxygen generating canisters. The canisters were capable of providing oxygen for at least 15 minutes. The same signal that energized the canisters turned on the 'OXYGEN FLOW' light on the second officer's panel. The passenger service mask flaps were held closed by permanent magnets. A solenoid, when energized, cancelled the magnets' polarity to allow the flaps to spring open. If the automatic deployment failed, the passenger oxygen system could be manually initiated through a passenger oxygen system manual switch at the second officer's station. Any oxygen mask flap in a passenger service unit (PSU) that failed to open automatically could be opened manually by inserting a latch release rod into a hole in the flap. Latch release rods were located at each cabin crew door station.

Supplementary oxygen was available in the cabin in portable 120 litre bottles stowed at each flight attendant's station. Each bottle had a single bayonet adapter to which an associated lightweight face-mask could be fitted.

1.7 Meteorological information

Weather conditions were not a factor in this accident.

1.8 Aids to navigation

Navigation aids were not a factor in this accident.

1.9 Communications

All relevant communications between the aircraft and air traffic control service units were on very high frequency (VHF) radio. Tape recordings of all frequencies used were available. A transcript of the communications between the aircraft and ATC from the time when descent clearance was requested until the aircraft descended to FL100, is included at Appendix 2.

1.10 Aerodrome information

Not relevant.

1.11 Flight recorders

The aircraft was fitted with a Fairchild model A100 Cockpit Voice Recorder (CVR) and a Lockheed Aircraft Services model 209 Digital Flight Data Recorder (DFDR).

1.11.1 Cockpit Voice Recorder

Since the time between the in-flight loss of pressurization and the aircraft coming to rest at London Heathrow exceeded the 30 minutes recording duration of the CVR, the information relating to the accident had been lost from the recording and the CVR was therefore not transcribed.

1.11.2 Digital Flight Data Recorder

In addition to the usual parameters, cabin pressure was also recorded on this DFDR. From this it was possible to clearly identify the cabin depressurization event, which occurred at 06:29:48 hrs UTC. Appendix 3, fig 1 is a plot showing the time history of selected flight parameters and recorded cabin pressure. From this it can be seen that the aircraft was in level flight at 37,000 feet, 274 kt calibrated airspeed (CAS) and heading 148°(M) when the event occurred. The aircraft then descended and eventually a safe landing was made at 06:57 hrs.

The times recorded on the DFDR were found to agree with the times recorded on the air traffic control tapes. The DFDR recording also showed that, whilst the aircraft was in level cruise at a pressure altitude of 37,000 feet, the cabin pressure was equivalent to a standard altitude of 7,030 feet, with a cabin pressure differential of 8.19 psi. At 0626.30 hrs, after the pressurization controller had been reset in preparation for landing, the cabin pressure increased slowly to a cabin altitude of 6,272 feet and a pressure differential of 8.52 psi. At 0629.48 hrs, the cabin altitude began to rise rapidly and at 0630.12 hrs the aircraft began to descend. The average rate of descent between 37,000 feet and 34,000 feet was 3,400 ft/min; increasing to an average of 7,500 ft/min between 34,000 feet and 22,000 feet; and then reducing to an average of 5,250 ft/min between 22,000 feet and 10,000 feet. The highest rate of descent was 8,500 ft/min at 30,000 feet. The highest recorded CAS was 377 kt as the aircraft descended through 22,300 feet.

The cabin altitude increased initially at 14,000 ft/min and 16 seconds later this rate of rise had moderated to 10,000 ft/min. The cabin altitude peaked at 20,600 feet, at which time the aircraft was descending through 27,000 feet and there remained a residual pressure differential of 1.63 psi. Thereafter, although the pressure differential continued to fall, the cabin altitude began to reduce. When the aircraft levelled-off at 10,000 feet, the cabin altitude stabilised at 8,500 feet as pressurizing air from the engines maintained a differential pressure of 0.66 psi. During the descent, the cabin altitude rose above 20,000 feet for 56 seconds and above 18,000 feet for 2 minutes and 18 seconds.

1.12 Examination of the aircraft

1.12.1 Post-landing inspection

After landing, an internal inspection of the aft cabin by the operator's maintenance personnel revealed that wall panels in the aft/left toilet compartments had been pushed back and the corners of the panels had pulled apart.

On the exterior of the aft fuselage, fibreglass insulation material could be seen hanging from access panel grills on the fuselage skin beneath the tailplane centre section. More insulation material was distributed around the interior of the unpressurized section of the aft fuselage and a split could be seen in the rear pressure bulkhead.

1.12.2 Initial structural examination

A detailed examination was made of the structure in the area immediately aft of the rear pressure bulkhead. Access was severely restricted, but it was established that the rear pressure bulkhead membrane had ruptured near the outer edge of the 8-9 o'clock gore panel (viewed from the rear), allowing a rectangular element approximately 2 feet high by 1 feet wide to flap outwards, as shown in Appendix 1, fig 3.

The damage to the aft toilet compartments was limited to outwards displacement of the lower aft decorative panels within the outer pair of toilet compartments, on the left side. This had produced splits at the joints between the panels and the waste towel boxes through which cabin air had vented into the aft fuselage, via the bulkhead rupture. (The bulkhead rupture was located at floor level, behind the waste towel box of the left outboard compartment). The bagged fibreglass insulation material which lined the inner face of the rear pressure bulkhead had been breached in the area of the rupture and the fibreglass material blown through into the aft fuselage. All emergency oxygen masks in the aft toilets had deployed correctly. The masks had also deployed in each of the other toilet compartments.

There was no evidence of any abnormality in the passenger cabin except for the presence of the emergency oxygen masks, all of which were deployed at the time of examination. However, it was established that the masks for seats 22 C, D, E and 24 F, G had not deployed at the time of the accident. The PSU flaps for these masks were closed when maintenance personnel first inspected the cabin after landing, but dropped down when they were touched. It appears that the flaps had 'stuck' slightly in their apertures, just sufficiently to prevent them falling unaided.

No abnormalities were evident in the flight deck. The crew oxygen masks were out of their stowages and reportedly had functioned correctly.

1.12.3 Detailed structural examination

On the basis of the preliminary examination detailed above, it was concluded that there were no technical factors which required investigation beyond those associated directly with the rear pressure bulkhead structural failure, and any implications which such a failure might have for the safety of the aircraft.

Adequate access to the failure could not be achieved without considerable engineering work to remove the toilet compartment and related systems. Additionally, the removal of the affected section of the bulkhead to permit laboratory examination required cutting into major structure. With the agreement of the AAIB Inspector, the aircraft was ferried unpressurized to a repair and maintenance facility at Cambridge Airport, where it was planned that the aircraft would undergo structural repairs to the bulkhead.

A detailed structural examination in-situ was carried out as an integral part of this repair work. Representatives from the operating company, the TSB, the CAA Safety Regulation Group, and the repair organisation (who were in close contact with the manufacturer) were present and were given full access to the investigation, since this phase of the work remained under the control of the AAIB Inspector. Once the in-situ examination was completed, the critical parts were removed under AAIB supervision and the aircraft was released to the operator.

1.12.4 *Rear pressure bulkhead failure*

The bulkhead had failed on the left side, close to the outer periphery of the 8-9 o'clock gore panel. Appendix 1, fig 4 shows an expanded view of this area, and the general shape of the fracture path.

The gore panel fracture extended circumferentially downwards from position '1', along the joint line between the 6 inch wide 0.040 inch thick doubler and the adjacent 0.020 in. thick bonded doubler panel, to the bottom of the panel at position '3'. It then turned inboard and ran along the radial stiffener frame as far as the next circumferential anti-tear strap at position '4', before turning upwards for a short distance.

1.12.5 *Detailed examination of bulkhead fracture*

Following examination and photography in-situ, the material containing the failed region was cut from the bulkhead, leaving the fractures intact, and taken to the Royal Aerospace Establishment metallurgical laboratory at Farnborough for examination.

A layer of dirt and yellow/brown staining was present on the fracture surfaces over approximately 18 inches of the circumferential fracture length, consistent with this part of the bulkhead fracture having been present for some considerable time prior to the final rupture. This pre-existing, or *'old',* fracture is shown as the solid black line in fig 4, extending from position '2' to position '3'. The radial fracture surfaces (*ie* grey fracture line from '3' to '4') and the uppermost 6 inches of the circumferential fracture surfaces (*ie* grey fracture line from '2' to '1') were clean. These fractures appeared to be fast rupture immediately preceding, or contemporary with, the '*blow-out*' event. The total fracture path length was approximately 37 inches.

The distribution of dirt and staining on the fracture surfaces was recorded and the surfaces then cleaned to allow an examination of the fine surface detail of the fracture faces. Microscopic examination of the cleaned old fracture region revealed evidence of a score-line along the aft face of the gore panel between the doublers, as shown diagrammatically at section "A-A" in fig 4. The score extended over the whole of the old fracture region and slightly beyond (the black line in fig 4 from '2' to '3'), a total distance of approximately 17.6 inches. The fracture path in the gore followed exactly the butt-join line for the whole of the score length; beyond the scored region, the fracture deviated from the butt-line.

1.12.6 *Detailed examination of bulkhead score*

Microsections taken through the fracture/score-line area indicated that the score had been produced by some form of tool which had been drawn along the edge of the 6 inch doubler, producing the score channel itself and also displacing material along the sides of the score channel. The score cross-section is clearly evident in the micrograph reproduced in fig 5, one of three sections taken through the fatigue fracture region. The outer edge 'corner' of the 0.040 inch doubler was cut back at a slight angle which matched the position of the score channel, as shown by the dotted line in fig 5, consistent with the passage of the score tool along the edge of the 0.040 inch doubler.

The score depth ranged from approximately 0.004 inch to 0.014 inch, and the width varied from about 0.012 inch to 0.016 inch.

A blue coloured adhesive, of a type visually similar to that which had been used to bond the doublers to the gore panel, could be seen filling the score channel in many areas. Very small slivers of aluminium-based swarf, consistent with debris from the scoring process, were evident in certain of the paint and adhesive layers adjoining the doubler butt-line. It was also noted that alternate paint layers in the butt region were loaded with evenly distributed aluminium flake or whisker-like particles. These particles were not obviously associated with the score process.

The maintenance and repair documentation for the aircraft had no record of any remedial work on the bulkhead during its period in service. The paint/adhesive/sealant layers suggested that the score had been produced during manufacture.

1.12.7 *Fatigue propagation*

The central region of the old fracture was found to comprise an area of fatigue, approximately 7 inches in length, which consisted of a series of *'thumbnail'* - shaped areas of fatigue growing from the aft face of the gore panel, *ie* from the interface between the gore panel and the bonded doublers, along the doubler butt-join line. Three of these thumbnails had broken through to the front face of the gore panel over a length of about 5 inches; the remaining thumbnails extended only partially through the thickness.

Extending approximately 2.5 inches beyond each end of this central *'fatigue'* region, were areas of fast fatigue fracture. The remaining, outermost, regions of the old fracture had apparently resulted from one or more bursts of fast rupture, which had occurred at some time in the past.

No evidence of corrosion or other potential fatigue initiating feature was found.

1.12.8 *Estimated period of fatigue crack growth*

The fracture was examined in detail using both high power optical and scanning electron microscopes. Three of the fatigue facets were studied in detail and very regular, clear, striations were evident near to the crack origins. Two of these regions were analysed to determine the rate of crack growth based on the underlying assumption that the cracking was solely caused by the flight pressurization cycles, and therefore that the striations represented the crack growth on a 'flight-by-flight' basis. A third area was chosen for growth rate analysis, from an area of fatigue cracking which appeared to be associated with an in-filling process between two adjacent thumbnail regions of fatigue growth.

Calculations of crack growth rates based on fatigue striation density in these regions indicated that the growth rate varied, with slow growth equivalent to around 6.7×10^{-6} inches per flight evident within the fatigue thumbnails, near to the origin, but more rapid growth equivalent to around 17.0×10^{-6} inches per flight in those regions where the thumbnails had merged together.

1.13 Medical and pathological information

Not relevant.

1.14 Fire

Not relevant.

1.15 Survival information

The periods of useful consciousness that may be expected for a normal healthy adult at high altitude approximate to:

at 30,000 feet	1 minute
at 25,000 feet	2 - 3 minutes
at 18,000 feet	30 minutes

These times may decrease if subjects have been exposed to medium altitude atmospheres during a protracted previous period. They are also optimistic for subjects with impairment of the cardio-vascular system. Below 25,000 feet the effects of hypoxia decline exponentially. At 18,000 feet, although there may be loss of consciousness, death is unlikely to result. Subjects may, however, suffer confusion, loss of orientation and, in some cases, hyperventilation.

The only threat to passenger and crew survival was from the effects of lack of oxygen (hypoxia). Cabin altitude in the cruise was 7,030 feet. When the rear pressure bulkhead fractured it rose rapidly to 20,600 feet and then descended to stabilise at 8,500 feet. Cabin altitude exceeded 18,000 feet for 2 minutes and 18 seconds and exceeded 20,000 feet for 56 seconds. There was thus no threat to the survival of the passengers.

1.16 Tests and research

None.

1.17 Additional information

1.17.1 Emergency descent procedure

The aircraft Flight Manual detailed the following procedure for an emergency descent:

"This procedure assumes the structural integrity of the aircraft. Do not exceed the airspeed limits. If structural integrity is in doubt, limit speed as much as possible and avoid high manoeuvring loads.

Throttle	CLOSE
Speed brakes	EXTEND

If desired, initiate turn (45° maximum bank)

Do not exceed maximum gear extending or extended speed.

Maximum speed with gear retracted is M.88 or 375 kt, whichever is less."

The emergency descent procedure described in the Company Operations Manual was as follows:

"EMERGENCY DESCENT

1. If an emergency descent is required, the Captain will call 'EMERGENCY DESCENT' and select the continuous ignition ON, cabin signs ON and the auto pilot OFF.

2. He will then simultaneously close the throttles and lower the nose to a target attitude of approximately 10° nose down and select the spoilers.

To attain the target attitude and prevent negative G forces being applied to the airframe in the event there is structural damage, a roll of up to 45° of bank may be desired. If structural integrity is in doubt, limit speed as much as possible and avoid high manoeuvring loads.

3. When the target airspeed of M.85/360 KIAS is achieved, adjust the pitch attitude to maintain the target speed (approximately 5° nose down).

4. At the same time, the First Officer will attempt to contact ATC or if unable, will select 7700 on the transponder. He will set the altitude select to the cleared altitude or the higher of the MSA (Minimum Safe Altitude) or 10,000 feet.

5. The S/O (Second Officer) will silently read the checklist correcting or drawing attention to any memorized item(s) omitted.

6. When stabilized in descent, the Captain, at an appropriate time, will call 'CHECKLIST, EMERGENCY DESCENT'".

1.17.2 Flight attendant procedures

The Air Canada flight attendants' procedures in the event of depressurization were:

"IMMEDIATE ACTION	Put on the nearest oxygen mask and sit down.

POST DEPRESSURISATION: When advised by the Captain that it is safe to move around, use the nearest portable oxygen bottle and administer oxygen to the passengers who require it. The flight attendant nearest the flight deck should determine if the pilots require assistance. The flight attendant(s) nearest to the washrooms should determine if occupants require assistance. On aircraft with lower or remote galley locations, the nearest flight attendant should determine the status and assistance requirements of those who were working in that area.

CAUTION DO NOT REMOVE YOUR OXYGEN MASK UNTIL ADVISED BY THE CAPTAIN THAT IT IS SAFE TO DO SO."

1.17.3 *Previous case of L1011 rear pressure bulkhead rupture*

Only one prior instance of rear pressure bulkhead rupture on an L1011 aircraft has occurred. In that case a slightly smaller 'D' shaped rupture (14 inches by 11½ inches) was produced adjacent to the 6 inch wide edge doubler at the top of the bulkhead, within the area indicated in Appendix 1, fig 1.

That accident, which involved a Cathay Pacific L1011 in December 1989, occurred whilst the aircraft was in the climb and passing 28,000 feet. Cabin altitude peaked at 18,000 feet.

Detailed laboratory reports on the failure were not available, but the manufacturer indicated that a circumferential fatigue fracture of the gore panel was found along the line of the 6 inch edge doubler, initiating from corrosion pits on the outer side of the gore, in the corner adjacent to the doubler. As the crack progressed, it was turned inboard by an anti-tear strap. The rupture then continued inboard before being turned again by the next anti-tear strap, thereafter running back circumferentially to form a 'D'-shaped flap which flexed upwards until it came into contact with the engine intake duct.

No evidence was found of scores or other defects, apart from the corrosion.

In response to that accident, FAA Airworthiness Directive (AD) 90-03-11 (89-NM-279-AD) and Service Bulletin (SB) SB-093-53-258 were issued on the 13 February 1990, requiring inspections of the affected area.

1.17.4 *Design and airworthiness requirements*

The potential for overpressure damage to occur in nominally unpressurized structures due to pressure hull rupture was first identified during the investigation of a British

European Airways (BEA) Vanguard accident[1] in Belgium, which occurred on 2 October 1971. In that accident, the strength of the rear pressure bulkhead was degraded by corrosion in an inaccessible area at the bottom of the bulkhead, which caused the bulkhead to rupture in an uncontrolled manner. The discharge of cabin air into the tailcone area resulted in the tailplanes and fin becoming pressurized, inducing displacement of the tailplane upper skins, tailplanes detachment and a consequent total loss of pitch control with an ensuing dive into the ground from 19000 feet. However, although the findings of that investigation were used by the Air Registration Board (ARB) to review the designs of pressurized aircraft on the UK register, and in all subsequent CAA evaluations of pressurized aircraft, no changes were made to British Civil Airworthiness Requirements (BCARs) to address specifically the dangers inherent in the release of high pressure cabin air into unpressurized structures, nor were design requirements introduced to address specifically the modes of failure of pressure bulkheads.

The L1011 aircraft type was certificated in the United States to Federal Aviation Regulations (FAR) Part 25, amendments 1 to 16, dated 1 February 1965. FAR section 25.365 required that there be no feature or characteristic that made the airplane unsafe for the category for which certification was required. The structure supporting the prescribed flight and ground loads (and any other structure that, if it failed, could interfere with continued safe flight and landing) was required to be designed to withstand the differential pressure loads resulting from a sudden release of pressure through the openings specified in section 25.365(e) at any approved operating altitude. In complying with this requirement, the differential pressure loads had to be combined in a rational and conservative manner with lg level flight loads and any loads arising from the emergency depressurization conditions. The loads could be considered as "ultimate", but any deformation associated with these conditions was required not to interfere with continued safe flight and landing.

Lockheed chose to design the structure against fail-safe criteria, supported by testing to demonstrate that the design fail-safe requirements would be met in service. The entire fuselage was also subjected to fatigue tests.

To demonstrate the fail-safe characteristics of the rear pressure bulkhead, two cuts were made in the bulkhead gore panels, one circumferentially and one radially, each of 10 inches initial length. With these simulated *'cracks'*, the bulkhead sustained limit load.

---

[1] See Appendix 5 references

During fatigue testing, the fuselage (with an intact and undamaged rear pressure bulkhead) was cycled through a total of 52,000 pressure cycles, after which there was no evidence of distress in any of the bulkhead gore panels.

The L1011 design was evaluated in 1970 by the ARB, (now the CAA) to BCAR Section D Issue 8, Structural Design Requirements, dated 1966, prior to the type coming onto the British Register. The FAA rules at the time, FAR 25.365 for cabin pressure loads and FAR 25.571 for fatigue or fail-safe life, were similar to those used by the ARB, except that the ARB required the fatigue testing to be extended from the original 30,000 pressure cycles to 52,000 pressure cycles. (Since July 1979, Joint Airworthiness Requirement (JAR) *25* has been adopted by the CAA as the U.K.'s sole airworthiness requirement for large transport aircraft.)

1.17.5 FAA reviews of structural requirements following major accidents

As a result of the major accident to a Turkish Airlines McDonnell Douglas DC-10[2] near Paris on the 3 March 1974, in which an underfloor cargo door separated from the aircraft and caused the main cabin floor to collapse due to the resulting excess pressure differential across the floor, with associated damage to the flight control systems which were routed through the affected area, the FAA issued AD 75-15-05. This required manufacturers of all large passenger transport aircraft, including the Boeing 747, Lockheed 1011, Airbus 300 and McDonnell Douglas DC-10, to review their cabin floor strength for an assumed instantaneous underfloor opening through the pressure hull of not less than 20 square feet. However, Lockheed found that it did not need to improve the floor strength of the L1011, and was thus deemed to have met the requirements of this AD.

In response to the later major accident to a Japanese Airlines (JAL) Boeing 747[3] in August 1985, when another instance of aft pressure bulkhead failure occurred leading to secondary overpressure damage to the vertical stabiliser structure and consequent loss of control, the FAA undertook a program to prevent similar failures on all transport category aircraft already in service, as well as on new transport types undergoing certification at that time. The major US manufacturers (Boeing, McDonnell-Douglas, and Lockheed) were requested to examine each of their models to determine if events similar to the JAL accident could occur. As a result of this work, and the results of the investigation into the JAL accident, several FAA AD's were issued which required design changes to Boeing 747, 757 and 767 aircraft types. These changes focussed upon the closure of the fin and tailplane structures at the root ribs, in order to prevent high pressure air from gaining access and producing overpressure damage to the empennage as had occurred on the JAL aircraft, and on

---

[2, 3] See Appendix 5 references

the Vanguard mentioned previously. Lockheed's study indicated that the L1011 fixed vent area of 760 square inches in the fuselage afterbody would provide more than adequate venting to compensate for the loss of the maximum panel area formed by the boundaries of the radial and circumferential reinforcements, *ie* approximately 470 square inches. It is not clear, however, to what extent the validity of the underlying assumption, regarding maximum rupture area, was tested.

This FAA program will eventually be replaced by a second regulatory program, which will retroactively require similar investigation and corrective actions to be taken on all transport aircraft operating under Parts 121, 125, and 135 of the Federal Aviation Regulations.

The FAA is also coordinating a proposed retroactive rule which will require evaluation of areas potentially affected by rapid decompression. This work has been prompted by adverse service experience, including the JAL accident, which indicates that normally unpressurized areas may become pressurized in the event of a pressure hull rupture. This work is related not only to structure, but also to components or parts that could, under such circumstances, develop differential pressure loads which might cause failure or interfere with the continued safe flight and landing of the aircraft. The retroactive rule will apply to all transport aircraft operated under Parts 121 or 135.

1.18 New investigation techniques

None.

2 Analysis

2.1 Initial safety action by AAIB

Following initial examination of this rear pressure bulkhead failure, the AAIB was concerned to find the presence of the mechanically-induced score on the aft face of the bulkhead diaphragm, from which the fatigue failure had emanated. In view of the possible implications of these findings for the condition of other L1011 aircraft in service, and also because of associated implications concerning the potential rupture size of any similarly defective rear pressure bulkheads, on the 21 December 1990 AAIB notified Lockheed, Air Canada, The TSB, NTSB, FAA and the CAA of its preliminary findings, in addition to making the following two Safety Recommendations:

> "(1) The Civil Aviation Authority and the Federal Aviation Administration, in conjuntion with Lockheed, instigate an in-service inspection of L1011 aircraft aft pressure bulkheads, capable of reliably detecting:
>
> 1. Fatigue cracking on the bulkhead structure
>
> 2. Scoring on the bulkhead gore-diaphragm.
>
> (2) The 'worst case' failure mode of the L1011 aft pressure bulkhead used for the original certification testing be reviewed in the light of this failure, and the findings from the recommended in service inspections, and modified to take account of the maximum anticipated failure which could occur, based on these findings. The Civil Aviation Authority and the Federal Aviation Administration expedite, in conjunction with Lockheed, an assessment of the venting capability of the (normally unpressured) aft fuselage to dissipate the maximum anticipated overpressurization of this zone, following a 'worst case' major failure of the aft pressure bulkhead, without incurring structural damage to the empennage."

Lockheed issued a Service Wire dated 21 December 1990 and followed this with SB 093-53-263 of 27 February 1991 which required a visual inspection of the rear pressure bulkhead around all four edges of the .020 inch thick doubler, on both the left and right sides of the bulkhead. Transport Canada also issued AD CF-90-28, requiring visual inspection of the rear pressure bulkheads, on 27 February 1991.

As a result of these inspections, one further instance of cracking of a rear pressure bulkhead was detected on an L1011 aircraft of a US operator, in a similar location to that found on C-GAGI. This operator also reported finding evidence of a score on the bulkhead diaphragm, associated with the crack. Lockheed checked the build records for both this aircraft and C-GAGI, but found no corresponding batch number or other aspect in common between these 2 bulkheads.

The FAA issued AD 91-07-03, amendment 39-6944, on the 3 April 1991 the relevant parts of which enforced SB 093-53-263 and provided alternative inspection procedures for L1011 aircraft which had been inspected in accordance with the Service Wire of 21 December 1990.

2.2 The emergency descent

As soon as the flight crew became aware of the loss of pressurization, their initial response was rapid and well coordinated. Whilst the first officer obtained clearance from ATC to descend, the second officer completed the appropriate checklist and the commander began an emergency descent. Both the aircraft Flight Manual and the Operations Manual required him to take account of the risk of structural damage to the aircraft. However he appeared to have decided that there was no such risk for he accelerated the aircraft to V_{MO} as the descent progressed. It is notable in this context that the two previous accidents associated with failure of rear pressure bulkheads, the Vanguard near Brussels in 1971 and the Boeing 747 in Japan in 1985, were both accompanied by separation of skins from the rear empennage. In addition, in 1973 a DC-10 in the United States suffered a rapid decompression following an engine disintegration which severely damaged the fuselage. Severe fuselage damage also occurred when a cargo door was lost from a Boeing 747 near Hawaii in 1989.

It is understandable, however, that the major concern of the commander at the time should have been the survival of his passengers. The cabin pressure was reducing rapidly to a level at which the occupants could have suffered permanent damage if they were not breathing oxygen, and the commander knew that it was urgent for him to descend the aircraft to a safer environment. He may also have been influenced by his past training. Because pilots are required to demonstrate maximum rate descents during type qualification testing, it is possible that, unless the risk of airframe damage is adequately addressed during company training, pilots will be conditioned to the type of descent they are required to demonstrate during type testing.

2.3 Flight attendant emergency procedures

In this accident the risk to the passengers was small. Cabin altitude was above 20,000 feet for only a short time, and the cabin attendants were able to resume their duties within 6 minutes, when the aircraft levelled at 10,000 feet. There is, nevertheless, concern that the present emergency procedures for cabin attendants in the event of rapid depressurization may not provide adequately for passenger survival in all cases.

In the event of loss of cabin pressure, most airlines require cabin attendants to seat themselves and put on the nearest passenger oxygen masks. As more masks are provided than there are seats, this procedure should be effective in ensuring, as it is meant to do, that cabin attendants survive and remain conscious to render assistance to passengers later, or to provide for safety if a further emergency develops. The procedure assumes that oxygen is available and will be used by all passengers, who will thus not be exposed to danger no matter how high the cabin altitude may rise. There is evidence, however, that it is unlikely that all passengers will correctly use the supplementary oxygen system, and present procedures for cabin attendants fall short of using all available resources to ensure the survival of these passengers.

A report by the NTSB in 1985 stated that many passengers paid insufficient attention to safety briefings and were ill-prepared to act properly if an emergency situation arose. The report cited several cases where, following a rapid depressurization, many passengers failed to activate and don oxygen masks. These cases are described in Appendix 4. Associated with that report was a Safety Recommendation to the FAA that automatically activated safety messages should be used to explain the operation of supplemental oxygen systems following loss of cabin pressurization. Some airlines have already brought suitable equipment into use for this purpose, but it was not installed on C-GAGI.

Although lack of preparedness would have had few ill effects on the passengers in this instance, it is not difficult to envisage circumstances where it could seriously affect survival. If a depressurization is accompanied by airframe damage then the rate of descent that can be achieved will be limited, particularly on those aircraft types that have an altitude, or a low airspeed limitation, on the lowering of the landing gear. Circumstances could arise, therefore, when passengers could be exposed for several minutes to cabin altitudes where they could suffer serious effects from hypoxia if they could not, or did not, use the supplementary oxygen system correctly. The assistance of cabin attendants would be needed to open oxygen compartment doors that failed to open automatically (latch release rods for this purpose are stowed at cabin attendants' door stations) and help would be needed by those passengers who failed to don their oxygen masks correctly. Elderly passengers and those with small children would be especially at risk and in need of help.

It would not be sensible to write a drill requiring all cabin attendants to don portable oxygen equipment because some of them might be some distance away from a portable oxygen stowage and, in any case, such equipment is not optimised for rapid donning. In many cases, however, some of the cabin attendants might be close enough to portable oxygen sets to bring them into use quickly; they could then give assistance to those passengers who needed it. It is therefore recommended that airlines should review their procedures for cabin attendants in the event of rapid cabin depressurization with a view towards ensuring a degree of flexibility, appropriate to the equipment in their aircraft, that would provide some continuing assistance to passengers during such an emergency. (Made 16 August 1991)

2.4 Failure of the rear pressure bulkhead

The detailed examination of the failed rear pressure bulkhead clearly identified the overall sequence of failure. This sequence began with a fatigue fracture which propagated from multiple sites along the butt-join between the outer 0.040 inch doubler and the 0.020 inch doubler. The initial, slow growth, fatigue fractures merged together and thereafter grew at a faster rate before developing into a tensile rupture mode of fracture which also followed the butt-join. This rupture was arrested as the fracture approached the lower corner of the panel, almost certainly because of the combined stiffness of the radial stiffener and doubler plate bounding the lower edge of the panel. The fracture was also arrested in its progress upwards towards the upper boundary of the panel, probably because of the influence of the anti-tear strap bounding the upper edge of the panel.

Having been arrested at these two points, the fracture appeared to have remained static for some considerable period of time, sufficient for the fracture surfaces to become stained a brown/yellow colour. This type of staining is typically found on old fractures in aircraft pressure hulls and is produced as nicotine and other impurities are strained from cabin air leaking through the crack over a long period of time in service.

Eventually, the lower fracture again extended in a tensile rupture mode, apparently in a single *'burst'*, turning inwards and running radially towards the centre of the bulkhead before being turned again, upwards, by the circumferential anti-tear strap. The removal of edge restraint along this second boundary of the panel allowed it to flap outwards under the cabin differential pressure loading. As the panel flapped outwards, the upper end of the original fracture was torn further, extending circumferentially upwards through the anti-tear strap before terminating approximately 1 inch beyond the anti-tear strap. It is a cause for concern that this fracture was not arrested by the anti-tear strap.

It has not been possible to positively establish why the final rupture occurred when it did, rather than on previous flights. No evidence of fatigue growth was found in the region where the fracture turned the corner, and therefore it must be presumed that the mechanism which precipitated the final radial rupture burst was solely an applied load which exceeded, possibly by a very small margin, the load which the bulkhead had experienced subsequent to the first fracture arrest.

The DFDR trace of cabin altitude showed a slight increase in pressure, to a value slightly above that which had applied during the cruise, when the aircraft began its descent on the accident flight. This slight pressure change was not, in itself, significant but it does offer an explanation of why the bulkhead ruptured at top of descent into Heathrow, rather than at the top of the climb out of Montreal Mirabel.

2.5 The fatigue process

The fatigue failure initiated from the base of a score on the outer face of the gore panel. This score (0.004 inch to 0.014 inch deep; 0.012 inch to 0.016 inch wide) would have critically reduced the fatigue strength of the bulkhead and there is no doubt that it provided a linear initiation region of high stress intensity along which the many fatigue thumbnails started to grow. The thumbnail fractures grew inwards through the thickness of the gore section from the bottom of the score channel, and were clearly driven by the tensile stresses in the gore - caused by a combination of membrane tension in the gore and, probably, by bending stresses near the outer surface of the gore panel caused by slight flexing of the bulkhead as it picked up fuselage differential pressurization loads. These fatigue thumbnails increased in size with each repeated flight pressurization cycle and ultimately they merged together to form an essentially continuous fatigue crack approximately 7 inches in length. Thereafter, the crack expanded in length for about 2.5 inches in each direction as a result of fast fatigue growth, with the fracture advancing along the butt-line. Crack propagation beyond this region was by a fast rupture mechanism, again along the butt-line, as far as the bottom corner of the panel.

The fatigue process comprised simultaneous growth of several fatigue fractures which merged together as they developed, with considerable variations in growth rate being evident as the fracture stress fields interacted. The only viable conclusion which can be drawn from the fracture growth rate assessments, based on analyses of several discreet fatigue regions involving both independent thumbnail fracture growth and merged thumbnail fracture growth, is that the growth rate would have ranged from a value of approximately 6.7×10^{-6} inches per flight initially to around 17.0×10^{-6} inches per flight later in the failure process as the fractures merged. Because the growth rate distribution over the fatigue region was not known, the number of flights associated with the fatigue region as a whole could not be calculated. However, at the maximum rate of growth observed, the number of pressure cycles required to have driven a single thumbnail crack from the base of the score through to the back face of the gore panel was estimated to be a minimum of 1500 load cycles, *ie* 1500 flights. C-GAGI had accumulated a total of 8308 flights up to the time of the accident.

2.6 The origin of the score

A blue coloured adhesive, visually similar to that used to bond the doublers to the gore panel, filled the score channel in several areas. No record of any repairs to the rear pressure bulkhead was found, indicating that the adhesive found its way into the score channel during manufacture. The position of the score channel in relation to the edges of the doubler sheets confirmed this view.

Microsections taken through the bulkhead thickness in the scored area showed a consistent relationship between the profile and position of the score channel, and the edge profile and position of the 0.040 inch thick doubler. These sections demonstrated beyond any reasonable doubt that the score had been produced by some form of metal blade, or other sharp tool, which had been drawn along the gore panel using the edge of the 0.040 inch doubler as a guide, as shown in Appendix 1, fig 5. This was most probably done to remove excess adhesive sheet stock from the gore panel after the 0.040 inch doubler had been laid in position, in order to provide a clean area at the butt-joint prior to laying the 0.020 inch doubler in position. The 0.040 and 0.020 inch doublers were then bonded as one assembly in an autoclave.

2.7 Design considerations

Even in the absence of scoring, the design of the bulkhead was such that a significant stress concentration would have existed along the line of the butt-join, caused by the diffusion of membrane stresses from the doublers into the gore panel proper, and back out again, as loads transferred across the butt-join. This stress concentration was not the sole cause of the fatigue fracture, but it must have contributed significantly both to the initiation of fatigue cracking in the scored gore panel on this particular aircraft, and also to the subsequent propagation rate of the fatigue crack.

The use of such a butt-join arrangement is difficult to understand from a stressing standpoint unless the 0.020 inch doubler was added to the original design as a modification, in which case a butt-join would have presented the simplest arrangement from a production standpoint, although introducing a local stress concentration along the butt-line. This stress concentration feature was probably assessed at the time and deemed to be acceptable.

Of the loads imposed on the bulkhead in service, only the main fuselage pressurization loading cycle is likely to have been of significance. Therefore, the loading spectrum required to accurately represent service loads during fatigue testing would have been readily predicted, and the fatigue test results - as they applied to the rear pressure bulkhead specifically - could reasonably have been expected to highlight any fatigue problems inherent in the design of the bulkhead. The satisfactory results of that fatigue testing were supported by the acceptable overall history of the L1011 rear pressure bulkhead in service and showed that whilst the detail design might not have been particularly good from a stressing standpoint, it was nevertheless acceptable, *provided that no damage was present which could raise the existing stress concentration above a tolerable level.* On this basis therefore, the design of the bulkhead might reasonably have been viewed as acceptable. However, in practice, the integrity of the bulkhead was compromised by the constructional arrangements which, with hindsight, provided the opportunity for operatives to create scores in the gore panel during manufacture as they cleaned the butt-region in preparation for laying-up the 0.020 inch doubler.

2.8 Inspection of rear pressure bulkheads

In view of the difficulty in visually inspecting for the presence of such scoring in service, it is recommended that Lockheed should devise and introduce specific non-destructive testing (NDT) inspections to detect the presence of scores in those areas of the L1011 rear pressure bulkhead which contain butt-joints between gore panel doublers. (Made 16 August 1991)

2.9 Potential hazards resulting from scores

Light scores, similar to that found on C-GAGI, have been known to produce rupture of pressure hulls on other aircraft types and history has shown that personnel working on aircraft structures are not always fully aware of the critical consequences of such damage. These problems have been recently examined in the USA.

On the basis of investigations carried out by the NTSB it was concluded that the critical nature of this type of slight surface damage was not fully understood by many personnel engaged in the repair and maintenance of aircraft structures. Prompted by this concern, an NTSB Recommendation was made to the FAA on August 9 1989, highlighting two examples where such scores had led to pressure hull rupture and recommending that the FAA should issue a Maintenance Bulletin drawing attention to the hazards associated with surface defects.

Although the score found on C-GAGI appeared to have been produced during original manufacture rather than during repair, the NTSB recommendation is entirely appropriate to this accident, and is reproduced below:

> "The National Transportation Safety Board recommends that the Federal Aviation Administration:
>
> Issue a Maintenance Bulletin to all manufacturers, airlines, air carrier maintenance organisations, and aviation maintenance training schools which:
>
> Informs them about the circumstances of (these two) incidents. Requests that they issue appropriate informational material to the personnel who perform work on aircraft structure, whether certificated

or non-certificated mechanics, about the serious consequences of minor practices on pressurised fuselage skin panels.

Outlines the proper techniques and tools for marking materials to prevent the possibility of creating fatigue initiation from minor scratches. (Class II, Priority Action) (A-89-79)

Direct all Principal Maintenance Inspectors to review the maintenance practices of the operators under their jurisdiction to determine that the certificated and non-certificated maintenance personnel are utilizing proper tools and repair techniques when marking structure for repair or painting. (Class II, Priority Action) (A-89-80)"

2.10 Certification and airworthiness aspects

At the time of the original certification of the L1011 in 1972, no airworthiness requirement existed which specifically addressed the potentially catastrophic structural damage which could occur due to the uncontrolled release of high pressure cabin air into a fuselage afterbody and empennage. The implications of such a failure had, however, become fully apparent in 1971 when the BEA Vickers Vanguard rear pressure bulkhead ruptured causing overpressure damage to the tailplane upper skins, separation of the tailplanes and total loss of control of the aircraft, with the death of all 55 persons on board. However, although the detailed findings of the subsequent investigation led the ARB (and later the CAA) to review the designs of pressurized aircraft, no action was then taken by the UK Regulatory Authority to amend BCAR's. The Turkish Airlines DC10 and Japan Airlines Boeing 747 accidents in 1974 and 1985 (para 1.17.5) however did, if belatedly, prompt the FAA to require a re-examination of the potential damage which could result from an uncontrolled rupture of rear pressure bulkheads. The L1011 design was then reviewed and considered to have adequate venting insofar as the vent area provided in the outer shell of the fuselage afterbody was greater than the maximum size of rupture which it was presumed would occur in the rear pressure bulkhead. Therefore no modifications were deemed to be necessary for the L1011.

The decision by the FAA to require no change to the L1011 design rested totally on the validity of the presumed maximum aperture size which could arise as a result of failure of the rear pressure bulkhead. It was presumed that the arrangement of anti-tear straps would limit the size of any (single) crack which could occur in any (single) gore panel, turning such a crack at right angles by means of the anti-tear straps and thereby allowing the section of panel bounded by the fracture to flap outwards, venting the pressure at a controlled rate and limiting further crack growth by reducing the pressure acting on the bulkhead locally in the area of the fracture.

The vent area produced by such a mechanism, involving a single panel flapping out, is indeed very much less than the 760 square inch vent area in the afterbody, and it would require a rupture extending into at least 3 bays to exceed significantly the vent capabilities of the afterbody. However, it is difficult to substantiate the presumption that a fracture, once it is running in a tensile rupture mode, could not continue to propagate in an unstable manner leading to a larger bulkhead failure, instead of the flapping panel mode of failure which was assumed. In the case of the fracture mechanism on C-GAGI, whilst it conformed broadly to the expected pattern, it did breach one anti-tear strap and it is not entirely clear how close the fracture came to the margin of stability. However, there was a lap splice and frame member every 2 bays circumferentially and it was this feature which caused the crack to turn at point '3', as shown in Appendix 1, fig 5.

It is therefore considered that, because of the pivotal importance of the assumed failure mode in the maintenance of empennage structural integrity following a rear pressure bulkhead rupture, the CAA and FAA should, as part of their response to Safety Recommendation (2) in paragraph 2.1., require a review of L1011 rear pressure bulkhead failure modes involving long fractures, extending into more than one bay, and having realistic stress intensities at the crack front.

Finally, in view of the critical importance of such aspects of pressurized cabin structural design, as graphically demonstrated by these major accidents over the last 20 years, it is clearly imperative that current UK/European Airworthiness Requirements are elevated to a higher standard in this area. It is therefore recommended that the CAA ensure that the standards of the European Joint Airworthiness Requirements for large public transport aircraft, JAR25, are raised at the earliest opportunity to the level of the proposed FAA regulations concerning the fail-safe design of pressure cabins. (Made 16 August 1991)

3 Conclusions

(a) Findings

(i) The flight crew were properly licensed and medically fit to conduct the flight.

(ii) The aircraft had been maintained in accordance with an approved maintenance schedule, and the Certificate of Airworthiness was valid.

(iii) The aircraft encountered a sudden cabin depressurization just before it commenced its final descent from FL370, but the flight crew reacted promptly and carried out an emergency descent to FL100, before continuing to land at Heathrow Airport without further incident.

(iv) The cabin depressurization was caused by a localised rupture of the rear pressure bulkhead at its left side, just above floor level, which occurred due to long-term fatigue crack propagation.

(v) The vented design of the normally un-pressurized fuselage afterbody satisfactorily prevented air pressure build-up within this zone and there was no resultant damage to the empennage.

(vi) Multi-site fatigue fractures had initiated along a score-line on the aft surface of the bulkhead pressure diaphragm, at the butt-line between the .040 inch thick circumferential doubler and adjacent .020 inch thick bonded doubler, but the combination of a stiffener and the bulkhead tear-straps limited the extent of the final ruptured area.

(vii) The evidence associated with the score indicated that it had originated at manufacture, probably as a result of some tool having been drawn along the side of the circumferential doubler.

(viii) Subsequent to an early Safety Recommendation arising from this investigation and resultant in-service inspections initiated by the manufacturer, one further instance of a cracked rear pressure bulkhead was detected on a US registered L1011, which was also found to be associated with a score at this location.

(ix) At present there are no reliable techniques to detect such scores on L1011 rear pressure bulkheads.

(x) It is apparent that subsequent to the AIB Investigation Report on the major fatal accident to a BEA Vanguard public transport aircraft in Belgium in October 1971, whilst the UK Regulatory Authority conducted an on-going review of all pressurized transport aircraft on the UK register, it did not undertake related action to amend British Civil Airworthiness Requirements to include fail-safe design requirements for cabin rear pressure bulkheads; it was not until the later major fatal accident to a Japan Airlines Boeing 747 public transport aircraft in August 1985 that the United States Federal Aviation Administration introduced a programme to address this critical aspect of pressurized cabins design.

(xi) The commander elected to accelerate his aircraft to V_{MO} during the emergency descent and his actions were entirely successful. However, had the aircraft sustained structural damage to its empennage as a result of the bulkhead failure and resultant fuselage afterbody pressurization he should have limited his speed and manoeuvering loads to reduce the possibility of structural problems, as stated in the Flight Manual and Company Operations Manual.

(xii) Whilst the flight attendants sat down and donned passenger oxygen masks during the emergency descent, had any passengers required urgent oxygen administration during the descent a more flexible response may have been required.

(b) Causes

The sudden cabin depressurization was caused by a localised rupture of the rear pressure bulkhead, behind the aft/left toilet compartment, which occurred as a result of fatigue cracking which had initiated due to the following factors:

(i) The presence of a score defect on the bulkhead diaphragm aft surface which had been inadvertently introduced during the manufacturing process.

(ii) The localised intensification of the bulkhead pressurization stresses by a bonded doubler butt-join discontinuity, which was co-linear with the score defect.

4 Safety Recommendations

The following Safety Recommendations were made during the course of this investigation.

4.1 The Civil Aviation Authority and the Federal Aviation Administration, in conjunction with Lockheed, instigate an in-service inspection of L1011 aircraft aft pressure bulkheads, capable of reliably detecting:

1. Fatigue cracking on the bulkhead structure
2. Scoring on the bulkhead gore-diaphragm. (Made 21 December 1990)

4.2 The 'worst case' failure mode of the L1011 aft pressure bulkhead used for the original certification testing be reviewed in the light of this failure, and the findings from the recommended in service inspections, and modified to take account of the maximum anticipated failure which could occur, based on these findings. The Civil Aviation Authority and the Federal Aviation Administration expedite, in conjunction with Lockheed, an assessment of the venting capability of the (normally unpressured) aft fuselage to dissipate the maximum anticipated overpressurization of this zone, following a 'worst case' major failure of the aft pressure bulkhead, without incurring structural damage to the empennage. (Made 21 December 1990)

4.3 Airlines should review their procedures for cabin attendants in the event of rapid cabin depressurization with a view towards ensuring a degree of flexibility, appropriate to the equipment in their aircraft, that would provide some continuing assistance to passengers during such an emergency. (Made 16 August 1991)

4.4 Lockheed should devise and introduce specific NDT procedures to detect the presence of scores in those areas of the L1011 rear pressure bulkhead which contain butt-joints between gore panel doublers. (Made 16 August 1991)

4.5 The CAA ensure that the standards of the European Joint Airworthiness Requirements for large public transport aircraft, JAR25, are raised at the earliest opportunity to the level of the proposed FAA regulations concerning the fail-safe design of pressure cabins. (Made 16 August 1991)

E J TRIMBLE
Inspector of Air Accidents
Air Accidents Investigation Branch
Department of Transport
October 1991

The Civil Aviation Authority's response to these Safety Recommendations is contained in CAA Follow-up Action on Accidents Reports (FACTAR) No 3/91, published coincident with this Report.