INCIDENT

Aircraft Type and Registration:	Lockheed L1011-385-1-14 Tristar, G-BBAH	
No & Type of Engines:	3 Rolls-Royce RB211-22B turbofan engines	
Year of Manufacture:	1974	
Date & Time (UTC):	20 June 1995 at 1645 hrs	
Location:	32°50' North 014°20'West	
Type of Flight:	Public Transport	
Persons on Board:	Crew - 14	Passengers - 401
Injuries:	Crew - None	Passengers - None
Nature of Damage:	Rupture of rear pressure bulkhead	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	48 years	
Commander's Flying Experience:	7,000 hours (of which 2,000 were on type) Last 90 days - 110 hours Last 28 days - 58 hours	
Information Source:	AAIB Field Investigation	

History of flight

After an uneventful flight from Manchester to Tenerife South, the aircraft was turned round and took off at 1548 hrs, with the commander as handling pilot, to return to Manchester. There had been no technical problems with the aircraft on the outward journey.

At 1645 hrs the aircraft was in the cruise at Flight Level (FL) 310 and Mach O.84, some 18 nm South of Lupex, a mandatory reporting point in the Casablanca Flight Information Region (FIR); the cabin differential was normal at 8.2 psi. Suddenly, the flight crew heard a loud 'muffled bang' followed by a feeling of pressure on their ears and the cabin altimeter indicated that the cabin pressure was 'climbing' at a rate greater than 2,000 ft/min. The flight crew donned oxygen masks and immediately commenced an emergency descent in accordance with their standard procedures. The commander was now manually flying the aircraft and the first officer was operating the radios. They had been working

Casablanca Radio and had broadcast their emergency on that frequency. Within the cabin, the purser and all but one of his crew had heard the bang and felt pressure on their ears; one cabin attendant was below in the galley and only felt the change in ear pressure. The purser noted that the passenger oxygen masks had not deployed and went immediately to the flight deck to inform the flight engineer who then deployed the oxygen masks manually. The automatic system had not activated because cabin pressure had not yet reached the appropriate altitude. All the oxygen doors opened, but some of the masks did not drop; these were pulled down by the cabin attendants, or adjacent passengers. One steward in the rear service area pulled one mask to activate it, but it came off in his hand. All the passengers complied with the crew's instructions and the pre-recorded emergency descent announcement was broadcast twice; this was automatically activated when the passenger oxygen masks deployed.

The commander levelled the aircraft at FL100 after completing the descent at a speed slightly less than the maximum operating speed. During the descent, the commander was informed by the purser that there were no problems within the cabin, apart from some degree of understandable shock. There had been a smell of burning within the cabin following the activation of the emergency oxygen masks, but the purser was aware that this was not unusual because of the degree of heat produced by the associated oxygen generators. However, this smell of burning did cause the passengers some understandable anxiety. After levelling, the flight crew made a full check of the aircraft systems. Apart from the pressurisation failure the only other apparent problem was that a landing gear 'Truck' light had illuminated; the crew considered that this may have happened because of the requirement to select the gear down during the emergency descent. The commander also considered that the aircraft had handled normally during both the descent and the level-off. By this stage the first officer had established communications with Lisbon ATC, who acknowledged their emergency and confirmed the aircraft position. The commander then reviewed the situation: G-BBAH was approximately half-way between Tenerife and Faro; the crew and passengers were well; there were no handling problems with the aircraft. The commander then made the decision to divert to Faro and informed the passengers of the situation and his intentions.

During the transit to Faro, 4,000 kg of fuel was dumped to reduce the aircraft landing weight to 160,000 kg. The 'Truck' warning required the use of the emergency landing procedure. After briefing the purser on this aspect, the commander informed the passengers of the need for an emergency landing. Within the cabin, the purser briefed his crew and the passengers on the forthcoming landing. The cabin crew then went to each passenger to confirm that they were all aware of the procedure. Thereafter, G-BBAH received full and effective priority from Faro ATC for their approach and landing on Runway 29. As speed was reduced on finals, the crew noted that the 'Truck' light went out. After landing at 1750 hrs, the aircraft was followed by the Airport fire vehicles to its designated stand where the other emergency services were positioned. The passengers and crew disembarked normally.

FDR and CVR information

The 30 minute duration CVR produced a good recording, but did not include the period of the decompression because of the subsequent cruise time to Faro Airport. The FDR parameter list did not include cabin pressure.

Rear pressure bulkhead construction

The rear pressure bulkhead is a thin shell structure comprising a series of 1 mm (0.040 inch) thick gore panels lapjointed to form a dome-shaped pressure membrane of approximately hemispherical profile, overlaid with a network of doublers and anti-tear straps as shown in Figure 1.

Constructional details are shown in Figure 2. The gore panels are 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 *waffle* pattern to the aft face of the bulkhead, subdivide each of the gore panels into ten elements of approximately rectangular shape. The purpose of the anti-tear straps is to limit the size of any rupture which might occur by encouraging tears to turn away from the anti-tear straps, resulting in a 'U' shaped *flap* which can blow outwards safely, venting the differential pressure across the bulkhead and inhibiting further propagation of the failure.

Around the outer circumference of the bulkhead, adjacent to its attachment to the fuselage proper, a series of 150 mm (6 inches) wide by 1 mm (0.040 inches) thick doublers are bonded to the forward/aft surfaces of each gore panel, mirroring the lap jointed constructional form of the gore panels proper. A large diameter auxiliary power unit (APU) air duct, and various other services, pass through the bulkhead in the outer segment of the 7 to 8 o'clock gore panel. The upper mid regions of the 11 o'clock to 1 o'clock gore panels incorporate a pair of large inward-vent valves. In each of these regions, the gore panels are reinforced by a bonded doubler, and the anti-tear straps are omitted.

The L1011 aircraft type was certificated in 1972, at which time no airworthiness requirement existed which specifically addressed the potentially catastrophic structural failure which can follow from a pressure bulkhead failure, due to the release of pressurised cabin air into parts of the aft fuselage and empennage which are not designed to withstand such internal pressures. An FAA review of the implications of rear pressure bulkhead failures, following a major accident to a Japan Airlines Boeing 747 in 1985, which was caused by such a failure, concluded that the venting incorporated into the L1011 aft fuselage structure was sufficient to cater for the limited size of bulkhead rupture which it was envisaged could occur, having regard to the subdivided nature of the design. Subsequent to an incident involving an Air Canada L1011 in December 1990 (described in more detail later), the Joint Airworthiness Requirement JAR 25.365(e) has been amended to include a requirement to assess fully the implications of a sudden release of pressure into any part of the airframe, and to ensure that all affected structure, both inside and outside of the pressure hull, is designed to withstand such a release at any operating altitude.

The bulkhead failure

Overall failure mode

The sudden decompression was caused by a partial failure of the rear pressure bulkhead at the location shown in Figures 1 and 2.

The failure comprised a 394 mm (15.5 inches) by 292 mm (11.5 inches) *letterbox* rupture of the pressure membrane at the top of the bulkhead just to the left of the aircraft centreline, immediately inboard of the 150 mm wide doubler which runs around the outer periphery. Figure 3 shows the rupture viewed from a position inside the pressure hull, looking forward and upward; the edge of the doubler is clearly visible. Figure 4 is a view from aft of the bulkhead on the left side, showing the rupture flap jammed up against the 'S' duct.

The failure had developed from a 100 mm (4 inches) long region of pre-existing circumferential cracking in the membrane gore panel adjoining the inboard edge of the doubler, (see Figure 3). The rupture subsequently propagated as rapid tears from either end of this pre-existing crack region. The rapid tears initially ran in an approximately circumferential direction before turning radially downwards (ie toward the centre of the bulkhead), due almost certainly to stiffness changes in the gore panel itself as the tears propagated, and the influence of radial frames and stiffeners. Having started to run radially inwards, toward the centre of the *dome*, both tears were then arrested by the first of the circumferential anti-tear straps which they encountered.

A sketch of the failure, giving approximate sizes and other details, is shown at Figure 5.

Bulkhead deformation

It was noted that the nominally circular (circumferential) profile of the edge of the 150 mm doubler was deformed inward slightly at a position just outboard of the pre-existing crack region, as though the bulkhead had been 'panted' inward (ie 'oil-canned') at some time in the past. This deformation is shown schematically in Section B-B in Figure 5, and is just discernible in the *line* of the edge of the doubler visible in Figure 3. Measurements of the deformation profile were made using a long straight edge held against the internal surface of the bulkhead in line with the edge of the doubler. These measurements suggested that the maximum depth of the dent was approximately 6 mm, at a point approximately 200 mm outboard of the end of the pre-existing crack region. The circumferential extent of the deformed region was difficult to quantify, but it appeared to cover an area from the outboard end of the pre-existing crack to a position about 900 mm outboard of that location.

Fracture details

Following a preliminary examination of the bulkhead at Faro, the aircraft was ferried back (unpressurised) to the UK where the failure was examined further in situ. The whole of the failure region, comprising the complete section of gore panel and doubler surrounding the failure, was then cut from the rest of the structure and taken to the AAIB at Farnborough, where it was subject to detailed examination.

Initial inspection under the microscope revealed that the 100 mm long region of pre-existing cracking had a ragged overall profile consistent with the amalgamation of numerous individual cracks to form a single fracture running parallel with, and approximately 3 mm beyond, the edge of the doubler. In addition, a very fine circumferential surface crack was noted in the paint and adhesive bead along the exposed edge of the 150 mm doubler on the inside surface of the bulkhead, but only in the area where the bulkhead had been panted inwards (see Section B-B in Figure 5), consistent with the tendency for such deformations to spring open the doubler joint. No corrosion products were visible in, or around, these cracks.

Examination of the fractures by metallurgical specialists at the DRA Materials Department confirmed that the pre-existing crack region comprised numerous small fatigue cracks originating from multiple origin sites on both sides of the gore panel. No evidence was found to suggest the presence of any score defect of the kind which had caused the bulkhead failure on the Air Canada aircraft in 1990 (described later), or any other form of manufacturing defect. No evidence was found of significant corrosion pits, or other surface defects, which could have served as primary fatigue crack initiators. Detailed examination of the fatigue cracks in the scanning electron microscope (SEM) showed that most of the fracture surfaces had suffered damage due to relative movement between the fracture faces over time, as the bulkhead flexed in response to pressurisation loads. A few small regions of undamaged fracture surface were found, however, and these were subject to detailed examination.

It was found that the deeper cracks had, in general, propagated from the forward (inboard) face of the bulkhead. The deepest of these cracks had penetrated approximately 0.58 mm (ie approximately 60% of the gore panel thickness), and reasonably clear fatigue striations were found over approximately the *final* 75% of this fracture face, with some banding being evident. However, the surface features on the *early* part of the crack, at 0.1 mm crack depth and less, had been largely obliterated by rubbing damage.

Attempts to determine the crack growth rates and the age of the crack were frustrated by rub damage to the fracture surfaces, which prevented the growth rates in the initial stages of crack propagation from being determined. Striation measurements in the later regions of crack growth revealed wide variations in the spacing of individual striations, and the spacing between striation bands was also highly variable. A plot was constructed of striation spacing against crack length and a *best fit* crack growth curve drawn through the (somewhat scattered) data points. From this, it was estimated that the deepest crack would have required some 1,300 cycles to propagate from a depth of 0.1 mm to its full depth of 0.58 mm. Both the absence of clearly defined surface detail in the initial 0.1 mm of the crack and the variability in spacing evident in the later part of the crack precluded a reliable estimation of the total growth period. Notwithstanding these uncertainties, however, on the available evidence it appeared most likely that the crack would not have been visible when the bulkhead was last subject to visual inspection at 3,142 flight cycles before the failure.

Examination of a transverse (radial) microsection through fatigue crack region revealed secondary fatigue cracks from the forward face of the gore panel, approximately 1.4 mm from the edge of the doubler. These cracks had originated in the 0.04 mm thick aluminium cladding layer, and exhibited characteristics typical of fatigue development in low strength cladding. At the cladding/alloy interface, these cracks began to grow at 90° to the sheet surface, in a manner consistent with tension fatigue.

A transverse section taken through the region of paint/adhesive surface cracking confirmed that these cracks did not extend into the gore panel itself.

No evidence of significant corrosion was present in either microsection.

Previous cases of bulkhead failure on the L1011

Prior to this incident, only two rear pressure bulkhead failures had been reported on L1011 aircraft. (Subsequently, on 24 August 1995, a major structural failure of the rear pressure bulkhead occurred on a Delta Airlines L1011; the aircraft landed safely. This involved a totally different and unrelated mode of failure, and is the subject of ongoing investigation by the US Authorities.)

Incident involving a Cathay Pacific L1011 in December 1989:

This incident involved a rear pressure bulkhead failure which was virtually identical to the subject failure in terms of rupture size, overall characteristics, and position.

Examination of the failed parts by the manufacturer revealed the presence of multiple fatigue crack origins on both the inner and outer surfaces of the gore panel, but with a greater density of origins on the outer surface. The paint layer on the outer surface of the bulkhead was cracked over a circumferential region which extended from the middle of, to slightly beyond (ie to the outside of), the origin (pre-existing crack) region. Sections through the paint-cracked area of the gore panel revealed corrosion pits at positions directly beneath the paint cracks, from which fatigue cracks had subsequently propagated and merged.

The manufacturer concluded that this failure had been initiated by the formation of a network of cracks, for reasons unknown, in the paint on the outer surface of the bulkhead. These cracks had allowed the ingress of chlorine-rich moisture, with consequent corrosion-attack of the gore panel outer face, causing stress raisers from which fatigue cracks subsequently grew in response to the cyclic pressure loading on the bulkhead.

After removal of the damaged material from the bulkhead (ie. the *rupture flap*), evidence of slight buckling deformation was noted on the gore panel in an area adjoining the lower edge of the rupture, ie on the opposite side to the origin region. This buckling was attributed to the rupture process, rather than pre-existing damage.

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

Incident involving an Air Canada L1011 in December 1990

This incident involved a rear pressure bulkhead rupture on the left side, close to the bulkhead-to-fuselage attachment frame, just above cabin floor level. The failure occurred in four stages:

i) Fatigue initiation in the gore panel at multiple sites along the butt join between the outer 1 mm thick doubler and an adjoining 2 mm thick doubler, caused by a manufacturing defect in the form of a 0.1 mm (0.004 inch) deep score line in the gore panel.

ii) Merging of the fatigue sites to form a region of circumferential fatigue cracking approximately 175 mm in length.

iii) Extension, by fast fracture, of the 175 mm long fatigue crack, increasing the total fracture length to approximately 450 mm circumferentially. At this point, the tear fractures were arrested by an anti-tear strap (at the top) and the presence of a doubler plate (at the bottom).

iv) After a significant period in this *arrested* state, sufficient to allow nicotine staining of the fracture faces to take place, the lower end of the fracture turned inboard and propagated radially inward in a single burst until it reached the next circumferential anti-tear strap, and was turned upward through 90º. During this process, the L shaped fracture in the gore panel flapped outward under the differential pressure loading. As the panel flapped outward, changes to the in-plane geometry of the gore panel caused the upper end of the fracture to break through the radial anti-tear strap, which up until that point had restrained it; however, the reduction in differential pressure locally prevented the fracture from progressing more than a short distance into the next panel.

That incident also highlighted difficulties experienced by certain passengers with the donning and use of the oxygen masks, and the related risk of hypoxia.

The associated AAIB investigation culminated in the publication of Accident Report No 3/91, which included the following Safety Recommendations:

- 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)

- 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 unpressurised) 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)

- 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 buttjoints between gore panel doublers. (Made 16 August 1991)

- 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)

Bulkhead failure sequence on G-BBAH

The absence of any significant corrosion pitting or other surface defects at the fatigue initiation sites, together with the presence of fatigue origins on both sides of the bulkhead, suggested that the fatigue cracking had been caused by stress reversals of a kind which would not normally occur on a pressure bulkhead of this type. In this connection, the presence of an *oil-can* type deformation immediately outboard of the fatigue initiation region was considered significant, insofar as it provided a mechanism whereby the bulkhead in the affected region would tend to adopt an 'S' shaped cross-sectional profile when relaxed (unpressurised), changing to a convex profile when pressurised. Such flexural changes would cause a ripple to run across the adjoining area as the oil-can deformation '*popped out*' under pressure loading, which in turn would have created stress reversals in the gore panel of the kind implicated by the fatigue growth. On the available evidence, therefore, the oil-can deformation of the bulkhead appeared to offer the most plausible explanation for the fatigue cracking which subsequently led to the bulkhead rupture.

There was no direct evidence of when the bulkhead deformation occurred. However, although not conclusive, the metallurgical evidence suggested that the fatigue cracks were not present when the bulkhead was last inspected 3,142 flight cycles prior to the failure. By implication, therefore, the bulkhead deformation was not likely to have been present for an extensive period before that time.

Access to the aft face of the bulkhead is extremely restricted and it would be easy for undetected deformation of the bulkhead to occur whilst engineering personnel gained access to the inside of the aft fuselage to carry out maintenance and inspection tasks in the area below the 'S' duct. In this regard, it is possible that inspection activities on the bulkhead carried out in response to the Cathay Pacific incident may themselves have introduced the observed bulkhead deformation on this aircraft.

Oxygen system

Although all the passengers eventually donned serviceable emergency oxygen masks, the system did not operate without problems.

For example, the oxygen supply tube on one of the passenger emergency masks in the rear vestibule was pulled right out of its housing in the ceiling panel. Inspection of the tube and its attachment fittings revealed no abnormality, and comparison of the tube's fit onto the discharge pipe in the housing was subjectively no different to that of the adjoining masks. It is possibly significant that this mask was situated immediately beneath the point where the bulkhead had ruptured; the noise and associated outrush of air possibly inducing a greater sense of urgency in the user of this mask than might have been the case elsewhere in the cabin, resulting in the tube being pulled with unusual vigour.

One passenger sitting towards the centre of the fuselage subsequently provided a detailed description of difficulties he had encountered. This passenger stated that when the masks had deployed, neither of the two masks above his head had dropped of their own accord from their stowage and he was obliged to stand up in order to pull them down. Having pulled his own mask down, he looked across to where his wife was seated (across the aisle from his own position) and saw that her mask had also evidently failed to drop, and that she was standing up, trying to reach the mask in order to pull it down. He tried to help her, but found that from his position in the aisle he could not reach it, and had to stand on the seat in order to pull it down. His wife then donned the mask and had no further problems.

However, when he returned to his own seat and attempted to use his mask, he found that he was unable to induce a flow of oxygen into it. He therefore tried the second of the two masks at his location, and found that this worked satisfactorily. Once settled, he studied the first mask which he had tried and noted that the tubing showed signs of having been folded tightly on itself, not *rolled up* as the others appeared to have been. He concluded that this had caused the tube to adopt *permanent* kinks at intervals along its length, restricting the oxygen flow when the mask had subsequently deployed.

This passenger also commented that although his (second) mask worked satisfactorily, the polythene bag attached to the mask did not inflate at all but instead remained with its sides *stuck together.* He also stated that a number of other masks (in addition to those at his own and his wife's positions) had failed to drop down out of their stowages, but as far as he could tell all of the stowage covers had opened successfully.

Subsequent interviews with the cabin crew revealed that, although all the oxygen mask stowage doors had opened correctly, a number of masks had failed to drop down out of their stowages; the exact number could not be accurately determined, but subjective views indicated at least 10%. Because of this, further enquiries were made to determine the periodicity and type of checks to which the passenger emergency oxygen system is subject. This revealed that the system is checked typically every 18 months, but the testing does not cover all the elements of the system. Generally, the testing consists of activating the emergency system but only after restricting the opening of all but a very few of the stowage doors, thereby stopping most of the masks from dropping; the few that are left unrestrained are at widely dispersed locations throughout the cabin. The rationale behind this test is that the covers are the most restrictive device and the dropping of the masks is a relatively simple action. Furthermore, the masks can be manually pulled down if they fail to drop. Additionally, the resetting of the masks, if they all dropped in test, would be a time-consuming exercise. There is also a possibility that the frequent refitting could result in a greater failure rate. Finally, a typical system on an aircraft would have 20% more masks than passenger capacity.

Safety Recommendations

As a result of the findings arising from this investigation, the following Safety Recommendations are made:

95-38: The Civil Aviation Authority and the Federal Aviation Administration, in conjunction with Lockheed should:

1. Review existing maintenance and inspection requirements, and if necessary instigate an in-service inspection of Lockheed L1011 aircraft aft pressure bulkheads, capable of reliably detecting:

i) fatigue cracking on the bulkhead structure

ii) *oil-can* deformations and other bulkhead abnormalities which could result in abnormal flexural modes in response to cabin pressure changes

2. Ensure that the attention of maintenance staff is drawn to the risks of subtle forms of damage being caused to the bulkhead structure, particularly in relation to the difficulty of gaining access to the aft face of the bulkhead and the risk of introducing *new* damage whilst carrying out inspections.

95-39: The CAA and FAA should consider recommending amendment of passenger briefings broadcast after emergency oxygen mask deployment to include reference to the possibility of smells of burning being produced by the normal operation of associated oxygen generator systems, where applicable.

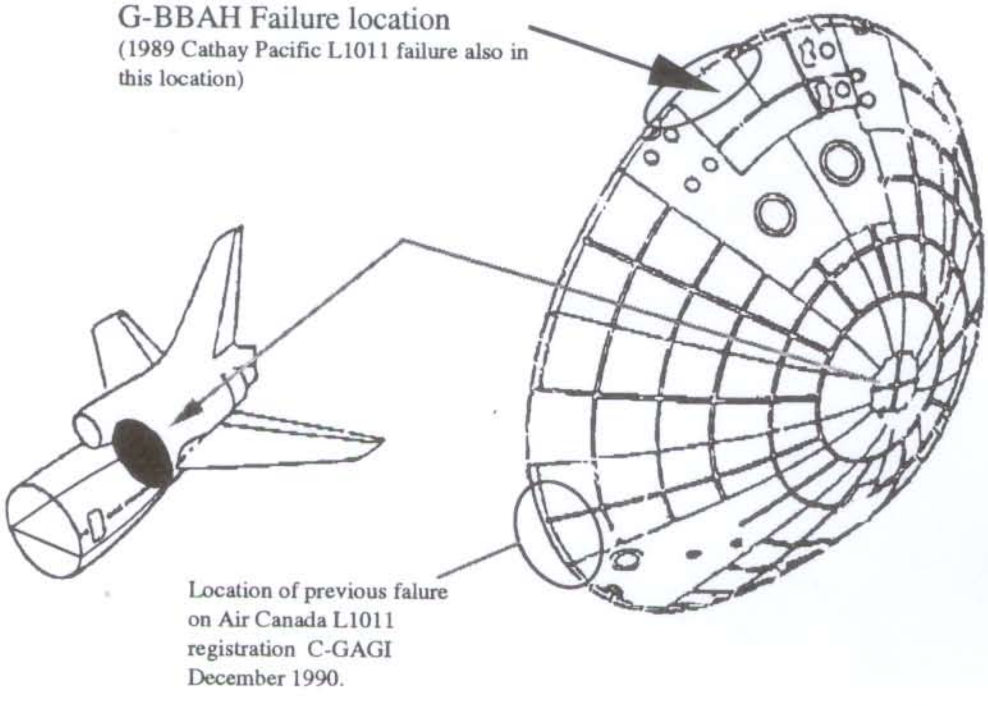
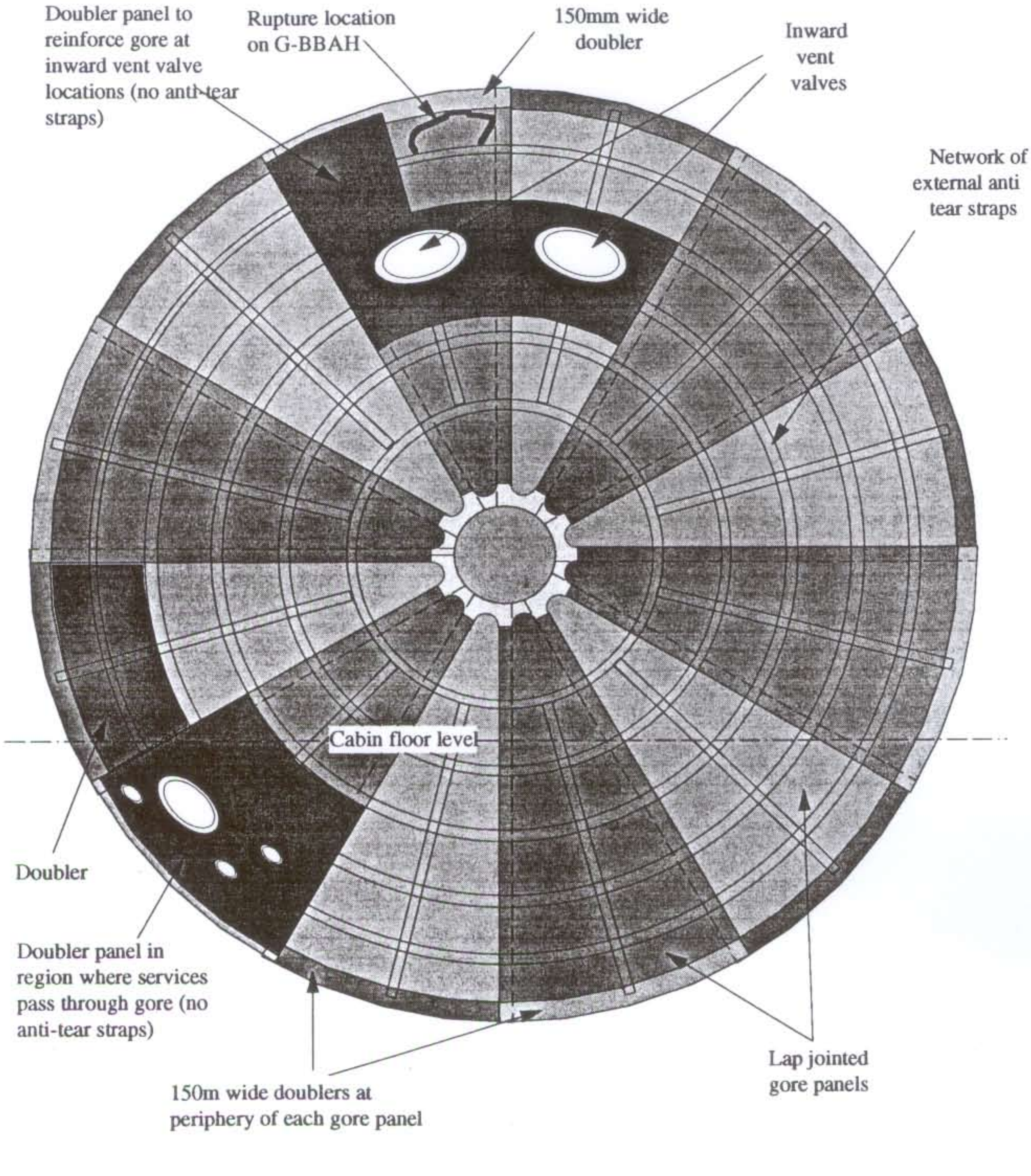

G-BBAH Failure location
(1989 Cathay Pacific L1011 failure also in this location)
Location of previous falure on Air Canada L1011 registration C-GAGI December 1990.

Figure 1



Doubler panel to reinforce gore at inward vent valve locations (no anti-tear straps)
Rupture location on G-BBAH
150mm wide doubler
Inward vent valves
Network of external anti tear straps
Cabin floor level
Doubler
Doubler panel in region where services pass through gore (no anti-tear straps)
150m wide doublers at periphery of each gore panel
Lap jointed gore panels

Figure 2

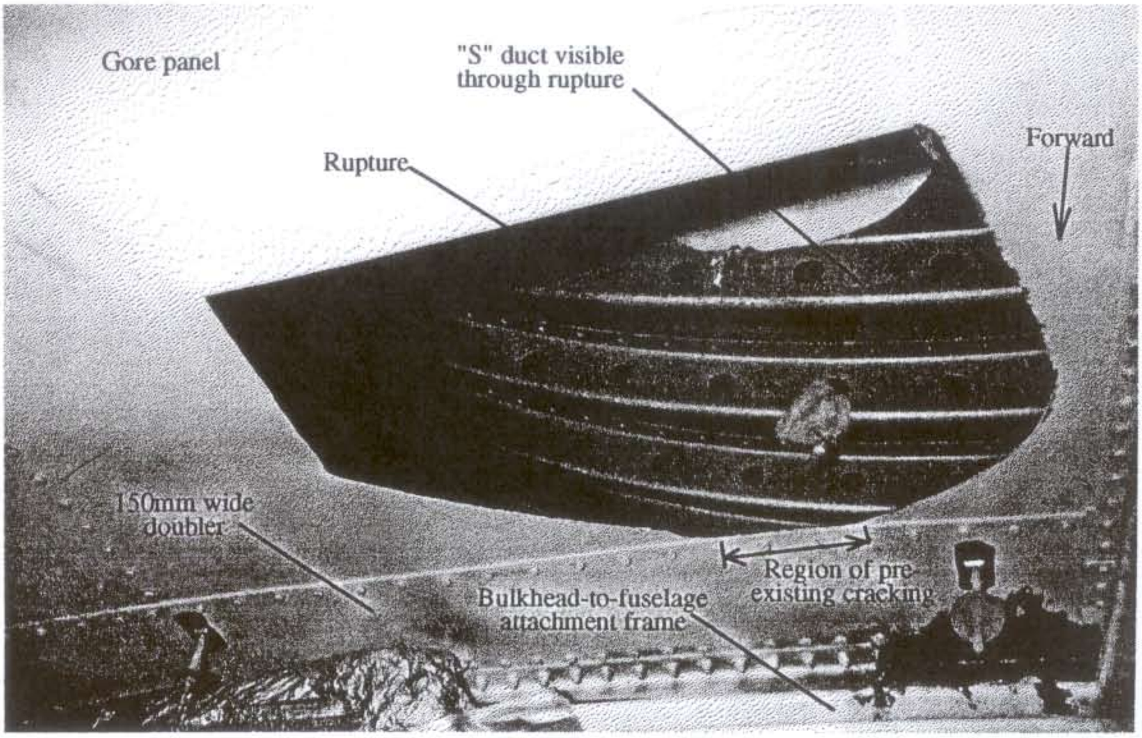


Figure 3
View looking up and foward from inside pressure hull

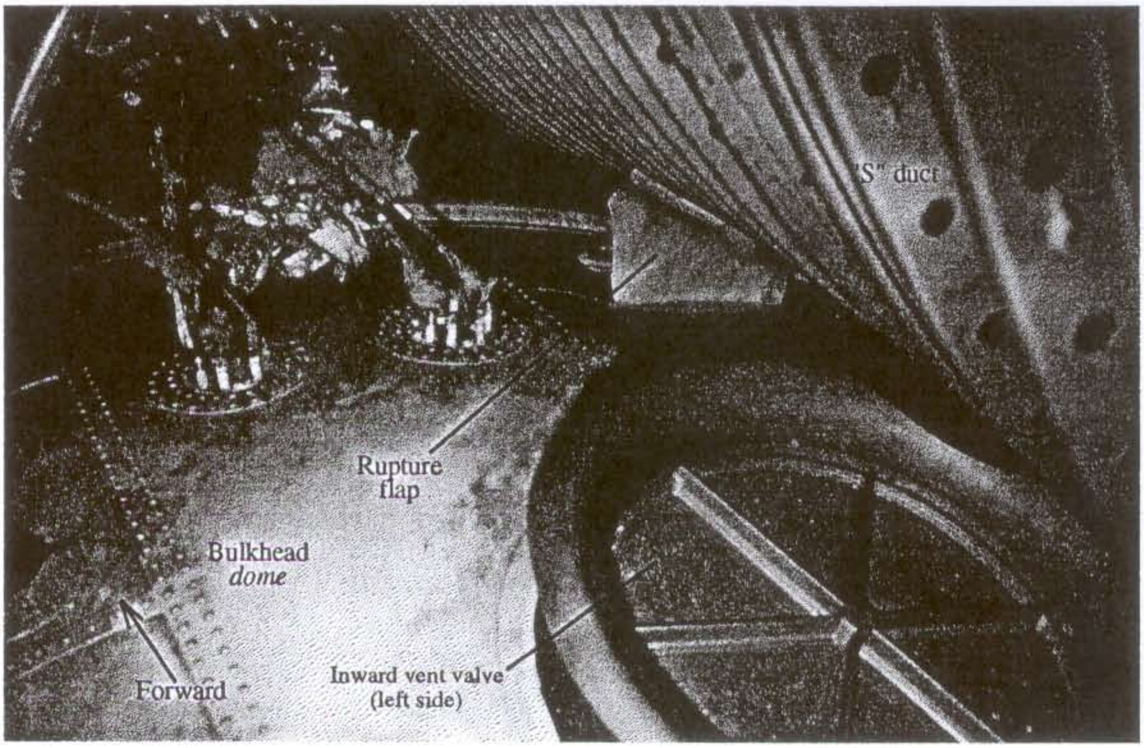


Figure 4
View forward onto aft face of bulkhead

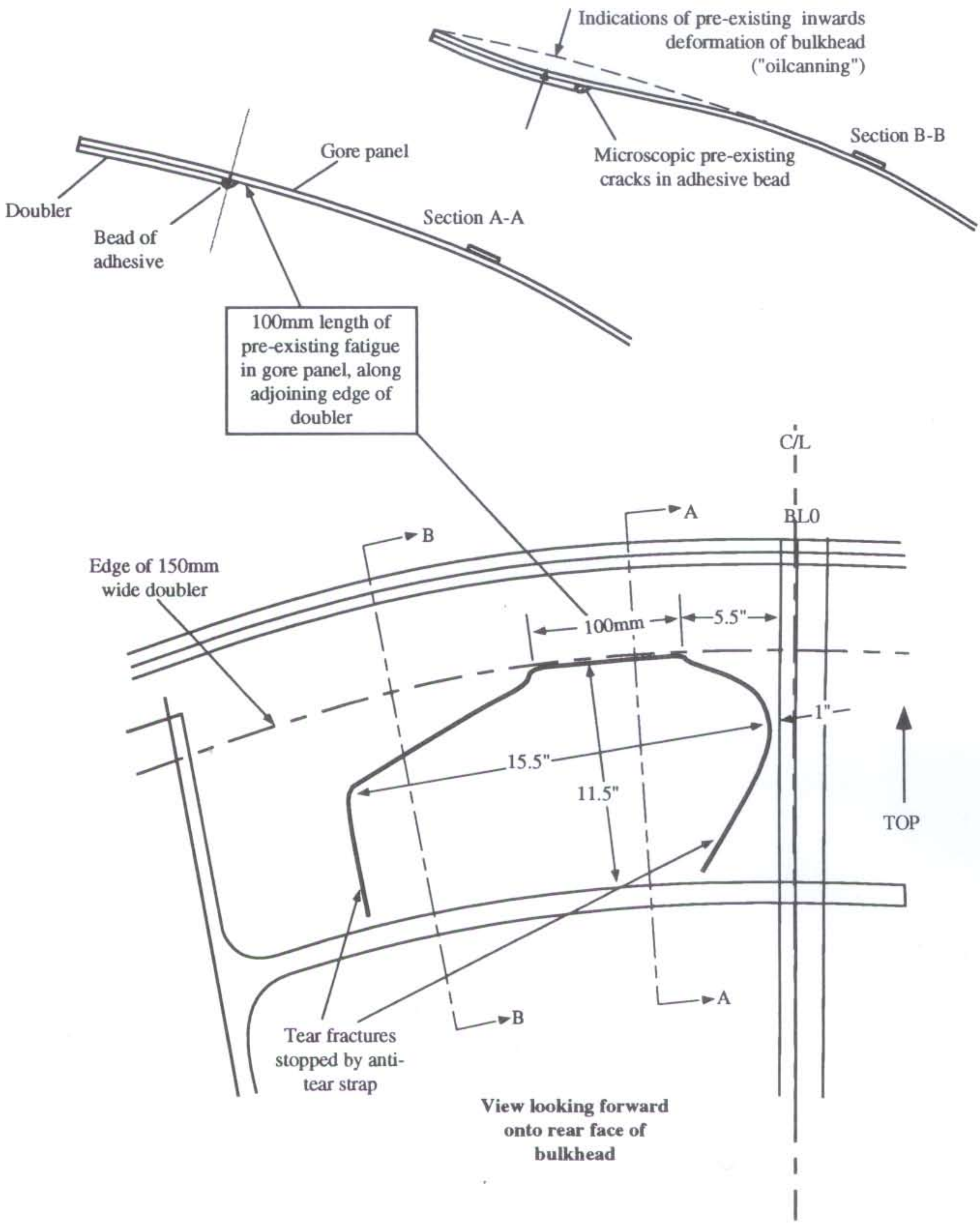

Indications of pre-existing inwards deformation of bulkhead ("oilcanning")
Section B-B
Microscopic pre-existing cracks in adhesive bead
Gore panel
Doubler
Bead of adhesive
Section A-A
100mm length of pre-existing fatigue in gore panel, along adjoining edge of doubler
C/L
A
BL0
B
Edge of 150mm wide doubler
100mm
5.5"
1"
15.5"
11.5"
TOP
Tear fractures stopped by anti-tear strap
B
A
View looking forward onto rear face of bulkhead

Figure 5