AIRCRAFT ACCIDENT REPORT 5/81

DEPARTMENT OF TRADE

Report on the accident to Boeing 747 - 121 N771PA at London Heathrow Airport, on 27 December 1979

LONDON
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Department of Trade
Accidents Investigation Branch
Kingsgate House
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17 July 1981

The Rt Honourable John Biffen MP
Secretary of State for Trade

Sir,

I have the honour to submit the report by Mr P J Bardon, an Inspector of Accidents, on the circumstances of the accident to Boeing 747 - 121 N771PA which occurred at London Heathrow Airport, on 27 December 1979.

I have the honour to be
Sir
Your obedient Servant

W H Tench
Chief Inspector of Accidents

Accidents Investigation Branch
Aircraft Accident Report No: 5/81
(EW/C 687)

Operator:		Pan American World Airways Inc
Aircraft:	*Type:*	Boeing 747
	Model:	- 121
	Nationality:	United States of America
	Registration:	N771PA
Place of Accident:		London Heathrow Airport Runway 23 Latitude: 51° 29′ North Longitude: 00° 27′ West
Date and Time:		27 December 1979 at 1839 hrs All times in this report are GMT

Synopsis

The accident was notified to the Accidents Investigation Branch at 1910 hours on 27 December 1979 and an investigation was commenced that night. The United States Accredited Representative together with his advisors arrived in London the following day and participated fully in the investigation.

The accident happened whilst the aircraft was being landed on runway 23 at London Heathrow Airport. At touchdown the number 4 pylon forward bulkhead, which supports the front of the engine, began to break free of the pylon because of weakening by fatigue and other pre-existing damage. The resulting downward movement of the engine during the landing roll ruptured the engine fuel feed pipe and several other connections with the engine including engine monitoring and fire warning circuitry. The high volume of fuel issuing from the ruptured fuel pipe caused a severe fire to develop under the number 4 pylon. The fire continued until the crew physically observed the fire as the aircraft was being turned off the runway at block 77(0), at which point the fire drill was carried out. This resulted in the closure of the fuel shut-off valve in the wing. The aircraft was brought to a halt and the airport fire service quickly brought the residual fire under control.

The report notes that the number 4 engine was involved in a collision with a baggage container (igloo) at Chicago Airport 3 years prior to the accident. It concludes that this collision may have been the initiating event in the chain of structural breakdown which culminated in the separation of the pylon forward bulkhead, which was the direct cause of the accident.

The report analyses the bulkhead failure and concludes that the failure of the bulkhead did not arise from any defect of design or deficiency in the certification process. However, deficiencies in the approved maintenance inspection procedures, are considered to have contributed to the defect in the forward bulkhead progressing to the point of failure.

The report reviews the concept whereby the pylon is designed to separate cleanly at a pre-determined load level in order to protect the wing structure from damage. The concept itself is not questioned, but the lack of any form of automatic fuel shut off that would operate coincidentally with pylon or nacelle separation is criticised and a recommendation is made to that effect.

1. Factual Information

1.1 History of the flight

The aircraft was engaged in a scheduled international cargo flight from JFK airport, New York to London Heathrow. The only occupants were the three flight crew members, namely the commander, co-pilot and flight engineer. The aircraft departed from New York at 1201 hrs on 27 December and after an uneventful flight, was landed manually by the commander on runway 23 at Heathrow at 1839 hrs. After a heavy touch down, the commander applied reverse thrust and the flight data recorder (FDR) read out indicated that maximum reverse engine pressure ratio (EPR) was obtained on all four engines. Shortly afterwards the flight engineer reported that the exhaust gas temperature (EGT) was approaching limits on No 4 engine, whereupon the commander began to reduce reverse thrust on all engines. As he did so, he felt the No 4 thrust lever give a sudden jerk and thereafter become immoveable. After reverse thrust had been cancelled on the other three engines, it became apparent to the crew that No 4 was not delivering reverse thrust, notwithstanding the position of the thrust lever. All the instrument indications were that the engine had run down and flamed out. The FDR read out showed that No 4 engine had ceased to deliver reverse thrust some 15 seconds after selection and some 10 seconds before reverse was cancelled on the other three engines. The Indicated Air Speed (IAS) at the time reverse thrust was lost on No 4 was 80 kts. Whilst the aircraft was moving slowly clear of the runway to the right, the co-pilot observed a large fire in the region of No 4 engine, although there was no fire warning indication of this on the flight deck. The co-pilot immediately reported the fire to Air Traffic Control (ATC) who had by then already activated the crash alarm. The crew carried out the engine fire drill and stopped the aircraft clear of the runway on a link taxiway at Block 77(0). The other engines were shut down. The fire was brought rapidly under control by the airport fire service which arrived on the scene as the aircraft cleared the runway. An emergency evacuation was therefore considered by the commander to be unnecessary.

1.2 Injuries to persons

Nil

1.3 Damage to aircraft

There was substantial damage to the No 4 engine support structure and also fire damage to the outer starboard wing, engine and pylon fairings.

1.4 Other damage

Nil

1.5 Personnel information

1.5.1 (a) Commander: Male age 58 years.

Licence: Airline Transport Pilot issued on 19 November 1976. A First class medical certificate was last issued on 17 July 1979.

	Aircraft ratings: DC4, DC8, C46, B707, B720, B727, B747.
Flying experience:	Total on all types: 29,800 hours. Total on the B747: 1,423 hours.
(b) Co-pilot:	Male aged 44 years.
Licence:	Airline Transport Pilot issued on 26 April 1973. A First class medical certificate was last issued on 12 July 1979.
	Aircraft ratings: DC8, B707, B720, B747.
Flying experience:	Total on all types: 8,159 hours Total on the B747: 3,559 hours
(c) Flight engineer:	Male aged 56 years.
Licence:	Commercial Pilot issued on 1 April 1965. Flight Engineer issued on 12 April 1967 rated for turbojet powered aircraft. A Second class medical certificate was last issued on 16 March 1979.
Flying experience:	Total on all types: 18,634 hours Total on the B747: 4,642 hours.

1.5.2 *Rest and duty periods*

Each crew member had been on duty for 7 hours 39 minutes at the time of the accident. Prior to reporting for duty at New York, each crew member had had a rest period of at least 24 hours.

1.6 Aircraft information

1.6.1 *General information*

(a) Type: Boeing B747-121 - Freight Transport

(b) USA Registration: N771PA

(c) Serial No: 19661

(d) Date of manufacture: 1 August 1970

(e) Registered owner: Pan American World Airways Inc since 20 August 1970.

(f) Certificate of Airworthiness: dated 1 August 1970. Validity subject to the aircraft being maintained in accordance with approved maintenance procedures.

(g) Conversion to cargo configuration: 30 May 1975

(h) Total airframe hours: 34,615

(i) Total cycles: 9,505

(j) Total hours No 4 pylon: 34,615

(k) Type of engines: 4 Pratt and Whitney JT9D-7D

(l) No 4 engine: Serial No 662388
Manufactured: 9 February 1970
Installed in
N771PA: 2 September 1979
Hours since installation: 1,269
Hours since major overhaul: 1,269
Hours since new: 27,924

1.6.2 *Aircraft weight and loading*

The maximum permitted take-off weight was 749,000 lbs and the maximum landing weight was 630,000 lbs. Actual weights were 743,000 lbs and 574,000 lbs respectively. The permitted range of the Centre of Gravity (CG) was between 15% and 31% of Mean Aerodynamic Chord (MAC). CG position was 21% MAC at landing.

1.6.3 *Maintenance*

A review of the maintenance history of N771PA found that the aircraft had been maintained in accordance with approved maintenance programmes under existing Federal Aviation Regulations. All applicable Airworthiness Directives (AD) were recorded and had been complied with, and service difficulty reports and mechanical interruption summary reports were in order. The aircraft maintenance logs were examined in detail for a period of six months prior to the accident. The review noted a number of discrepancies recorded relating to No 4 engine reversal. Also on 9 August 1978 the forward and aft upper mount fittings were found to possess "excessive" play during the pre-installation inspection of No 4 engine. On 6 January 1979 during the engine pre-installation inspection of No 4 pylon the inspector observed missing bushing and excessive play in the forward mounts and that excessive play existed in the aft upper mount fitting. The aircraft was cleared to fly in this condition until the next engine change. An unscheduled engine change was carried out on 26 August 1979 when a "loaner" engine from another airline was installed as a result of high exhaust gas temperature on No 4 engine. On 2 September 1979 the aircraft returned to JFK where the "loaner" engine was removed and replaced by the unit which remained in service until the accident. At this time the aft engine mount was found to be beyond manufacturer's limits and a repair was carried out involving the installation of new bolts and bushings in the pylon strut aft mount to reduce the play within permissible limits. A replacement aft engine mount fitting was ordered, which was programmed for installation at the next scheduled engine change.

The Pan American maintenance inspection schedules with respect to the pylon structure require it to be inspected both externally and internally, but the forward 'doghouse' fairing, which covers the front face of the forward bulkhead, was not scheduled for removal as a preliminary to these inspections. The interior of the pylon was inspected via the nacelle equipment access doors (NEAD), and these permit the rear face of the forward bulkhead only to be viewed. The forward fairing is scheduled for removal for the internal inspection of the fairing itself and also its latching mechanism, part of which is located on the forward face of the forward bulkhead. The locking mechanism of the bolts on the forward mount are "key pointed" during this inspection. There is no structure inspection of the forward bulkhead that specifically addresses the forward side of the forward bulkhead. However, it is understood that it is frequently examined on an opportunity basis, together with other areas of the aircraft's structure, at times not necessarily dictated by the inspection schedule.

The inspections scheduled during power plant removal/replacement do call for a detailed structural inspection of the horizontal and vertical firewalls, i.e. the forward bulkhead and the forward spar web, and these are carried out approximately every 2,575 flight hours, this being the average engine removal time.

The NEADs were removed during the B19 check on 12 December 1979 during which time no discrepancies were noted. The forward fairing was last removed during a C–7 inspection of 8 June 1979, again with no recorded discrepancies. The aircraft had not been included in the Pan American strut sampling programme during the six month period prior to the accident.

The Boeing 747 Maintenance Program Development (BMPD) is derived from the Handbook Maintenance Evaluation and Program Development MSG–1 and the FAA MRB Report, Boeing 747/747 SP Maintenance Program. The airline maintenance programme is, in turn, derived from the BMPD. The BMPD requires a number of inspections of the forward bulkhead region and these are as follows:

(i) check engine mount support fittings and thrust links via the NEAD.

(ii) check nacelle strut interiors, firewalls and sealant (ribs, spars and fittings) electrical, tubing etc via the NEAD.

(iii) a leak check of the horizontal fire walls at 20,000 hours.

(iv) check fail safe bolts (forward mount).

(v) check engine mounts, fireseal, cowl support structure, component heat shielding and drag struts.

The BMPD defines a check as a thorough examination of an item, component and/or system for general condition, as applicable, with special emphasis, *inter alia,* on proper attachment, fasteners, obvious damage and cracks.

The leak check referred to in the BMPD schedule involves the flooding of the lower forward firewall area in order to check the integrity of the joints between the spar web and the adjacent chord members. This inspection did not form part of the Pan American inspection schedule until mid 1978. It had not been performed on N771PA up to the time of the accident, though it was scheduled to be carried out at a later date.

1.6.4 *B747 engine and strut design criteria*

The ultimate design load factors for the JT9D engine and pylon installation in every case exceed those set out in Part 25 of the Federal Aviation Requirements (FAR). In the case of landing loads, the structure is assessed as "not critical" against the FAR Part 25 requirement of 10 ft/sec vertical velocity. The nacelle and pylon structure was designed to accept reverse thrust loads multiplied by a factor of 2.5.

The maximum design load of the front engine mount on an outboard pylon is 61.7 KIPS in the downwards direction. A typical vertical load peak on touch down is approximately 10 KIPS which increases with the application of reverse thrust to approximately 15 KIPS. The greatest in-flight loads on the forward mount in the downwards direction are met during the descent when the engine thrust is at a minimum.

1.6.5 *Previous incident*

The aircraft was in collision with a baggage igloo at Chicago airport on 5 November 1976, resulting in light damage to the No 4 engine nacelle. At the time the aircraft had flown 22,696 hours and 6,295 cycles.

1.7 Meteorological information

After the accident, the Meteorological Office provided an appreciation of the weather at Heathrow for the relevant period. The appreciation contained the following information:

General situation:	Warm sector conditions with a strong moist SW airflow over the London area.
Weather:	Moderate rain.
Cloud:	8/8 nimbostratus at 1500 ft with varying scattered to broken stratus at 1000 ft below the nimbostratus.
Visibility:	5 kms
Wind:	The anemometer readings from the site nearest the point of touch down indicated a relatively steady wind in the period immediately preceding the landing. Average wind values measured at 30 second intervals for the two minutes leading up to the moment of touch-down were as follows:

203°/24 kts
202°/20 kts
204°/18 kts
200°/18 kts

A gale warning was in force as was SIGMET information regarding occasional severe turbulence.

The latter was included in the broadcast by the Automatic Terminal Information Service (ATIS) which the crew had received before commencing their approach to land. After the accident, the crew reported that wind and turbulence had not presented any problem during the approach and landing.

The accident occurred during the hours of darkness.

1.8 Aids to navigation

Not relevant.

1.9 Communications

Before the aircraft's approach ATIS information had been satisfactorily received and communications established in turn with Heathrow Approach on 119.5 MHz, Heathrow Director on 120 MHz and Heathrow Tower on 118.7 MHz, the latter frequency being the one in use at the time of the accident. After they had closed the engines down the crew were advised that the Flight Deck/Fire Service Communication Frequency of 121.6 MHz was available, but although they acknowledged this message, no communication on that frequency was subsequently established, presumably because the flight deck was evacuated shortly afterwards.

1.10 Aerodrome and ground facilities

Heathrow Airport is at an elevation of 80 feet and has three runways, 28L/10R, 28R/10L and 23/05. At the time of the accident single runway operation was in force, using Runway 23, but with Runway 28L available on request. Runway 23, the one used by N771PA, is 2,357 metres long and 91 metres in width, with the whole length available for landing; construction is of concrete. Approach lighting consists of high-intensity centre-line lights, with four cross-bars; threshold lights are low-intensity greens, and runway lights are high intensity bi-directional edge lights. Visual Approach Slope Indicators (VASIS) and three-bar VASIS are both installed, and both set at 3.

At the time of the accident all lighting systems were operating and serviceable. The runway was wet.

1.11 Flight Recorders

1.11.1 *Flight data recorder (FDR)*

The aircraft was fitted with a Lockheed 209 digital flight data recorder, to ARINC 573 standard. It was mounted in the aft equipment bay in the pressurised cabin. Twenty parameters plus 27 discrete switch positions were recorded. Readout was carried out at the premises of the NTSB in Washington DC, as facilities did not exist in the UK. The whole 25 hour record was replayed, outputting a limited number of parameters, in order to check if any heavy "g" loads had been encountered and in fact none had. A full replay of all parameters was carried out for the descent on the accident flight. The replays obtained were of very good quality with few "dropouts".

The FDR indicates that the aircraft touched down with about 1.5 degrees of nose-up pitch and 4 degrees of bank angle to starboard and at a speed of 140 kts IAS. The peak normal acceleration recorded on touchdown was 1.55 g although as the sampling rate was only 4 per second it is possible that the maximum normal acceleration experienced was slightly higher than this. A hard landing is one involving a normal acceleration in excess of 1.7 g. The peak lateral g recorded was 0.12 to port and the descent rate on touchdown (from the radio altimeter) was 540 ft/min.

By some 3 to 4 seconds after touchdown all four thrust reversers had been deployed and maximum reverse EPR was obtained some 6 to 9 seconds after touchdown. Between 12.5 and 16.5 seconds after touchdown No 4 engine EPR reduced and the reverser position indications for that engine reverted to stowed, without any in transit indications. The aircraft continued its run with 3 engines in reverse thrust until some 26 to 28 seconds after touchdown when the EPR was reduced and the reversers on engines 1 and 3 were stowed by 50 seconds after touchdown. The indications were that engine 2 reverser remained in the deployed position.

1.11.2 *Cockpit voice recorder (CVR)*

A Fairchild A100 CVR was fitted to the aircraft and was mounted beside the FDR. The last 3 minutes of the recording, which was of fair quality, were transcribed.

1.12 Examination of Wreckage

1.12.1 *Preliminary examination*

The aircraft was examined at the Pan American maintenance hanger at London Heathrow during the early hours of 28 December. The aircraft had suffered damage to the starboard wing as a result of fire. This damage was confined to the structure in the general area aft of the No 4 engine. The trailing edge honeycomb and composite structure was extensively burned and the lower wing skin was buckled as a result of heat.

The engine had broken away from the pylon at the forward end but had remained attached by its rear mount.

Since the damage was clearly localised, a detailed examination of the whole aircraft was not undertaken. Small pieces of debris from burned control surfaces, wing trailing edge panels and engine cowling were recovered from the runway surface and also on the grass area adjoining Block 77(0) where the aircraft had come to rest. There were no witness marks that could be associated with the aircraft in the touch down area.

The only ground mark was a slight scrape in the grass adjacent to Block 77(0) just short of where the aircraft was stopped. This scrape was in a position and of a character which could only have been produced by a light contact between the underside of No 4 nose cowl and the ground. There were no anomalies in the flight deck settings, all of which were compatible with the events which took place. The No 4 thrust lever was still jammed in the reverse thrust position. The No 4 fire extinguisher handle had been pulled and the other power unit extinguisher handles were normal. The No 2 thrust reverse mechanism was still deployed, which was at variance with the cockpit lever setting, but this is not considered relevant to the accident.

1.12.2 *Power plants examination*

1.12.2.1 *Nos. 1, 2 and 3 power plants and pylons*

These power plants were not examined, but the forward bulkheads of the pylons at these stations were inspected. On No 2 pylon, three loose lock bolts were found and on No. 3 pylon, five loose lockbolts. The pylons were otherwise free of significant defects.

1.12.2.2 *No 4 engine – general*

The No 4 engine was examined externally both prior to and after removal at London Heathrow. With the exception of fire damage and the distortion of the rear upper section of the jet pipe resulting from the "binding" in this area following the dropping of the front of the engine, nothing abnormal was observed. The fan cowl was found to carry a label stating that the cowl should not be used on outboard engines, but following enquiries addressed to the Boeing Company and to Pan American at their New York facility, it was established that the requirements dictating this restriction had been removed, but the cowl label had not. The engine was examined following removal to establish whether there had been any seizure which might have caused a sudden stoppage sufficient to overload the pylon. Since the engine could be turned manually from the fan end and the HP stage turned by the crank socket used for bore scope examination, the possibility that an engine seizure could have caused the pylon failure was therefore discounted.

The engine was subsequently shipped to the Pan American engine overhaul facility at New York where it underwent detailed strip examination under the direction of the National Transportation Safety Board (NTSB). No defects or abnormalities which could have had any bearing on the failure of the pylon were found.

1.12.2.3 *No 4 engine - configuration*

The thrust reverse system was in the fully retracted position. The system is operated by bleed air from the engine compressor and is fairly rapid in operation. The system would be capable of retracting the reverse thrust mechanism on the air pressure available during rundown after a flame out.

1.12.2.4 *No 4 engine - installation*

The engine forward mount was intact and still attached to the forward bulkhead which had torn free from the pylon. No abnormalities were noted on the engine mount assembly. However, a number of bolts securing the engine mount fittings on the forward bulkhead were loose, some to the extent that they could be turned easily by hand.

The rear mounting comprises a system of links which, in combination, carry vertical, side, thrust and torque reaction loads, but do not provide any yaw restraint or pitching restraint, these loads being reacted by the front mount.

The rear engine mounting remained intact in so far as the engine was restrained adequately. It did, however, partially fracture as a result of the short couple wrenching loads induced in it following the forward bulkhead detachment. This short couple produced overload failures in 2 of the 3 links on the left side of the mount and distortion of the rear mount ring frame on the engine adjacent to the right hand vertical links. The damage sustained was such that very little additional load would be required to produce complete failure of the rear mount.

1.12.2.5 *Engine controls - No 4 engine*

The engine control teleflex cable to the No 4 engine had fractured at the pylon/engine interface as a result of the separation of the bulkhead, which allowed the engine to drop. The cable inner and outer sections were jammed together at the point of fracture. The engine control cable system was checked between the pylon teleflex unit and the cockpit pedestal lever and found to be satisfactory.

1.12.2.6 *Engine fire detection and extinguishing systems*

The engine fire detection system was rendered inoperative by the disruption of the wiring following the partial detachment of the engine. Those fire extinguisher bottles which were operated by the No 4 fire handle were checked and found to be in a discharged state, suggesting that the fire extinguishing system had functioned normally, except for the disruption of the extinguishant plumbing to the engine bay caused by the partial engine detachment.

1.12.2.7 *Exhaust Gas Temperature (EGT) System*

The EGT gauge wiring to the cockpit from the pylon was checked and found to be satisfactory and the EGT gauge was subsequently operated normally.

1.12.3 *Examination of the pylon structure (Reference Appendix A)*

The No 4 pylon forward bulkhead had fractured permitting the front of the engine and the bulkhead, with the forward fairing still attached, to drop until the fan cowl was approximately 6 inches from the ground. The failure of the pylon bulkhead which carries the forward engine mounting had occurred as a result of three separate failure mechanisms:

(1) fretting and wear at the joint between the lower bulkhead chord and the forward spar web,

(2) fatigue cracking in the bend radii of each of the lower ends of the bulkhead "horse-collar" chord, and

(3) overload tear type failure extending upwards from the fatigue cracks and across the upper region of the bulkhead diaphragm, forming an inverted "U" fracture which resulted in complete detachment of the bulkhead.

The mating surfaces of the inconel spar web and the titanium "L" section chord were very extensively worn with heavy "galling" of the surfaces. The holes in the spar web which accommodate the 23 solid monel rivets were all extensively worn to an oval or a kidney shape, with the maximum diameter of the worn holes being in the order of 0.030″ to 0.070″ oversize on the original 0.187″ diameter. The under surface of the web had been worn by the heads of the rivets, producing a lightly dished counter-sink effect, and a number of the holes had significant burrs thrown up around their circumferences on the upper surface of the web. The corresponding holes in the bulkhead chord contained the rivet shanks which were still tightly held with no sign of movement, but the section of shank which passed through the web was completely worn away leaving domed or conical shaped rivet stubs protruding. The profile of the rivet stub protrusion when viewed along the plane of the spar web took the form of a smooth curve with maximum protrusion of 0.075″ at the centre reducing to zero at the ends.

The lockbolt holes at each end of the bulkhead chord were, with two exceptions, very extensively worn and the corresponding holes in the spar web and the forward ends of the spar chord were similarly worn. The degree of ovality of these holes was as much as 0.060″ in excess of the original diameter, but one hole was completely unworn and another had just perceptible wear. The hole profile through the bulkhead chord showed a greater degree of wear at the top of the hole than at the bottom producing a tapered hole profile. There was also very extensive wear of the upper edges of these holes producing a deep counter-sink effect, which on first examination could be mistaken for intentional counter-sinking during manufacture. A number of lockbolts were recovered from the interior of the pylon adjacent to the bulkhead. None of these was complete; one had an undamaged shank but the tail of the bolt had fractured at the neck and the fracture surface was polished, suggesting that it had broken some time ago and had been tumbling around inside the pylon. Another was complete except for its retaining collar, which had been pulled off leaving a sheared out ring of collar material still in situ in the neck of the bolt. The head ends of four other bolts were found; all were extensively worn on the shank diameter producing a "necking" down to about 0.15″ diameter and with the tail sheared off at the point of greatest wear. The heads of these bolts were also extensively worn on the undersides, with the corners of the heads worn to a shape approximating to that of a rounded counter-sink bolt. A number of steel washers were also found, all of which were worn on the upper surfaces to a profile which could be matched to the wear profile of the lock bolts. In addition, the most worn washers were also heavily dished in a manner which exactly matched the counter-sink wear of the upper regions of the lock bolt holes in the bulkhead chord. Each of the worn lockbolts and washers could be positively matched to the bulkhead chord to spar joint using the wear profile. In the case of the bolts with no shank wear, circumferential ring marks on the shank could be matched with the interfaces of the bulkhead chord to spar web, and spar web to spar chord.

Fatigue Failure

The horse collar chord was found to have fatigue cracking extending upwards for a distance of 2.5 inches in the bend radius on the port side of the chord and 1.9 inches on the starboard. The cracks, which were similar, had a number of small secondary branches and had grown from multiple origins on the inside surface of the chord, indicating that the fracture had propagated as a result of a plate bending mode of flexure. There was evidence of similar fatigue cracking in the light alloy doublers which adjoin the inside of the lower ends of the chord. The fatigue fracture faces were damaged because of relative movement before final failure and because of this and the absence of flight load data, it was not possible to carry out any quantitative analysis of the cracks.

Tear Fracture

The tear failure of the upper region of the horse collar chord and the upper bulkhead diaphragm occurred as a result of overload in a downwards direction with some degree of load component inboard.

Materials

Hardness checks on the materials involved did not reveal any significant deviations from specification.

1.13 Medical aspects

Not applicable.

1.14 Fire

There was a severe fire resulting from the spillage of fuel from the ruptured engine fuel feedpipe. The fire caused severe damage to the wing underside in the region aft of and outboard of the No 4 pylon. The wing damage comprised buckling of the interspar skin due to heat and considerable burning of the honeycomb trailing edge structure and flying control surfaces.

The whole of the aft section of the engine side cowl was burned heavily on the underside, leaving only the remnants of the frames and inner skinning.

The inside of the engine side cowl, just below the point where the fuel pipe and control unit teleflex cable entered the engine, was distinctly sooted but there were no signs of extreme heat.

The fire was not indicated in the cockpit because of the severance of the fire detection system wiring. The crew operated the fire extinguisher handle for No 4 engine when they saw the fire from the cockpit window. This action closed the low pressure fuel shut-off valve in the wing which stemmed the flow of fuel feeding the fire. The airport fire services intervened very quickly and extinguished the fire. The disposition of burnt debris on the ground indicates that the greater part of the fire damage occurred after the aircraft had slowed down and come to a halt.

At Heathrow the main Fire Station is on the north side of the aerodrome, with a sub-station in the central area, near the end of Pier One, not far from Block 77(0), where the aircraft cleared the runway. ATC alerted the Fire Service at 1839 hrs, just before the aircraft declared the emergency. Appliances at the sub-station consisted of one Rapid Intervention Vehicle (RIV) and two Nubian Major Foam Tenders, each of 1800 gallons water capacity. The vehicles from the sub-station reported themselves in action at 1841 hours. The appliances from the main station, consisting of two Nubian Majors, two RIVs and a Land Rover were in attendance by 1844 hrs by which time the fire was apparently out. The vehicles from the sub-station had employed 40 gallons of Fluro-protein foam and 15 gallons of Aqueous Film Forming Foam to deal with the fire and continued to play water on the area of the fire as a cooling medium. Total consumption of water was 3,800 gallons; the vehicles from the main station did not need to employ any media or water.

As soon as the alarm was received at the Fire Station, the Watchroom employed the alarm system to call in the London Fire Brigade and the London Ambulance Service. The first of these vehicles was at Rendezvous Point south by 1848 hrs, near the threshold of Runway 05 and all were in attendance at the scene of the accident by approximately 1905 hrs. A total of 15 appliances and 7 ambulances were provided by these two organisations.

1.15 Survival Aspects

Since the fire was brought rapidly under control, due to some extent to the close proximity of the airport fire service sub-station to the scene of the accident, there was no need for an evacuation by the crew using the emergency equipment. Survivability was therefore not a factor.

1.16 Tests and research

1.16.1 *Further research*

Fretting and Wear Properties of Inconel, Titanium and Monel

Attempts were made to obtain reliable data on the fretting rate and wear rate of inconel against titanium and inconel against monel. Although data does exist for fretting rates of titanium against titanium and inconel against inconel, it was not possible to interpret this data to give a quantitative estimate of the fretting and wear rates for titanium against inconel and inconel against monel. The data did, however, suggest that the fretting and wear rates would be high, and would probably be generally similar to titanium against titanium.

Possible thermal effects

Calculations were made to explore the effects of differential expansion on the rivets, bolts and the material sandwich making up the bulkhead lower chord to spar joint. It was found that the temperature induced stresses in the rivets and bolts were such that no permanent deformation of the joint would occur as a result of the temperature changes likely to be encountered by the bulkhead.

Calculations of Operating Stresses in the Spar

Check calculations were made to establish the stresses in the forward bay of the spar. It was found that this region of the spar had adequate strength reserves and that the zone of the forward spar which would fail first under increasing sideload would either be the bulkhead lower chord to spar joint, or, possibly, the spar web in the forward bay, which could buckle. The bearing strength of the web was found to be closely matched to the shear strength of the fastener group joining the spar web to the bulkhead.

1.17 Additional information

1.17.1 Cracked pylon on British Airways 747 Registration G–AWNA

Following the accident to N771PA information came to light detailing a similar failure on a British Airways 747. It would appear that on 1 October 1976 a crack was discovered in the left side of the horse collar chord on the No. 4 pylon. There was no immediate explanation for the crack and an in-house decision was made to stop drill as a temporary measure for further action at the Inter Supplementary Check with continuous monitoring at London Overnight Transit (LOT) checks for progression of the cracks in the interim. On 22 March 1977, during the subsequent Inter Supplementary Check, the crack was assessed as having not progressed beyond the stop drill hole and the defect was carried forward for reassessment at the next major check, which was at that time scheduled for November 1977. In the interim the LOT Checks were to be continued to monitor for crack progression. For some reason which is not clear the bulkhead was not monitored and on 20 January 1978, during an engine change, the bulkhead was found to be cracked in the order of 4½ inches on the left side and 6 inches on the right side. In addition there were reports of "sheared" fasteners on the bulkhead lower chord to spar joint and buckling of the forward bay of the spar web. The bulkhead was replaced and the spar web and lower bulkhead chord repaired. The damaged horse collar chord was returned to Boeing for their evaluation, and Boeing telexed a reply on 3 March 1978 advising that the review of the hardware and damage indicated that "an overload started the fracture and continuous low cycle fatigue propagated damage". The telex also indicated that there had been no previously reported case and that the buckled lower spar web indicated a severe side load had been encountered. It was later established that on 25 February 1974, whilst the aircraft was parked on the apron at New York, the intake cowl of No. 4 engine was struck by an oil servicing vehicle causing light damage. At the time of this incident, the aircraft had flown a total of 9,460 hours. When the crack in the horse collar was first discovered in October 1976, the aircraft had flown 19,703 hours. On 20 January 1978, when the crack was found to have progressed beyond the stop drill hole and a further crack was found on the right side, the aircraft had flown 25,194 hours.

1.17.2 Pylon manufacturing techniques (Reference Appendix B)

Although Boeing designed the pylon and retain full design authority, the pylons for the 747 are all built under sub-contract by Rohr Industries Inc. Because the build technique could have had a bearing on the failure of the forward bulkhead, the method of assembly was examined. The forward section of the pylon is built up as follows:-

(1) The spar web, chords and web stiffeners are joined at the ends of the stiffeners by lockbolts.

(2) The spar assembly is placed in a "drive – matic" automatic rivetting machine. This machine clamps the material to be joined, drills the fastener hole and then places and clinches the fasteners, which in this case are monel solid rivets. The rivetting process is started at the rear of the spar and is continued forward until all of the monel rivets in the forward bay of the spar are in position.

(3) The spar is placed in an assembly jig together with the forward bulkhead, which has been assembled separately. The bulkhead lower chord and the forward edge of the web are clamped by a clamp bar with six jacking screws.

(4) The fastener holes are drilled in the joint by a pneumatic drill with automatic feed operating in guide bushes located in the clamp bar and the 8 holes for the steel lockbolts are reamed to a close tolerance.

(5) The 23 monel rivets are fitted, tail end uppermost, together with the 8 lockbolts securing the bulkhead chord to the spar web and chords.

There is no de-burring of fastener holes as a matter of course. It was noted that the inconel material was very prone to heavy burring, especially when being cut by a drill which was beginning to lose its cutting edge. The burrs took the form of a cylindrical ring around the periphery of the hole or, in extreme cases, the burr formed a complete disc-shaped "cap" which lifted and turned over to lie at the edge of the hole. Such burrs occurred only at the free surface of the spar chords and web stiffeners and were subsequently trapped under the rivet tail. Burrs of this type were considered by the manufacturer to be acceptable.

It was noted that the forward edge of the spar web at the end of stage 1 (in the assembly sequence above) was, typically, flat. However, after the rivetting process had been carried out in stage 2, the forward edge of the spar web was usually bowed, with up to ¼ inch bow at the centre of the forward edge being typical.

A pylon assembly was inspected when stage 4 had been completed prior to the installation of the fasteners. By means of a feeler guage, burrs could be detected in the interface between the bulkhead lower chord and the forward edge of the spar web. There was no dismantling of the unit to remove these burrs and this was contrary to the requirements of Boeing Process specification BAC 5004, which was current at the time of manufacture of the pylon fitted to N771PA.

Following assembly to the bulkhead in stage 5, the web was found to be pulled up against the lower bulkhead chord in the vicinity of the rivets, but a small gap was sometimes noted between the web and the chord in the regions between the rivets and the web in the forward bay of the spar was often bowed, with a noticeable "oil can" effect.

In the centre of the web in the forward bay there is a tooling hole which is used to hold the web down during the assembly process. This hole is filled with a solid rivet, a process which tended to produce a local dishing of the web around the rivet.

Following the accident to N771PA certain changes were made to the standard of build with respect to the pylon. The lower spar web has been increased in thickness and the fasteners used in the whole of the forward bay area have been changed from monel solid rivets and 3/16 lockbolts to larger diameter bolts exclusively.

In the case of those pylons already in service, a Service Bulletin called for the inspection of all fasteners for looseness and the replacement of any loose fasteners with oversize fasteners. This inspection is to be repeated every 4000 flying hours. As an alternative to re-inspection, a doubler can be installed at the forward end of the sparweb, following the repair of any cracks found and the rivets and lockbolts replaced with bolts in accordance with the revised standard of build.

1.17.3 *Post-accident fleet inspection*

On 29 December 1979, the FAA issued an Airworthiness Directive (AD) applicable to all B747 aircraft equipped with JT9D engines (except the 7Q series), requiring the visual inspection within 25 hours time in service of all the fasteners attaching the forward mount bulkhead to the horizontal firewall for looseness. Coincident with this, the manufacturer issued an Alert Service Bulletin (No. 747-34A 2069R1) in amplification of the AD.

The number of aircraft affected was 340, of which 328 were inspected. No information was received with respect to the remaining 12, all of which were Iranian operated.

Altogether, 1,311 pylons were inspected, including the remaining three on N771PA. Nineteen were found to have loose lockbolts, one with a missing lockbolt and another with a missing lockbolt collar. In two cases, working rivets were also reported.

In addition to N771PA and G-AWNA, three other aircraft were reported to have a pylon with a cracked bulkhead chord, though none were associated with loose fasteners. In each case however, the pylon involved was No. 4.

1.17.4 *Certification and design aspects*

At an early stage of the investigation, the manufacturer was asked if the pylon was considered to be a fail safe structure or a safe life item. The Company replied as follows:

> "The departure of an engine/pylon from a 747 will not result in the loss of the aircraft. Engine/pylon loss is a controllable event not requiring exceptional piloting skills. The 747 can be controlled during and following such an event and brought to a safe landing. As a result, the pylon structure and its attachment to the wing have not been certified under the provisions of FAR 25.571 although many elements of a damage tolerant design philosophy have been included."

The Federal Aviation Requirement (FAR) referred to by the manufacturer states in part that:

> "Those parts of the structure (including wings, fixed and moveable control surfaces, the fuselage, and their related primary attachments) whose failure

could result in catastrophic failure of the airplane, must be evaluated under the provisions of either paragraph (b) and (c) of this section."

Paragraph (b) relates to Fatigue Strength and states in part that: "The structure must be shown by analysis, tests, or both to be able to withstand the repeated loads of variable magnitude expected in service."

Paragraph (c) is concerned with Fail Safe Strength and states in part that: "It must be shown by analysis, tests or both that the catastrophic failure or excessive structural deformation, that would adversely affect the flight characteristics of the airplane, are not probable after fatigue failure or obvious partial failure of a single principal structural element."

The company were asked to clarify their statement that the pylon structure and its attachment to the wing were not certified under the provisions of FAR 25.571. Their response was as follows:

> "The engine nacelle and pylon structure is designed, with fuse pins, to separate from the wing at a predetermined load level. The design philosophy is that wing structural integrity is to be preserved to prevent fuel spillage. Safe separation of the pylon ensures this. Document D6–30314 includes coverage of this separation relative to the fail safety of the airplane. FAR 25.571 (c) as it applies to the 747, requires that catastrophic failure is not probable following a failure of a single structural element. We have shown in D6–30314 that the separation of an engine or of the pylon and nacelle is not catastrophic and hence we do comply with 25.571 in this respect. Since the basis of our fail safe compliance is safe separation it was unnecessary to determine the possible result of any other structural failure in the pylon or nacelle for certification."

Document D6–30314 referred to by the company set out Boeing's case at the time of certification that the engine nacelle and pylon structure was a fail safe item. Inherent in the design was the provision of structural fuses (ie hollow sheer pins) at the wing to strut attachment points to protect the wing from damage in the event of nacelle overloads. A primary consideration was the prevention of wing fuel cell rupture. In the case of an overload in the downwards direction, such as might be experienced during abnormal flight or landing events, the pylon will start to break away from the wing structure at either the forward or aft wing to pylon attachments with the failure at a predetermined load level of the fuse pins provided at those points. The break away then progresses to the other fuse pins,resulting in the rotation of the nacelle and pylon assembly under the wing box and separation from the aircraft in the aft direction. The correct sequence of failure is ensured because the wing structure has been designed to be sufficiently stronger than the fuse pins. The company drew attention to the fact that the B707 also employs the fuse pin concept and that the fail safe characteristics of the structure had been demonstrated in a number of nacelle separation incidents.

It was also stated in the reference document that fuel shut-off in the event of pylon separation is achieved by the flight crew acting in accordance with emergency procedures. There is no provision for automatic fuel shut-off, though it was considered at an early stage in the design of the aircraft. It was rejected because studies indicated a possible degradation of safety in the event of inadvertant operation of the system during a critical phase of flight.

2. Analysis

2.1 Strut Failure Sequence (Reference Appendix A)

There was no evidence of the type of fire damage normally associated with an airborne fire, but the character and distribution of the fire damage was entirely consistent with the aircraft being brought to rest above a fire centred around the aft end of the No 4 engine with a wind blowing from the port forward quarter. This assessment accords with witness evidence.

The No 4 pylon forward bulkhead, which carries the forward engine mount, had fractured allowing the front of the engine to drop until restrained by the rear mount, and the adjacent engine teleflex control cables, electrical cables and engine fuel feedpipe had been pulled apart at the point where the power unit interfaced with the pylon. The bulkhead fracture displayed no evidence of heat damage and the forward end of the pylon was outside the fire damaged area. It is clear therefore that the failure of the bulkhead cannot be attributed to the fire. In fact, the indications were that the bulkhead failure occurred first, allowing the engine to drop and in doing so pull apart the cables and the fuel feed pipe. The argument in support of this proposition is given added weight if the probable sequence of events following a severance of the engine service connections is viewed against the actual events which occurred.

The close proximity of the engine fuel feedpipe to the engine control unit teleflex cable and the electrical looms would result in each of these items pulling apart within a short time of each other, probably very shortly after bulkhead separation. The fuel pipe rupture would result in the full fuel flow discharged downwards into and around the No 4 engine cowl where it would come into contact with the hot surfaces of the turbine casing. Spontaneous ignition of the fuel may or may not occur at this time depending upon the fuel air ratio and degree of mixing, but the fuel spray outside the cowl could be expected to ignite from the jet efflux. After a short delay, whilst residual fuel in the fuel system is consumed, the engine would flame out. The engine control teleflex cable is rigged in such a way that, if the cable were stretched until fracture occurred, the inner cable would pull the engine control unit to the "full forward thrust" position and the cockpit thrust lever to the "full reverse thrust" end of its travel. If the cable and controls were set in the reverse thrust position when the bulkhead became detached, then the effect of stretching the cable would initially be to reduce reverse thrust, then disengage reverse thrust and finally increase forward thrust to maximum. Final failure of the cable could be expected to produce a considerable recoil kick at the flight deck lever. The severance of the electrical cables would result in the disablement of the fire detection system for No 4 engine and the engine instruments.

Taken together the likely sequence following bulkhead detachment would be the dropping of the engine, causing a disconnection of the engine services which would result in loss of engine monitoring parameters together with an undemanded reduction in reverse thrust and disengagement of the reverse thrust mechanism, followed by a kick at the control pedestal as the cable snapped. There is a possibility that the engine could spool up momentarily in forward thrust but it would then flame out. An external fire would, in all probability, start around the No. 4 aft pylon area but the slip stream would tend to keep the flames relatively clear of the structure until the speed decayed.

The close similarity between these predicted events and those which actually ocurred strongly suggest that the separation of the No 4. pylon bulkhead was the event which precipitated the accident.

The question as to whether the bulkhead separated completely in one action, or whether it partially fractured and then finally broke free at a later point in the accident sequence, can be resolved with some degree of confidence if the high No. 4 EGT is considered in the context of the accident sequence.

The static overload failure of the cracked bulkhead occurred as a result of an applied download with an inboard load component. Such a loading component would occur at initial touch-down as a result of the engine inertia loads and the associated gyroscopic couple. The predominant load during thrust reversal is a steady download, although an apparent sideload could occur due to structural stiffness changes as the fracture progresses. On the basis of the loading actions, the initial touch-down appears to match most closely the observed characteristics of the bulkhead failure, but the fact that full reverse thrust was achieved on No 4 suggests that either the bulkhead did not tear completely free of the pylon at touch-down, or alternatively, that the bulkhead fracture and separation occurred together at the point of reverse thrust selection, in which case the No 4 EGT indication would have been coincidental. However, if the initial touch-down resulted in a fracture of the bulkhead sufficient to pull the fuel feedpipe partially apart producing a significant fuel leak into the engine cowl but not so great as to starve the engine of fuel, then one might expect a high EGT, resulting from a fire external to the turbine section, as reverse thrust was increased. This is exactly what occurred during the accident sequence and it is reasonable, therefore, to conclude that the bulkhead fractured during the initial touch-down, and that the application of reverse thrust completed the process of separation at the forward bulkhead.

2.2 Pylon Bulkhead Failure (Reference Appendix A)

Detailed examination of the detached bulkhead revealed three distinct modes of failure:

(1) Fatigue cracking in the bend radius at the lower end of the inconel "horse-collar chord" with multiple origins on the inside surface.

(2) Static overload tear type fracture of the sides of the bulkhead above the fatigue fracture zones and across the top of the bulkhead diaphragm, forming a continuous fracture in the shape of an inverted "U".

(3) Combined fretting and wear failure of the rivetted and bolted joint between the titanium bulkhead lower chord and the inconel spar web.

The static overload portion of the bulkhead fracture contained ample evidence indicating that the fracture had occurred very recently whereas the fatigue fracture zones and the fretting/wear failure of the bulkhead lower chord to spar web joint were clearly failures which had been propagating over a very considerable period of time. The principal question arising is, therefore, whether the fatigue failure preceded the fretting/wear failure or vice versa. The characteristics of the fatigue failure on both sides of the horse collar chord are compatible only with a plate bending mode of flexure about an axis lying approximately along the bend radius of the chord. The design of the front engine mount is such that the bulkhead can only carry vertical and side loads together with the torsion resulting from the offset side load relative to the torsional axis of the pylon. The vertical loads in the bulkhead are transferred to the pylon as shear in the vertical members of the horse collar chord and the sideloads are transferred as shear through the bulkhead lower chord to spar web. The torsion is carried as shear around the periphery of the bulkhead. It can be seen therefore that under normal loading conditions, and with the structure intact there is no way that bending stresses of the type, which must have been present to produce the fatigue cracking, can have occured. The failure of the bulkhead lower chord to spar web joint has, in contrast, occurred as a result of shear load transfer similar in type, but not necessarily magnitude, to that normally experienced in service. Furthermore, the wear at the joint would result in a change of stiffness of the structure insofar as side load transfer is concerned, with the result that instead of the side loads transferring as shear through the lower chord to spar web joint, the load path would be through the bottom ends of the horse collar chord into the lower forward ends of the side skins and from there the loads would diffuse inwards to the spar web via the spar chords. This loading action would continue until the structure had flexed sufficiently to bring the worn fasteners and fastener holes into bearing contact, beyond which point further increases in side load would be accommodated by shear transfer in the normal way. The diffusion of the side loads through the lower ends of the horse collar chord would induce bending stresses and flexure in the lower ends of the chord of precisely the type which caused the fatigue cracking. It is therefore clear that the sequence of failure, so far as the bulkhead itself is concerned, was the breakdown as a result of fretting and wear of the lower chord to spar web joint which gave rise to induced bending stresses in and fatigue cracking of, the horse collar chord. The fatigue cracking propagated until the residual strength of the horse collar chord was reduced to the point where it could no longer carry the service loads imposed upon it on the night of the accident.

Because the fatigue and static overload fractures are seen as an entirely logical outcome of the primary failure, the analytical effort has been directed mainly to understanding the failure of the rivetted and bolted joint between the bulkhead lower chord and spar web.

2.3 Failure of the Bulkhead Chord to Spar Web Joints (Reference Appendix A)

The bulkhead lower chord to spar web joint failure is characterised by extremely heavy wear damage which obliterated any evidence of the incipient failure stage. Because the propagation of the failure is entirely the result of wear, the wear properties of the materials used in the joints are of some significance.

Attempts to obtain data for the wear and fretting characteristics of the two principal materials involved, inconel and titanium, met with limited success. It would appear that reliable data on wear rates is not available and such fretting data as is available is limited to inconel against inconel and titanium against titanium. The evidence which is available however suggests that the fretting rates for titanium, and to a slightly lesser degree for inconel, are very much more severe than for the materials more typically used in airframe construction, and it is considered reasonable to infer from this that the fretting of titanium against inconel will also be severe. Although there is also a lack of quantititative wear data as opposed to fretting data for these materials, titanium is known for its very high wear rate with heavy galling of the surface, and the indications are that inconel will exhibit similar characteristics. Certainly the damage on N771PA, which exhibits very heavy galling and wear of both materials, supports this hypothesis. Evidence was also found which indicated that at high temperatures, such as would be found in a more typical environment for these materials, eg turbine engines, the fretting characteristics are very much less severe than at the lower temperatures experienced by the bulkhead.

It appears from the available evidence that the heavy wear, which led to the fatigue cracking and failure of the bulkhead, is to be expected given the probable wear properties of titanium and inconel in combination. However for wear to occur, there must be relative movement, although the fretting data suggests that such a movement need only be extremely small. How this small amount of initial relative movement occurred will never be known with certainty because the subsequent wear has obliterated all evidence of the incipient failure stage. However, there are several possible mechanisms which might have produced the initial movement; side load sufficient to produce permanent deformation of the fasteners and/or fastener holes; shortcomings in manufacture and quality control; fretting wear occurring as a result of normal elastic strain; environmental factors such as vibration or temperature. There is some evidence which suggests that fretting of these materials does occur at low stress levels with purely elastic strain, but in this case the absence of wide-spread damage throughout the aircraft fleet tends to rule out such a mechanism, which would be common to all pylons of this design, as a primary cause of initial looseness. The other options however must be considered in more depth.

Taking the possibility of a manufacturing defect first, it is clear that such a defect could take the form of over size or out of limits fastener holes, under sized fasteners or inadequately pulled up fasteners, all of which would result in potential relative movement at the joint under an applied side load. Before such a defect could be signigicant however, it would require the majority of fasteners on the joint to be defective because the strength reserves under normal flight loads are very considerable. In addition, it would also be necessary for the inspection procedures to miss each of the defective fastenings. Although there is no direct evidence for or against defects at manufacture, it is considered on balance very unlikely that defects of this kind caused the initial failure of the joint. However, certain features of the joint arising as a result of manufacturing techniques do have some significance.

The drilling characteristics of inconel are such that unless the sheet material is clamped tightly and the drill very sharp, a cylindrical burr will be thrown up around the edge of the finished hole. Burrs around rivet holes in the web adjoining the spar chords on N771 PA and the method of producing the holes in the web at the bulkhead chord connections indicate that the probability of burrs being present on the fastener holes at the forward edge of the web is very high. The monel rivets are positioned at the joint with the tail end uppermost, so that the upset head is formed against the thick titanium channel section. Whilst this has the advantage of not spreading the hole in the thin inconel sheet, it does have the disadvantage that swelling of the rivet shank during head forming will tend to cause the shank to bind up in the thick titanium section. This binding will allow the channel section to react the upsetting loads rather than the head end of the rivet, with the result that the clamping pressure applied by the finished rivets could be much less than otherwise. The combined effect of the presence of burrs and the rivet orientation is that the "clamping footprint" and clamping pressure will potentially be much reduced, making movement easier and concentrating fretting wear at the interface between the top of the burr and the bulkhead chord. The resulting wear would tend to reduce the height of the burr and consequently the clamping pressure, leading ultimately to the potential for vertical movement of the web against the rivet shanks. Although the primary load transfer is shear, which should not give rise to any vertical movement of the web, a third feature of the construction method, that is the tendency when rivetting up the web to the spar chords to induce a bow into the forward bay of the web, does provide a mechanism whereby vertical movement under load can occur. As the side load changes direction, the tension stress axis in the web will swing from an approximate 45° orientation one way to 45° the other way, which will tend to cause a "ripple" to run across the forward end of the web each time the side load changes direction. The resulting movement at the rivets will cause wear of the rivet shank and the rivet hole diameter, providing potential for lateral relative movement, from which point the wear process can accelerate to the point where failure occurs. However, this proposed wear mechanism, although it will greatly accelerate the wear, does not by itself explain the initiation of the wear process because some initial lateral movement is still necessary in order to wear the top of the burr.

The effects of differential expansion of the joint sandwich and the fasteners due to temperature changes were considered as a possible means whereby the fastener end load could be increased to the point where axial crushing of the burr could occur, thus providing the potential for vertical web movement, without the need for wear initially. This movement potential could then be exploited by the web "ripple mechanism", referred to earlier. However, though calculations support this hypothesis, the temperature changes necessary to achieve it would be somewhat outside those which could have been experienced by the bulkhead region of the pylon.

Consideration was also given to the possible effects of vibration, but no mechanism could be found whereby the loosening process could be initiated by vibration, although vibration at the front engine mount, such as might have occurred during the period noted in the service history when excessive mounting play was observed, would almost certainly act to accelerate the fretting and wear process.

By a process of exclusion therefore, one is led to the conclusion that some form of overload sufficient to cause a permanent deformation of the holes in the web must have occurred. Check calculations of the shear strengths of the fasteners indicate that the static strength was rather greater than the ultimate design load condition, which is itself approximately 4 times the normal maximum flight side load. The bearing strength of the inconel web was also found to be very closely matched to the rivet shear strengths and the general impression was of a well balanced piece of structure which should more than adequately cater for any side loads generated during flight. Indeed, the strength reserves are such that a flight induced load, sufficient to put a permanent set into the fasteners or fasteners holes, would require a manoeuvre of such gross proportions as to probably produce failures elsewhere on the aircraft and would almost certainly be recorded in the aircraft records. In the absence of such a record it can be concluded with some confidence that a flight induced side overload was not the cause of initial looseness. The only remaining possibility for applying an overload to the pylon is that of accidental damage caused by, for example, collision with a ground obstacle or a vehicle.

In the case of the British Airways aircraft G—AWNA, referred to earlier, which appeared to have suffered an almost identical failure of the No 4 pylon with similar crack propagation lengths but without the final overload fracture of the bulkhead, examination of the aircraft records revealed details of a collision between a ground vehicle and the No. 4 engine cowling in 1974. The resulting damage consisted of a score in the side of the engine cowl, which could only have occurred as a result of the vehicle striking the side of the cowl at a shallow angle, thus inducing a side load in the pylon. Two years later when the bulkhead was found to be cracked it was stop-drilled and after a further two years the damage had reached the stage where it was similar to N771PA. Although there is no way of knowing for certain whether or not the collision produced a sufficient side load to produce a small degree of looseness at the joint, the absence of any other evidence for damage initiation suggests that it probably was the cause. The period of time between the "event" and the two recorded stages of crack growth are in line with the kind of propagation period one might intuitively expect. In the case of N771PA, an extensive search back through the aircraft's records was made in the light of the knowledge about G–AWNA, and it was found that a collision between the No 4 engine and a baggage container (Igloo) had occurred at Chicago Airport in 1976. This was the only incident recorded which could have had any bearing on the bulkhead failure. The similarity in the period and flight hours between the collision and the failure in the case of both aircraft is apparent and lends support to the view that these collisions could have been the initiating factors for each failure.

A consideration of all the available evidence and all the possible failure mechanisms lead to the conclusion that the failure occurred as a result of reduction in strength of the bulkhead attachment to the pylon caused by fatigue cracking of the lower ends of the horse-collar chord, and that this cracking occurred as a result of extreme fretting and wear damage to the lower bulkhead to spar web joint following an initial overload of the joint, possibly resulting from a collision with a ground vehicle. The high fretting and wear rate properties of the inconel and titanium materials used in the joint, the probable presence of burrs on the inconel web, the orientation of the monel rivets and the presence of a bow in the forward bay of the web are all considered to be factors which caused the minor damage sustained initially to propagate into the total failure of the front bulkhead.

It is not considered that this conclusion is invalidated by the other three cases of cracked collar chords, which were found during the fleet inspection, none of which were apparently associated with loose fasteners. It is considered possible that stresses built into the lower corner of the bulkhead during assembly would, if the stresses were very high, lead to cracking as a result of normal flexure occurring during service. In such cases, the cracks would tend to stop once they had relieved the in-built stresses. Equally, the combination of some degree of built-in stress together with a slight, even possibly imperceptible degree of joint loosening, resulting from a minor collision, could result in cracking, which again would tend to slow down as the local in-built stresses were relieved and the stiffness of the corner reduced. Though no record could be found of a ground collision involving any of the three aircraft concerned, it must be of some significance that the No 4 nacelle/pylon was again involved in each case. This suggests that No 4 engine nacelle may be particularly vulnerable to collision damage, either during taxying or whilst the aircraft is parked and is being approached by service vehicles from its starboard side.

As regards the loose fasteners found during the fleet inspection, they were all, with two exceptions, lockbolts situated at the ends of the lower chord. It is considered that these loose fasteners were not the result of collision damage because such damage would tend to affect all the fasteners at the joint. This conclusion is reinforced by the fact that the looseness appears to be randomly distributed amongst all engine stations and it is therefore considered that the loose lockbolts have no bearing on the accident.

2.4 Inspection procedures (Reference Appendix B)

The inspection schedule used by Pan American is based upon the Boeing BMPD (Boeing Maintenance Planning and Data Document) which in turn is derived from the Boeing MSG–1 and FAA MRB (Maintenance Review Board) documents. It should therefore reflect the combined experience and expertise of manufacturer, airworthiness authority and operator. Nevertheless the fact that the bulkhead failure reached the stage that it did clearly indicates that the inspections which actually took place were not able to detect the failure at an early stage. This anslysis therefore examines the Pan American schedule and the BMPD in an attempt to establish whether the inspections called up were capable of finding the subject damage at an early stage and whether those inspections specified were properly executed.

Pan American Schedule

Regular Inspections

The regular inspection which calls for external and internal inspections of the pylon structure is accomplished by removal of the access panels on the side of the pylon. The forward fairing is, however, called up for removal during the 'forward fairing inspection', in which the inspector is tasked with the inspection of the forward fairing structure and latching mechanisms; no reference is made to the forward pylon bulkhead structure. It can be seen that neither of these inspections cover fully the structure of the forward bulkhead, primarily because there is no specific inspection of the forward face of the bulkhead with the fairing removed, but also because of the position of the EPR transmitter close to the forward bulkhead, which restricts visual access.

It is clear that the most obvious signs of distress in the early stages of failure would be fretting products around the rivet heads on the web underside and, perhaps, cracking in the lower regions of the horse-collar chord. Both of these features would be visible from an inspection of the forward bulkhead with the forward fairing removed. Although it is probable that fretting products and a gap between the web and the lower bulkhead chord would be visible on the inside of the pylon, such visible effects would only become obvious at a later stage and would be in a position where they would be partly obscured by the EPR transmitter. Cracking of the horse-collar chord may also be visible internally, but because of the distance of such cracks from the access opening and the presence of the EPR transmitter, confidence in finding such cracks at an early stage cannot be high. Whilst it would not be possible to detect the failure from an examination of the structure through the access panels in the side of the pylon, the probability of success is small compared with that of an inspection with the forward fairing removed. The question which must be answered is, therefore, whether it would be reasonable to expect an inspector to either remove, on his own initiative, the forward fairing during the pylon internal/external structure check and inspect the forward face of the bulkhead, or, during the forward fairing check, to extend his structure inspection to include the forward bulkhead.

It is appreciated that the inspectors, who would normally carry out such work, are invariably conscientious and painstaking in their work. They would not normally regard the written text of the inspections as rigid boundaries, and would extend their inspection to cover the general area. Nevertheless, whilst such excursions on the part of the inspector may occur, it is not reasonable to expect the inspector of the bulkhead, using mirror and torch to view the lower corners of the bulkhead and the bulkhead to the web joint, as a part of the fairing inspection. It is considered more probable that an inspector may call for the removal of the fairing during the internal structure inspection, but it is not considered reasonable to rely on such diligence alone.

It is concluded therefore that the regular inspections on the pylon were not, by themselves, sufficient to provide the necessary confidence of finding bulkhead failures at a sufficiently early stage. This conclusion is reinforced by the very obvious fact that the subject failure must have been covered by many of the prescribed inspections, a number of which would have been carried out at a stage when the failure was well advanced, and yet the failure remained completely undetected.

It is worthy of note that the forward bulkhead forms the boundary between the "power plant" and the "pylon". The possibility that this demarcation led to the forward face of the bulkhead unintentionally falling between the two, and consequently being omitted, cannot be ignored.

Pylon Sampling Inspection

The pylon sampling inspection programme does not cover every aircraft, but only a proportion of the fleet and is intended to provide broad data on structure performance in service. These inspections called for examination of the engine mount fittings on the forward bulkhead but did not include any specific reference to the bulkhead or adjoining structure, and it is therefore probable that these inspections would not highlight a bulkhead failure, even if an aircraft with a failure was amongst those inspected.

Engine Change Inspections

One of the inspections detailed during an engine change calls for "thorough visual inspection of vertical and horizontal firewalls and bottom of pylon". This inspection clearly addresses the external structure of the pylon in the region of the forward bulkhead and the adjoining forward spar, and any missing fastener heads and a sagging spar web at the forward edge should be clearly visible. The fact that this inspection did not bring to light the failure at the time of the engine change on 2 September 1979 at the Pan American facility in New York, nor during the preceding engine changes at other locations, suggests that the damage may not have been visible at those times, although, by then, the bulkhead lower chord/spar web joint was probably in an advanced stage of deterioration.

BMPD

The BMPD is, in broad terms, similar to its derivative the Pan American schedule. It calls for inspections of the engine mountings, which in the case of the forward mounting, are located on the forward bulkhead. However these inspections require the removal of the forward fairing. In addition there are instructions to "check nacelle strut interiors, firewalls, and sealant (ribs, spars and fittings), electrical tubing etc" via the nacelle equipment access doors (NEADs). In as much as the forward bulkhead is a firewall, which is called up for a general inspection with all the nacelle equipment access doors removed, a general examination of both forward and rear faces of the bulkhead is clearly specified. In this respect the BMPD does appear to cover the area in question, albeit in a general way.

Summary of Analysis of Inspection procedures

It is concluded that the BMPD does specify an inspection of the forward bulkhead on both sides which, if carried out according to the definition of the terms "check" as specified in the BMPD, should be capable of bringing to light failures of the type found on N771PA before reaching a critical stage. The Pan American schedule however did not at the time adequately cover both faces of the forward bulkhead structure as a routine check item, though it is conceded that it was examined at other times on an opportunity basis. Since the accident, Pan American have raised an inspection item that specifically requires the removal of the pylon forward fairing for access to and inspection of the forward face of the bulkhead. A recommendation is made in paragraph 4 of this report that other operators similarly change their procedures where this is not already the case.

2.5 Certification and design aspects

It is, perhaps, inevitable that with the events of the DC10 accident at Chicago still a recent memory, a parallel would be sought between that accident, since it involved the separation of an engine nacelle and pylon, and the one which occurred to N771PA.

Though both accidents bear a superficial resemblence because each involved a pylon failure, there is, in fact, no comparison to be made. To express it simply, the essential difference between the two failures is that in the case of the B747, the nacelle and pylon structure was designed to separate from the wing at predetermined load level whereas in the case of the DC10 the intention was that it should remain attached. Therefore in the case of the DC10, compliance with FAR 25.571 was necessary with respect to the pylon structure inasmuch as the possible effect of any failure within the structure on the flight characteristics of the aircraft had to be determined. In the case of the B747 this was unnecessary because the basis of the design was that any failure of the pylon structure could be tolerated in the context of fail safety since whatever load is placed on the structure, the worst that can happen is a clean separation at the wing to pylon interface.

Separation elsewhere in the engine nacelle or pylon structure, due to fatigue or some other mechanism, must therefore always be a less severe event, since in that case, the wing to pylon attachment will remain unaffected and thus the wing structure itself. It is, of course, the integrity of the latter that has to be preserved in order to avoid wing fuel cell rupture, an event that would undoubtedly hazard the aircraft.

The underlying assumption that is implicit in the company's approach to fail safety is that the separation of the nacelle and pylon structure is a controllable event, not requiring exceptional piloting skills, and that a safe landing can be made. There is, of course, only the manufacturer's assurance that this is so, but since this claim is obviously not lightly made, there is good reason to accept it, especially when it is viewed against the service record of the B707, which has demonstrated that nacelle separation at a predetermined load level is a viable proposition with respect to aircraft controlability.

2.6 Fire Aspects

Whereas fail safety in the purely structural sense is undoubtedly achieved by designing the pylon to separate without damaging the wing structure, it is less certain that the occurrence of fire as a direct result of separation was sufficiently considered in the context of its effect on the overall safety of the aircraft. As happened in the case of the accident to N771 PA, a major fire occurred after the nacelle began to separate due to the ignition of fuel escaping from ruptured fuel lines by the hot section of the engine as it rotated under the wing box. This was a fire over which the crew did not have any direct control other than the ability to shut off the fuel. Since there were no flight deck indications of a fire, the speed of their reaction was dependent upon them actually seeing the fire. In fact, it was some 40 seconds after the fire broke out that the crew shut off the fuel, according to data derived from an analysis of the FDR.

Clearly the risk of fire following separation would have been eliminated had some means of automatic fuel shut-off been provided. Certainly the damage to N771PA would have been considerably less had the fuel been cut off coincident with the separation of the nacelle. As it was, all the damage to the outer wing was caused by fire and was sufficiently extensive to require replacement of that section of the wing.

Though the validity of safe nacelle and pylon separation as a concept is not questioned, it would seem that by not making provision for automatic fuel shut off at both the wing to pylon and engine to pylon interfaces, the concept was not taken to its logical extent. It is acknowledged that the feasibility of installing such a system was examined during the initial design stage but was rejected because it was considered that it could not be made sufficiently reliable. However, that was some 20 years ago, and it may well be that advances in engineering since that time would enable an adequately reliable system to be devised. It is recognised that to be completely effective, provision would need to be made to shut off the fuel in the event of separation occuring at either the wing/pylon interface or the engine/pylon interface. This could be done with self sealing couplings, for example, but whatever the options it is recommended that the feasibility of providing an automatic fuel shut off system should once again be examined. Without such a system the aircraft and its occupants are exposed to greater hazard than might otherwise be the case, particularly in the case of separation incidents occurring on the ground, when the release of fuel affects directly the survivability of those on board.

3. Conclusions

3.1 (a) *Findings*

(i) The aircraft had a valid Certificate of Airworthiness and its documentation was in order.

(ii) The aircraft had been maintained in accordance with an approved maintenance schedule and all airworthiness directives had been complied with.

(iii) The flight crew were properly licensed and well experienced.

(iv) The landing at London Heathrow, though heavy, did not constitute a hard landing such as would require the inspection of the aircraft. Though the landing precipitated the failure of the No 4 pylon forward bulkhead, it was in no way solely responsible for it.

(v) The accident occurred as a result of the fracture, on touch down, of the No 4 pylon forward bulkhead, which carries the forward engine mounting. As a direct consequence of the fracture, there was a partial detachment of the engine nacelle from the pylon as a result of a sustained download on the forward mount during the application of reverse thrust.

(vi) The bulkhead had long term pre-existing damage which may have originated when the No 4 engine nacelle was in minor collision with a baggage igloo in November 1976. This collision could have initially loosened the bulkhead attachment structure sufficiently to allow fretting and wear to develop. This in turn resulted in fatigue cracking and final overload failure of the structure. The residual strength of the structure immediately prior to failure in relation to the ultimate design load could not be determined. However, at the time of failure, the aircraft was operating well within its design envelope.

(vii) The separation of No 4 nacelle was incomplete but it is probable that had it continued it would have followed the manufacturers' predicted sequence.

(viii) The fire which occurred following nacelle separation was caused by the release of fuel under pressure being ignited by exhaust gases. There was no indication given on the flight deck of the fire because of the severance of electrical services. The crew were therefore not immediately aware that a fire had broken out until it had reached significant proportions. There was therefore a considerable delay before the fuel was shut off. Had provision been made for the fuel to be shut off automatically coincident with the separation of the engine from the pylon, considerably less damage would have been caused to the aircraft.

(ix) With the exception of the leak check, the inspection schedules that form part of the periodic checks carried out by the operator were inherently incapable of detecting the onset of bulkhead failure. However, the inspection called up by the BMPD was capable of detecting the failure.

(x) The inspection procedures associated with power plant changes specifically addressed the front face of pylon forward bulkhead and those carried out in August and September 1979 should have been capable of detecting the damage to the bulkhead attachment structure had it been visible at that time.

(xi) The pylon structure was not required to be evaluated against FAR 25.571 since the designed separation of the pylon in the event of overload rendered such an evaluation unnecessary. However a re-appraisal of the possible effects of fire following separation is considered necessary in the context of overall safety, particularly in the case of accidents occurring on the ground.

(xii) The absence of any fleetwide symptoms of incipient or actual failure of the forward bulkhead confirms that the failure that occurred to N771PA and the partial failure involving G–AWNA were unique events which were not indicative of an inherent design fault.

(b) *Cause*

The accident was caused by the failure of the forward bulkhead of the No 4 pylon when it was subjected to landing loads after it had been weakened by pre-existing fatigue. A major contributory factor was the absence of any routine check item which might otherwise have detected the onset of failure at an early stage.

4. Safety Recommendations

It is recommended that:-

4.1 Where it is not already the case, the inspection schedules relating to the forward pylon bulkhead specifically address the forward face of the bulkhead, including a check on the condition of the spar web to chord joint.

4.2 Consideration be given to the possible effects of fire occurring as a result of pylon separation in the context of overall safety, especially in the case of accidents occurring on the ground. In particular, it is recommenced that provision for automatic fuel shut-off in the event of pylon or nacelle separation be considered.

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