



Australian Government

Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY REPORT

Aviation Occurrence Investigation AO-2008-053

Interim Factual

**Depressurisation
475 km north-west of Manila, Philippines
25 July 2008
Boeing Company 747-438, VH-OJK**

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CONTENTS

THE AUSTRALIAN TRANSPORT SAFETY BUREAU	vi
FACTUAL INFORMATION	1
History of the flight.....	1
Injuries to persons	2
Damage to the aircraft.....	3
Airframe	3
Oxygen system damage	7
Engine number-3	11
Cabin – R2 door.....	12
Electrical.....	18
Flight control	19
Other damage	19
Cargo	19
Personnel information	20
Aircraft information	21
Aircraft general.....	21
Cabin door	21
Flight control system	21
Oxygen system description.....	22
Oxygen cylinder description.....	23
Oxygen cylinders installed	23
Oxygen system maintenance	24
Fuselage maintenance.....	27
Survival factors	27
Cabin – safety systems	27
Crew and passengers	28
Passenger oxygen system performance	28
Flight recorders	29
Recording system operation	30
Recorder recovery	31
Results	31
Sequence of events.....	32
The flight	32
Cylinder event	33

Tests and research	34
Explosive residue testing	34
Oxygen gas analysis	34
Valve components	35
Exemplar cylinders	36
Engineering examination	36
ONGOING INVESTIGATION ACTIVITIES	45
Engineering	45
Survival factors	45
Flight recorders	45
SAFETY ACTION	47
Aircraft operator	47
ATSB safety action	47
Safety advisory notice (AO-2008-053-SAN-006)	48
Safety advisory notice (AO-2008-053-SAN-007)	48
Aviation research and analysis reports	48
ATTACHMENT A: AIRCRAFT STATIONS.....	49
ATTACHMENT B: OXYGEN CYLINDER LOCATIONS	50
ATTACHMENT C: PASSENGER OXYGEN SYSTEM	51
ATTACHMENT D: FLIGHT DATA RECORDER PLOTS	52
ATTACHMENT E: PROBABLE OXYGEN CYLINDER	
TRAJECTORY	53
Probable oxygen cylinder trajectory (continued)	54

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Figure 9 and the diagrams presented within Attachments A, B and C of this report were provided courtesy of the Boeing Company.

Abstract

On 25 July 2008, at 0922 local time, a Boeing Company 747-438 aircraft (registered VH-OJK) with 365 persons on board, departed Hong Kong International airport on a scheduled passenger transport flight to Melbourne, Australia. Approximately 55 minutes into the flight, while the aircraft was cruising at 29,000 ft (FL290), a loud bang was heard by passengers and crew, followed by the rapid depressurisation of the cabin. Oxygen masks dropped from the overhead compartments and it was reported that most passengers and crew commenced using the masks. The flight crew carried out the 'cabin altitude non-normal' checklist items and commenced a descent to a lower altitude. A MAYDAY distress radio call was made on the regional air traffic control frequency. After levelling the aircraft at 10,000 ft, the flight crew diverted to Ninoy Aquino International Airport, Manila, where an uneventful visual approach and landing was made.

Inspection of the aircraft by the operator's personnel and Australian Transport Safety Bureau (ATSB) investigators, revealed a rupture in the lower right side of the fuselage, immediately beneath the wing leading edge-to-fuselage transition fairing. The rupture extended for approximately 2 metres along the length of the aircraft and 1.5 metres vertically. It was evident that one passenger oxygen cylinder (number-4 from a bank of seven cylinders along the right side of the cargo hold) had sustained a sudden failure and forceful discharge of its pressurised contents, rupturing the fuselage and propelling the cylinder upward, puncturing the cabin floor and entering the cabin adjacent to the second main cabin door. The cylinder had impacted the door frame, door handle and overhead panelling, before presumably falling to the cabin floor and exiting the aircraft through the ruptured fuselage, as the cylinder was not located within the aircraft.

In the absence of the failed cylinder, the ATSB, with the assistance of the aircraft manufacturer, has obtained a number of exemplar cylinders from the same production batch. A program of engineering assessments is examining the compliance of the cylinders with the original production specification, the damage tolerance of the design, and the potential mechanism for cylinder failure. To date, the investigation has not identified any verifiable deficiency in the cylinder design. Preliminary analyses of the cabin safety systems and crew/passenger experiences have indicated that the aircraft oxygen systems had operated satisfactorily, despite the damage sustained during the rupture and depressurisation events. The investigation is continuing.

THE AUSTRALIAN TRANSPORT SAFETY BUREAU

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal bureau within the Australian Government Department of Infrastructure, Transport, Regional Development and Local Government. ATSB investigations are independent of regulatory, operator or other external organisations.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

Purpose of safety investigations

The object of a safety investigation is to enhance safety. To reduce safety-related risk, ATSB investigations determine and communicate the safety factors related to the transport safety matter being investigated.

It is not the object of an investigation to determine blame or liability. However, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

Developing safety action

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to proactively initiate safety action rather than release formal recommendations. However, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation, a recommendation may be issued either during or at the end of an investigation.

The ATSB has decided that when safety recommendations are issued, they will focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on the method of corrective action. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations. It is a matter for the body to which an ATSB recommendation is directed (for example the relevant regulator in consultation with industry) to assess the costs and benefits of any particular means of addressing a safety issue.

About ATSB investigation reports: How investigation reports are organised and definitions of terms used in ATSB reports, such as safety factor, contributing safety factor and safety issue, are provided on the ATSB web site www.atSB.gov.au

FACTUAL INFORMATION

This interim report provides a summary of factual information that has been derived from the continuing investigation of the subject occurrence – building upon the information presented in the preliminary report (ISBN 978-1-921490-65-1). As the investigation is ongoing, readers are cautioned that there is the possibility that new evidence may become available that alters the circumstances as depicted in the report.

History of the flight

At 0922 local time (0122 UTC¹) on 25 July 2008, a Boeing 747-438 aircraft, registered VH-OJK, departed Hong Kong International Airport on a scheduled passenger transport service to Melbourne, Australia. On board the aircraft (operating as flight number QF30) were 346 passengers (including four infants), 16 cabin crew and three flight crew (captain, first officer and second officer).

The flight crew reported that the departure and climb-out from Hong Kong was normal, with the aircraft established at the assigned cruising altitude of 29,000 ft (FL290) by 0942 (0142 UTC).

At 1017 (0217 UTC), the captain and first officer reported hearing a ‘loud bang or cracking sound’ with an associated airframe jolt. At that time, the autopilot disconnected and the first officer, who was the pilot flying at the time, assumed manual control of the aircraft. Multiple EICAS² messages were displayed, including warnings regarding the R2 door status and cabin altitude³. The second officer, who was in the forward crew rest position, returned to the first observer’s crew seat and all flight crew donned oxygen masks before completing the ‘cabin altitude non-normal’ checklist. At that time, the aircraft was approximately 475 km to the north-west of Manila, Philippines.

The cabin crew reported that shortly after the bang was heard, oxygen masks fell from most of the personal service units in the ceiling above passenger seats and in the toilets. Most passengers started using the oxygen masks soon after they dropped. All cabin crew, who were engaged in passenger service activities at the time, immediately located oxygen masks to use. Some crew located a spare passenger mask and sat in between passengers, while others went to a crew jump-seat at an exit, and one used a mask in a toilet.

Approximately 20 seconds after the event, the captain reduced the thrust on all four engines and extended the speed brakes. The first officer commenced the descent while the captain declared a MAYDAY⁴ on the Manila flight information region (FIR) radio frequency.

¹ Universal Time Coordinated (previously Greenwich Mean Time, GMT).

² Engine Indication and Crew Alerting System.

³ The altitude corresponding to the air pressure inside the aircraft cabin.

⁴ International call for urgent assistance.

At 1024 (0224 UTC), the aircraft reached, and was levelled at an altitude of 10,000 ft, where the use of supplementary oxygen by passengers and crew was no longer required.

After reviewing the aircraft's position, the flight crew elected to divert and land at the Ninoy Aquino International Airport, Manila, and landing preparations subsequently commenced, including the jettisoning of excess fuel to ensure the aircraft landing weight was within safe limits. The flight crew reported that many system failure messages were displayed, including all three instrument landing systems (ILS), the left very high frequency (VHF) omnidirectional radio-range (VOR) navigation instrument, the left flight management computer (FMC) and the aircraft anti-skid braking system.

The crew reported that at all times during the ensuing descent into Manila, they were able to maintain the aircraft in visual flight conditions. With radar vectoring assistance from Manila air traffic control, the captain, who had assumed the pilot flying role, conducted an uneventful approach and landing on runway 06, with a smooth touchdown, full reverse thrust and minimal braking. Emergency services were in attendance after the aircraft was stopped on the runway, after which intercom contact was made with a ground engineer and the aircraft verified as being safe to tow to the airport terminal and disembark the passengers via a terminal airbridge.

Injuries to persons

None of the passengers aboard the aircraft reported any physical injuries to the cabin crew immediately following the depressurisation event, or to the operator's staff upon arrival in Manila. The Australian Transport Safety Bureau (ATSB) subsequently conducted a survey of all passengers on the flight. Of the survey respondents who reported that they had experienced some pain, the majority described symptoms and experiences associated with the rapid depressurisation of the aircraft cabin. Those included ear pain and/or 'popping', temporary loss of hearing and headaches. Many passengers also reported high levels of anxiety and feelings of panic, with associated physiological symptoms such as a racing heart. The survey questioned the passengers as to whether they had experienced any unusual effects during the depressurisation – effects that may have suggested the individual was experiencing the onset or development of oxygen deprivation (hypoxia). Several passengers reported feelings of faintness, light-headedness and/or tremors. However, it was unclear as to whether those symptoms were associated with hypoxic effects, or the anxiety brought upon by the situation.

ATSB investigators interviewed all members of the aircraft's flight and cabin crews. Several of the crew reported experiencing ear discomfort and 'ringing' immediately following the event. However, none sustained any injury or physical condition that incapacitated them in any way.

During the interviews, it was noted that several cabin crew members had become very distressed during the depressurisation and were initially unable to carry out emergency tasks. Senior cabin crew reported that those staff were withdrawn from duty for a period, after which they were able to resume duties and assist passengers.

Damage to the aircraft

Airframe

An initial inspection of the external aircraft surfaces on the ground in Manila revealed the complete loss of the right wing forward leading edge-to-fuselage fairing, with separation occurring along the lines of interconnection between the fairing and fuselage skins (Figure 1). In the area exposed by the fairing loss, was an inverted T-shaped rupture in the fuselage skin, with several items from within the forward cargo hold partially protruding from the rupture (Figure 2). The approximate vertical centreline of the skin rupture was positioned at fuselage station⁵ (STA) 820, with skin damage extending longitudinally for 79 inches (201 cm), from STA 777 to STA 856. Vertically, the rupture extended for approximately 60 inches (152 cm) between fuselage stringer⁶ 31 at the top, to stringer 38 at the lower extent of the damage. While some of the fuselage skin had folded outward and away from the rupture, it was evident that an area of skin and structure equal to approximately one-half of the total ruptured area had separated from the aircraft and was not recovered. On the basis of measurements taken around the ruptured areas, the total area of the skin rupture was estimated at around 1.74 square metres (2,700 square inches). Figure 3 illustrates the extent of the fuselage rupture as viewed from outside the aircraft.

An examination of the rupture profile and fuselage skin damage found that all fractures were typical of a ductile tearing mechanism, with no evidence of corrosion, prior cracking or pre-existing defects in any of the areas examined. Along the forward edge of the rupture void, an area of skin presented a sharply folded appearance, with an outward curvature that appeared to match the profile of the breathing oxygen cylinders installed internally along the fuselage wall (Figures 4 and 5).

Rearward of the fuselage rupture, several localised areas of scuffing, puncture and scoring were evident along the underside of the aircraft, extending along a diagonal path from the ruptured area rearward toward the left body landing gear (Figure 6). Elongated score marks were also noted extending for several metres around the left side of the rear fuselage – typically around STA 1880 to STA 2000.

On the left side of the aircraft fuselage, immediately forward and below the L2 door (approximately STA 790), the external blowout doors of both pressurisation relief valves were latched open (Figure 7). The relief valves provided protection to the aircraft against excessive differential pressures, with the external latching doors providing a positive indication of valve operation. Aircraft systems documentation specified that the valves open at a differential pressure of 63.8 kPa (9.25 psi) to vent the fuselage interior to the ambient atmosphere. An additional relief setting of 66.9 kPa (9.7 psi) acts as a backup.

⁵ Fuselage stations are measured in inches from the front of the aircraft, with the forward surface of the aircraft's nose (radome) located at fuselage station (STA) 90 (Attachment A).

⁶ Stringers are longitudinally oriented reinforcing sections used to increase the strength and rigidity of the fuselage pressure shell.

Figure 1: Fuselage rupture – external view



Figure 2: Fuselage rupture with protruding cargo



Figure 3: Extent of the fuselage rupture, after removal of further transition fairings



Figure 4: Sharply folded area of fuselage skin



Figure 5: Oxygen cylinder held against skin fold to illustrate conformance



Figure 6: Panel damage to the rear of the rupture site



Figure 7: Pressure relief valve blowout doors open (arrowed)



Oxygen system damage

Following removal of all cargo materials and lowering of the hold right-side curtain panels, it was found that the fuselage rupture was aligned with the nominal position of the number-4⁷ passenger emergency oxygen cylinder; one of seven such cylinders in a bank along the right side of the hold (Figure 8). A further six cylinders were located in a central location within the ceiling of the cargo hold. The number-4 cylinder was missing from the bank, with the upper support bracket bent downward and both the retaining strap and lower cradle not present (Figure 9). The adjacent number-5 cylinder lower support cradle had been pulled downward and away from the cylinder as a result of the fuselage rupture. However, the upper cylinder mount and strapping remained secure and the cylinder gas connections intact (Figure 10).

Each of the passenger oxygen cylinders had three connected stainless steel lines – an overpressure relief vent line, a delivery line and a service/filling line. The filling and delivery lines were fed through a tee-piece from a common cylinder connection, with a pressure regulator and transducer integral to the assembly. The number-4 cylinder valve had fractured and separated from the system lines in several locations around the valve assembly (Figure 11):

- the service/delivery T-piece had fractured from the cylinder valve outlet, with the damaged and partly intact pressure reducer remaining connected to the delivery line (Figure 12)
- the service line had fractured through the thermal compensator fitting at the service/delivery T-piece (Figure 13)
- the overpressure relief vent line had fractured immediately before its connection into the common line for the cylinder bank (Figure 14). The green indicator

⁷ Cylinders were numbered (for the purposes of this investigation) from the front of the cargo hold.

disk within the overboard discharge port at the end of the common vent line (refer to the Oxygen system description) was found intact and in-place.

Figure 8: Forward cargo hold wall with remaining six oxygen cylinders



Figure 9: Fuselage rupture coincident with mounting position of the number-4 oxygen cylinder



Figure 10: Number-5 oxygen cylinder adjacent to fractured fittings and lines from the number-4 cylinder



Figure 11: Oxygen cylinder and valve illustration – points of fracture marked in red, oxygen delivery line in green

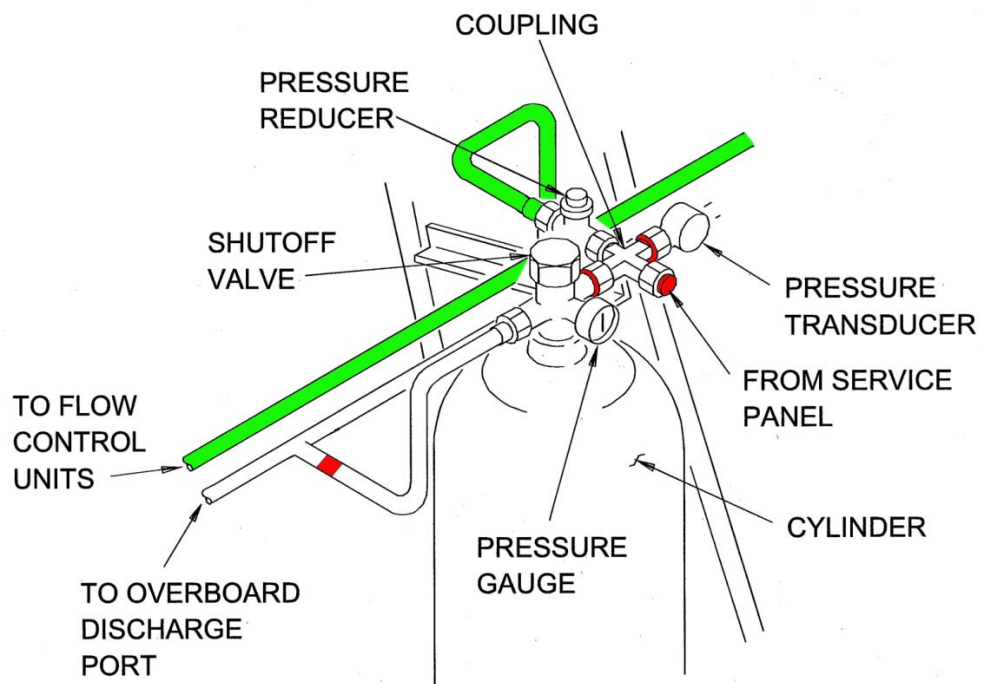


Figure 12: Number-4 cylinder pressure reducer and tee-piece - fractured away from cylinder valve at arrowed connection

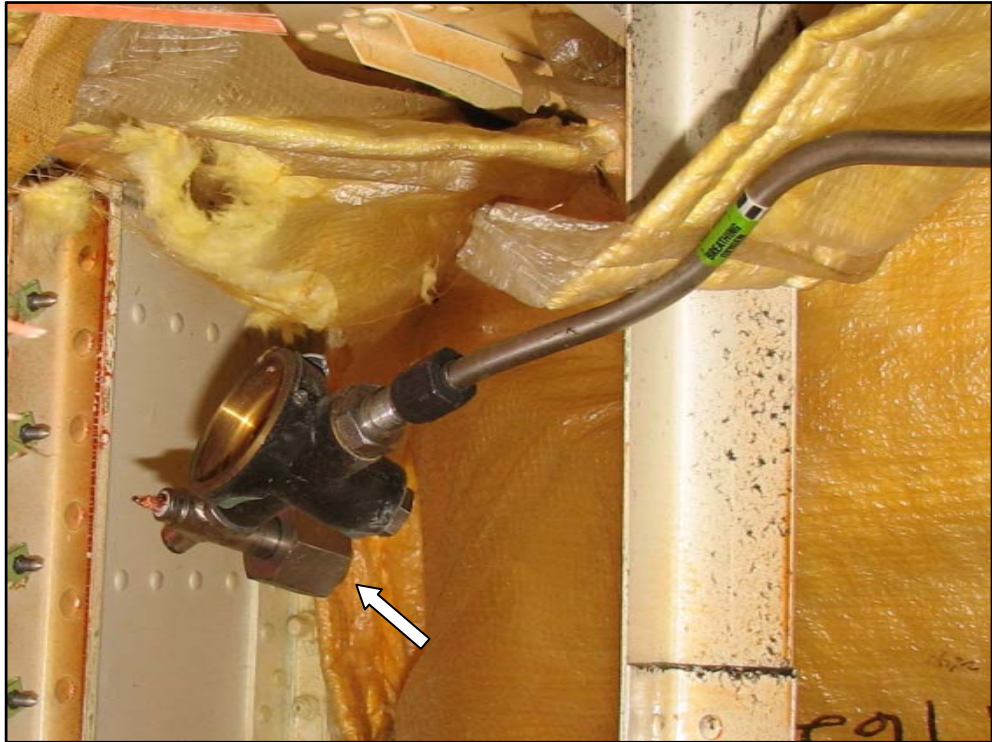


Figure 13: Number-4 cylinder service line fracture (arrowed)



Figure 14: Number-4 cylinder overpressure discharge line fracture (arrowed)



Close examination of all exposed connections, fittings and lines showed no evidence of heating, sooting or discolouration that might have suggested localised combustion had occurred within or in proximity to the cylinder and its connections. Similarly, all structural, panel and cargo surfaces that surrounded the fuselage rupture showed no evidence of heating or damage associated with combustion effects. There were no unusual coatings, deposits or sprays of foreign material noted over any of the surfaces exposed to the event.

The pressure gauges on all 12 remaining passenger oxygen cylinders showed all to have been exhausted i.e. zero internal pressure remaining.

Engine number-3

Several small pieces of structural honeycomb material of the type comprising the wing leading edge fairing were found trapped around the edges of panels within the left side of the number-3 engine pylon (side facing the rupture). A small indentation and cut was found within the number-3 engine intake acoustic panelling, located immediately inside the plane of rotation of the engine fan (Figure 15). There was no evidence of damage to the fan blades themselves, nor was there any evidence of the ingestion of debris into the engine core.

The aircraft operator reported that an internal boroscopic inspection of the engine while in Manila, identified some damage to the turbine components, although the nature of the damage suggested that it was unrelated to the depressurisation event. The engine was changed as a precaution.

Figure 15: Damage to acoustic lining (arrowed) behind the number-3 engine fan



Cabin – R2 door

The R2⁸ door into the aircraft's main cabin was located directly above the fuselage rupture (at STA 830). An external panel located between the two door hinges showed localised outward bulging from a point immediately below the upper hinge, with the forward edge of the panel raised above the surrounding fuselage skin (Figure 16). The main external door handle was in the fully closed position, however the upper and lower door gates⁹ were partially retracted.

Within the aircraft, the cabin around the R2 door had sustained substantial damage and disruption (Figure 17). The cabin floor to the left and immediately inside the R2 door frame had sustained an impact that created a single circular perforation approximately 20 cm (8 inches) in diameter, located immediately above the number-4 oxygen cylinder position (Figure 18). Fragments of the cabin flooring and covering extended down into the hole. Above the hole, the forward partitioning panel between the door and the row 26J and K seats showed an elongated green coloured abrasion, leading upward to an area of impact damage at the mid-height position of the forward R2 door frame (Figure 19). The door escape slide shroud (bustle) also showed vertically-oriented scoring and green smear marks along the corner and forward facing surface. The portable walk-around oxygen cylinder normally located in an alcove just inside the R2 door was not present and was not accounted for in a subsequent search of the aircraft.

⁸ The R2 door was the second main cabin door on the right side of the aircraft.

⁹ The cabin door gates are flap-like panels at the top and bottom of the door that are retracted by the door opening mechanism, to allow the door to move outward through the door frame opening.

Figure 16: Cabin R2 door – damage to external panelling



Figure 17: Interior of R2 door and cabin – location of floor hole arrowed



Figure 18: Hole in cabin floor – viewed from position of number-4 oxygen cylinder. Broken yellow lines mark the normal route of the first officer's aileron control cables



Figure 19: Door frame damage, green paint smear and rotated R2 door handle



The internal door handle was found in approximately the one-o'clock position (looking from inside), with the turned-in handle end embedded into the door lining material. That position was consistent with a movement through approximately 120 degrees from the fully-closed (locked) position. A 180 degree handle movement represented the fully open position. The downward facing surfaces of the handle end (when the door is in the locked position) showed damage and abrasion consistent with impact against another object. Inspection of the internal door systems showed the handle shaft had fractured and the actuating cam plate and retainer had pulled away from its associated mechanism (Figure 20), allowing the handle to rotate freely. As such, the handle position as observed inside the cabin was not indicative of the actual door security.

Above the R2 door within the cabin, the overhead panelling, fixtures and utility storage compartments had sustained extensive impact damage. The panels above the door frame had been pushed inward, exposing the overhead structure and pressure reservoir for the door emergency power assist opening system (EPAS, Figure 21). Amongst the impact damage, it was observed that an unusually uniform semi-circular section had been forcibly cut from the panelling and access door (Figure 22), with the cut-out section later recovered from above the damaged storage compartment casing. The diameter of the cut-out region closely matched that of the passenger oxygen cylinders (Figure 23). Adjacent to the cut-out opening was a semi-circular area of crushing damage to a partitioning panel (Figure 24); the damage being of a similar diameter to the cut-out section. A light fitting, normally present in the overhead panels had sustained upward crushing damage and presented clear green paint smears of a similar colouration to the marks on the partition panel and door bustle.

Various items of debris were found around the aircraft cabin in the vicinity of the R2 door. Of note, this included fragments of the number-4 oxygen cylinder valve handle, the valve pressure relief assembly and the valve body itself. A fragment of the valve body was also recovered from within the damaged area on the door frame.

A thorough search of the cabin and overhead ceiling void space failed to locate any part of the number-4 oxygen cylinder itself.

Figure 20: R2 door panel underside – fractured shaft and separated plate

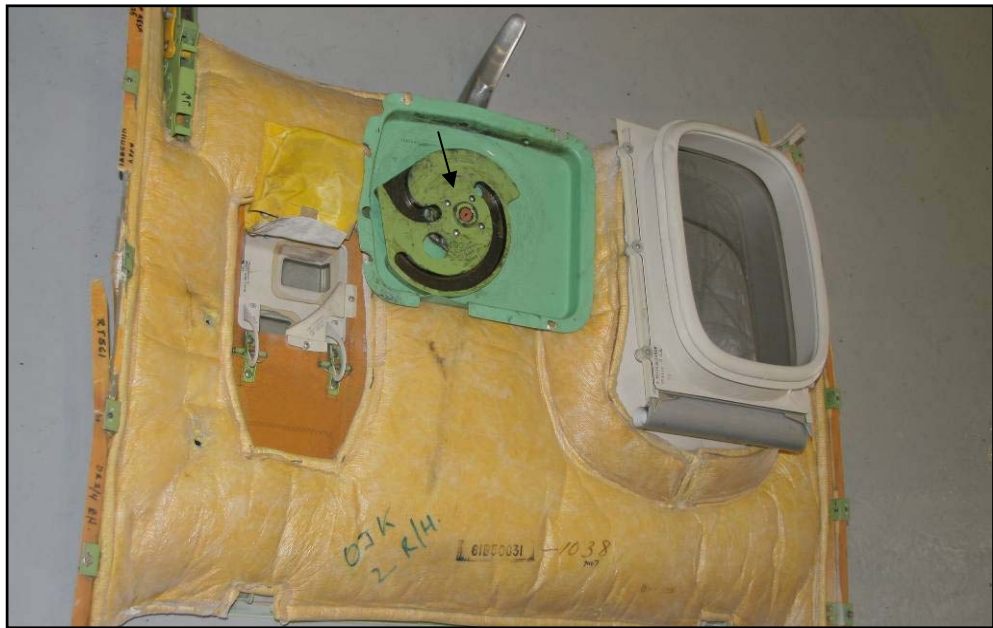


Figure 21: Damage above R2 door, exposing the EPAS cylinder (arrowed)



Figure 22: Cut-out section found in panels above the R2 door



Figure 23: Panel with cut-out placed against another oxygen cylinder to illustrate the conformance in diameter



Figure 24: Semi-circular damage in partition of compartment above R2 door



Electrical

Numerous electrical cables and cable bundles routed through the lower aircraft fuselage near the point of rupture had sustained damage or been severed by the rupture event. Approximately 85 discrete conductors from six separate bundles had been affected.

The ATSB requested the aircraft manufacturer to carry out an analysis of the damaged wiring to determine the possible effects on the functionality of the aircraft oxygen system. Of the 85 damaged wires, 38 were identified as serving the operation and monitoring of the oxygen system. The majority of those were 22-gauge conductors originating from the cylinder pressure transducers and feeding an averaging unit that provides a total system pressure indication on an EICAS status page.

Several fractured wires would have affected the functionality of the oxygen system flow control units (FCU) and the system reset solenoid. According to the manufacturer's analysis, the fractured wires would have impaired the flight crew's ability to:

- manually select operation of the passenger oxygen system
- verify passenger oxygen system activation by an indication on the EICAS
- activate or deactivate the flow of therapeutic oxygen
- reset the passenger oxygen system.

It was noted that normal activation and control functions of the system based on cabin altitude, would not be affected by the damaged wiring.

Flight control

Both right side (first officer's) aileron control cables, routed along the right side of the fuselage above the passenger oxygen cylinders, had been fractured during the rupture event. All separated cable ends showed the irregular splaying and unwinding of the cable wires; characteristic of a tensile overstress failure. The nature of the cable failure and the proximity of the cable route to the cabin floor damage immediately above the number-4 oxygen cylinder location (Figure 18), indicated that the cables had been fractured as the cylinder was projected upward after rupturing.

Other damage

Cargo

The forward hold of the aircraft contained both containerised and palletised cargo. All passenger baggage was located within conventional metal containers positioned forward of the point of rupture. None of the containers within the hold showed evidence of damage or other markings that could be associated with the rupture event. The cargo adjacent to the fuselage rupture was a plastic wrapped and netted pallet of general freight in cardboard boxes and similar. The cargo packed along the side closest to the rupture had been pulled towards the opening, with several items becoming lodged within, and protruding from, the void (Figure 25). Items packed near to the fuselage rupture showed varying degrees of forced impact type damage and a section of aluminium structure from the hold framework was recovered from amongst the packaging. There was no evidence of an explosive event having originated from within the cargo itself, and a review of the cargo manifests showed no items that could be considered capable of causing or contributing to such an event. Reconciliation of the recovered cargo by the freight service provider accounted for all items on the manifest.

Figure 25: Cargo pallet adjacent to fuselage rupture (view looking to the rear)



Personnel information

Table 1 summarises the operational qualifications and experience of the flight crew at the time of the occurrence.

Table 1: Flight crew qualifications and experience

	Captain	First Officer	Second Officer
Licence Category	ATPL ¹⁰	ATPL	ATPL
Instrument rating	Command	Command	Co-pilot
Last Class-1 medical	27 Sep 2007	20 May 2008	27 Jun 2008
Total flying hours	15,999	12,995	4,067
Total on 747-400	2,786	5,736	2,292
Total last 30 days	67h 48m	96h 57m	67h 48m
Total last 90 days	221h 54m	251h 27m	137h 33m

¹⁰ Air Transport Pilot License.

Aircraft information

Aircraft general

Table 2: General aircraft details

Aircraft type	Boeing Company 747-438
Serial number	25067
Year of manufacture	1991
Registration	VH-OJK
Certificate of Airworthiness	SY 45 valid from 17 June 1991
Certificate of Registration	last issued on 24 October 2005
Total airframe hours	79,308
Total airframe cycles	10,419
Last 'A' maintenance check	13 June 2008, at 78,967 h, 10,357 cyc
Last 'D' maintenance check	9 April 2004, at 58,367 h, 8,173 cyc

Cabin door

All main cabin doors of the 747-400 aircraft type were designed as outward-opening 'plug doors'. A plug door is designed to be physically larger than the doorway opening, and mates with the frame around the full circumference when in position. It is designed to increase the security of the pressurised fuselage, with pressurisation loads serving to force the door more tightly against the frame. Retractable gates at the top and bottom of the door serve to allow it to move inward and then sideways through the door frame during the opening and closing process when the aircraft is not pressurised. The plug door design provides for a level of protection against inadvertent or intentional attempts to open the door while the aircraft is in flight. A latch mechanism holds the door in the closed position when the aircraft is not pressurised.

Flight control system

The Boeing 747-400 flight control system was a hydraulically-assisted mechanical arrangement, with inputs from the primary cockpit controls being translated to the control surface actuating systems via cables. The systems were designed to provide complete duplication and redundancy between the captain's and first officer's controls, such that the failure of any particular system would not lead to a loss of functionality affecting aircraft controllability. Basic certification specifications for all modern transport category aircraft require this behaviour by design. In respect of the first officer's aileron control cables that were severed in the occurrence, those were duplicated by the captain's system, the cables from which were routed along the opposite (left) side of the forward cargo hold. Interlinks between the aileron systems provided the necessary redundancy in this instance, ensuring the continued safety of flight after the event.

Oxygen system description

The 747-438 aircraft was equipped with three separate supplemental breathing oxygen systems. Use of oxygen by passengers and crew is necessary if cabin pressurisation is lost during high-altitude flight. A diluter-demand¹¹ system provided oxygen to each flight crew station and an independent, continuous flow¹² system served the passenger cabins, crew rest areas, toilets and cabin crew stations. Portable oxygen equipment was also stored throughout the passenger cabins for medical and walk-around use. All three systems were of the pressurised gaseous storage type, with no chemical oxygen generators employed on the aircraft.

The passenger oxygen system consisted of 13 high-pressure (12,755 kPa / 1,850 psi) steel cylinders, each with an integral shut-off valve, pressure gauge and over-pressure protection system (frangible disk). Each cylinder carried a quantity of oxygen equivalent to 3,256 litres (115 cu.ft) when charged to 12,755 kPa (1,850 psi) at ambient conditions of 1,013 HPa (760 mmHg) and 21 °C (70 °F). Seven of the cylinders were located along the right side of the forward cargo hold; the remainder positioned within the void space between the cargo hold ceiling and the main cabin floor (Attachment B). A coupling with an integral thermal compensator and check-valve connected each cylinder to an electrical pressure transducer and pressure reducer. The cylinder over-pressure protection system was designed to operate in the event that cylinder pressure rises to between 17,237 – 19,133 kPa (2,500 – 2,775 psi). In that instance, the internal frangible disk bursts, venting the cylinder contents into a manifold that flows to an overboard discharge port located rearward of the forward cargo door. A green coloured disk was recessed into the port to protect the pipe-work internals and to provide an external indication of pressure relief in the event of a cylinder valve burst disk rupture.

System servicing was achieved by replenishing the cylinder contents from a common service panel, or by individual replacement of the depleted cylinders. A common high-pressure manifold line fed each cylinder from the service panel.

The outlet of each cylinder, after being reduced to around 4,150 kPa (600 psi) via the pressure reducer, was directed to a common supply line that fed a bank of three parallel-connected continuous flow control units (FCU). Internal aneroids within each unit sense the cabin altitude, and automatically actuate the units if the cabin altitude increases to between 13,250 to 14,500 ft. The system was also designed to be activated manually via a switch on the flight deck. On activation, oxygen was metered into the low-pressure distribution manifold, which fed the passenger and cabin crew service units. The flow control units regulated the pressure of oxygen fed to the service units in proportion to the cabin altitude, with a greater pressure (hence flow) being delivered at higher altitudes. System information from the manufacturer indicated that the flow control unit delivery pressures could vary from 69 kPa (10 psig¹³) at 14,000 ft cabin altitude, to 296 kPa (43 psig) at 40,000 ft. Activation of the passenger oxygen system was accompanied by an EICAS 'PASS OXY ON' message, the commencement of an automated passenger address

¹¹ A diluter-demand oxygen system provides diluted or 100% oxygen flow as required by the breathing action of the user.

¹² A continuous flow oxygen system delivers a constant stream of oxygen to the user, once the system and mask have been activated.

¹³ Psig – pounds per square inch gauge – a pressure measurement relative to the surrounding atmosphere (ambient).

announcement, and the illumination of the cabin lighting. Attachment C provides a schematic overview of the aircraft passenger oxygen supply system.

The passenger service units located in the overhead panels above the seats carried one or more oxygen modules, each containing a valve assembly and oxygen masks. When activated, the passenger oxygen system delivers an initial pressure surge which actuates the latch valve plunger, forcing the module cover open and allowing the masks to fall. The passenger must then grasp and pull down on the mask assembly, which pulls an actuating pin from the valve assembly and allows oxygen to flow to the mask. Should the module cover fail to open, the internal latch may be disengaged using a dedicated tool and the cover opened manually.

Oxygen cylinder description

All passenger oxygen cylinders installed in the Boeing 747-400 aircraft were produced as seamless, single piece deep-drawn and forged units from heat-treated Chromium-Molybdenum alloy steel material. The cylinders measured nominally 22.8 cm outside diameter by 75.1 cm long (8.98 in x 29.56 in) with a specified minimum wall thickness of 2.87 mm (0.113 in). The cylinder design incorporated a constant thickness hemispherical base and body, transitioning to a spin-forged upper dome and neck. The machined neck threads were specified as a 1-11.5 American National Standard Taper Pipe Thread (ANPT) with a ± 1 turn gauge tolerance.

The internal surface finish required a minimum 1000 mg/ft² of phosphatised coating for corrosion inhibition. External coating specifications required primer and overcoats of 2-part catalysed urethane paint.

The cylinders had been manufactured to comply with the requirements of the United States Code of Federal Regulations (CFR) Title 49 (Transportation), Part 178 (Specifications for Packagings), Subpart C (Specifications for Cylinders) §178.44 '*Specification 3HT seamless steel cylinders for aircraft use*'. The cylinders were identified as type DOT3HT-1850¹⁴, and were allocated the manufacturer's part number 801307-00 (for the cylinder-valve assembly) and the equivalent Boeing part number 60B50087-7.

Oxygen cylinders installed

Due to periodic removal and replacement for maintenance or replenishment purposes, the cylinders installed in VH-OJK at the time of the occurrence were of varying ages and serial numbers (Table 3).

Table 3: Details of the passenger oxygen cylinders fitted to VH-OJK at the time of the occurrence

Location	Serial No.	Manufactured date	Fitted to aircraft date
Right side #1	240341	Feb 92	16 Jun 07
Right side #2	ST30395	Oct 01	14 Jun 08
Right side #3	ST20539	Apr 01	19 Jan 07
Right side #4	535657	Feb 96	14 Jun 08

¹⁴ United States Department of Transportation, 1,850 psi nominal operating pressure

Location	Serial No.	Manufactured date	Fitted to aircraft date
Right side #5	666845	Mar 99	01 Mar 06
Right side #6	240293	Dec 91	07 Jan 08
Right side #7	239949	Nov 91	07 Jan 08
R Fwd O/H	883198	May 89	07 Jan 08
L Fwd O/H	686764	May 98	01 Sep 06
R Mid O/H	805949	Sep 04	17 Nov 07
L Mid O/H	686716	Jun 99	28 Sep 05
R Aft O/H	679454	Apr 99	07 Jan 08
L Aft O/H	71505	Jan 91	22 Jul 07

From the aircraft operator's records of installed equipment, the missing (presumed failed) oxygen cylinder was identified as serial number 535657. Records obtained in the United States by representatives of the National Transportation Safety Board (NTSB), identified the cylinder as one of a batch of 94 such items manufactured and certified in February 1996. The production batch serial number range commenced at S/N 535585 and concluded at S/N 535678.

Oxygen system maintenance

Routine maintenance

Records from the aircraft operator provided a history of general maintenance actions carried out on the passenger and crew oxygen systems (Table 4) during and since the last major inspection (D-check) completed on 9 April 2004.

Table 4: Oxygen system maintenance history

Activity	Date
Crew system cylinder and plumbing inspection	25 March 2004
Passenger system test	1 April 2004
Therapeutic system test	3 April 2004
Passenger system pressure indication test	3 April 2004
Crew and passenger portable cylinder check	9 February 2008
Crew and passenger system cylinder and plumbing inspection	11 February 2008

Checks of the fixed oxygen cylinder pressure indication system were also conducted during routine aircraft maintenance inspections – the last three checks being conducted on 1 March, 17 April and 14 June 2008. Passenger oxygen cylinders number-2 (SN: ST30395) and number-4 (SN: 535657 – the failed item) were fitted to the aircraft during this last check; replacing cylinders that were due for requalification testing.

Non-routine maintenance

Aircraft equipment operational faults and conditions requiring maintenance action were documented in the aircraft's technical log system. Copies of all log entries

and remedial actions from the date of the number-4 cylinder installation (14 June 2008) to the date of the occurrence, were obtained and reviewed by the ATSB, with a view to identifying any issues that may have been experienced with the aircraft oxygen systems, and any maintenance activity that may have been conducted in the vicinity of the passenger oxygen system cylinder installation.

During the period 14 June to 16 July 2008, the only technical log entries relating to oxygen systems were those recording the ad-hoc use and replacement of portable oxygen bottle and masks, and the installation and removal of temporary oxygen cylinders for passenger therapeutic purposes. On 16 July 2008, the logs noted a fluctuation in the flight-deck indication of the crew oxygen system pressure. In response, a physical check of the cylinder pressure was made, together with a check of the electrical interconnections to the system pressure sensing transducers, with no unserviceabilities identified. An entry into the aircraft's minimum equipment list (MEL¹⁵) was also raised at that time to permit continued operation of the aircraft. Over the subsequent days of operation, several further log entries had been made regarding the indicated fluctuation of crew oxygen system pressure. In all cases, physical checks confirmed the system to be within the serviceable pressure range.

The only entry in the technical log relating to the passenger oxygen system was made on 22 July 2008, when the crew noted an EICAS status message 'PASS OXY REFILL' during a flight from Los Angeles, USA to Sydney, NSW. Under normal circumstances, that message would be displayed if the passenger oxygen system pressure falls below 11,032 kPa (1,600 psi). The log action entry reported that ground checks could not duplicate the message, and checks of the system pressure on the EICAS, the system servicing (refill) panel and the individual cylinders themselves, found that all indications were within serviceable limits.

Oxygen cylinder maintenance

The US federal regulations under which the cylinder design was certified, required that each cylinder be subject to periodic requalification in order to remain approved for use. Under US CFR Title 49 §180.209, specification 3HT cylinders must be requalified at intervals not exceeding 3 years. Under an exception provided in CFR Title 49 §175.8, the FAA allows installed cylinders that have reached or passed their requalification date, to remain in service until the next significant scheduled maintenance visit of the aircraft in which they are fitted. Installed cylinders that have passed their requalification date may not be serviced or filled until requalified.

Requalification requirements for specification 3HT cylinders state that the cylinder must undergo internal and external visual inspection, followed by a hydrostatic pressure test within a water jacket, for the determination of the cylinder volumetric expansion¹⁶ while under pressure. The hydrostatic test pressure was specified to be

¹⁵ An MEL is a document approved by CASA that contains the conditions under which a specified aircraft may operate, with particular items of equipment inoperative, at the time of dispatch. It provides a time interval for the rectification of the faulty item, relevant to the operational significance of the item. This document is carried on board the aircraft and provides the Pilot In Command with clear guidance to make an informed decision as to whether the particular flight should or should not proceed.

¹⁶ Both elastic and permanent (plastic) expansion criteria for acceptance are specified.

1.667 (5/3) times the nominal cylinder service pressure, which equates to 21,256 kPa (3,083 psi) for the cylinders in question.

In addition to the periodic requalification requirements, DOT-3HT cylinders carry a mandatory retirement life of 24 years from the date of the original test as marked on the cylinder, or after 4,380 discrete pressurisations (recharge cycles).

The cylinder manufacturer's component maintenance manual for part number 801307 series cylinder and valve assemblies mirrored the regulatory requirements for cylinder requalification, and provided additional guidelines and requirements for routine cylinder maintenance operations.

Failed cylinder history

Records from the cylinder manufacturer and the aircraft operator allowed the compilation of a life-time history / sequence of events table for the failed oxygen cylinder.

Table 5: Cylinder S/N 535657 sequence of events

Date	Event
3 Jan 1996	Cylinder manufactured and certified (including hydrostatic testing)
14 Feb 1996	Delivered to Qantas installed in a new Boeing 767 aircraft (VH-OGQ)
2 Feb 1999	Removed from VH-OGQ for requalification
3 Apr 1999	Inspection and second hydrostatic testing – accepted
10 Apr 1999	Fitted to B747-400, VH-OJL (ceiling middle position)
20 Feb 2001	Moved to ceiling aft right position, VH-OJL
24 Feb 2001	Moved to ceiling aft left position, VH-OJL
24 Feb 2001	Moved to ceiling middle right position, VH-OJL
20 Jan 2002	Removed from VH-OJL
8 Mar 2002	Inspection and third hydrostatic testing – accepted
29 Mar 2002	Fitted to B747-300, VH-EBY (right sidewall #7)
31 Jan 2005	Removed from VH-EBY
3 Feb 2005	Inspection and fourth hydrostatic testing – accepted
22 Feb 2005	Fitted to B747-400, VH-OJK (ceiling aft right)
7 Jan 2008	Removed from VH-OJK
26 May 2008	Inspection and fifth hydrostatic testing – accepted
14 Jun 2008	Refitted to VH-OJK (right sidewall #4)
22 Jul 2008	Physical (visual) check of cylinder pressure
25 Jul 2008	Cylinder failure event

All requalification testing and inspection of the aircraft oxygen cylinders had been carried out at the operator's in-house workshops and facilities. Following the occurrence, a series of inspections of those facilities was carried out – initially by representatives of the Australian Civil Aviation Safety Authority (CASA), and subsequently by a team of investigators from the ATSB, NTSB, US Federal Aviation Authority (FAA), Boeing and CASA. The purpose of the inspections was primarily to gather information on the procedures and processes employed for

handling, servicing and inspecting the oxygen cylinders, and to discuss the broader issues and ongoing investigation with the technical staff. Compliance with regulatory, original equipment manufacturer's (OEM) requirements and general best-practice was examined.

In summary, the inspections did not identify any significant issues or deviation from appropriate practice that had the potential to affect the integrity of the cylinder-valve assemblies. It was noted that while the operator's engineering group maintained a quality system accredited to the requirements of the ISO 9000 series of standards, the hydrostatic testing and oxygen workshops did not carry formal third-party technical accreditation for the performance of the inspections and tests carried out on the cylinders. Although not mandatory, such accreditation (provided by agencies such as the National Association of Testing Authorities – NATA) provides an additional level of external assurance that the test methods and techniques employed are valid, the testing officers' training and qualifications appropriate, and equipment is serviceable and calibrated.

Fuselage maintenance

The aircraft operator carried out a review of their maintenance records for the aircraft fuselage in the vicinity of the damaged zone (STA720 to STA880 and fuselage stringer 29 to 40 on the right side) and reported that those records showed no evidence of prior damage or repair activity in that area.

Survival factors

Cabin – safety systems

Investigators conducted a comprehensive walk-through examination of the aircraft's cabin and a survey of the safety systems; in particular, the status of the passenger oxygen masks and equipment (Figure 26).

The following preliminary observations were made during that examination:

- there were 353 passenger seats in the aircraft
- 476 passenger oxygen masks had deployed from their overhead compartments
- 426 passenger oxygen masks were pulled down (i.e. activated for use)
- row 53 centre overhead passenger service unit was hanging down
- forward crew rest and customer support manager station masks had not deployed
- the covering on the rear surface of the partition in front of seats 40A,B,C was damaged
- floor pressure relief panels were open at seats 24A (2), 25A, 37K and 54A
- one mask hose was detached from the ceiling fitting at seat 4K (3 masks deployed).

Crew and passengers

ATSB investigators interviewed all 16 cabin crewmembers and documented their individual recollections of the flight and the outcomes of the occurrence. Those responses were correlated against the timeline for the development and progress of the occurrence (as obtained from the flight data recorder). Additionally, the operator conducted an assessment of the crew and passenger response to the occurrence and the performance of the cabin safety systems. The findings of that assessment were provided to the ATSB to assist in the overall investigation.

The ATSB has conducted a survey of those passengers on the flight for whom contact details were available. The survey was provided as a written questionnaire, requesting completion and return. As of the end of January 2009, 46.8% of the passengers surveyed had returned a response (164 of 350).

In general, the cabin crew and passengers reported similar experiences during the event and the diversion to Manila. The final investigation report will contain an examination and analysis of the cabin events, however the following key observations were noted:

- Prior to departure of the aircraft from Hong Kong, the audio track from the safety demonstration video was not functioning – requiring the cabin services manager to recite the safety briefing over the cabin public address system.
- Immediately after the depressurisation event, the automatic emergency announcement system did not function.
- Some passengers reported that the oxygen masks did not deploy from the passenger service units (PSU) above their heads, requiring a cabin crewmember to manually open the PSU.
- Some passengers reported that the elastic straps on the oxygen mask were too loose, or did not tighten.
- Some passengers reported that the mask bags did not inflate, and as such, they were unsure if oxygen was flowing to the mask.
- The cabin crew reported that some passengers were wearing their masks, but had not pulled the masks down to activate the flow of oxygen.

Passenger oxygen system performance

The 13 P/N 801307-00 aviators' breathing oxygen cylinders fitted to the aircraft for passenger and cabin crew use, had a combined capacity of 42,338 litres (1,495 cu.ft) at standard temperature and pressure¹⁷, when filled to the nominal 12,755 kPa (1,850 psi) pressure.

Damage to the physical components of the passenger oxygen system included the loss of the number-4 cylinder, the fracture of the cylinder service (filling), overpressure relief and output fittings, and the localised disruption to the electrical systems associated with the contents measurement, flow control and system monitoring functions. The common line directing the output of all right-side cylinders to the oxygen flow control system had not been compromised. Figure 11

¹⁷ For the purposes of the investigation, standard temperature and pressure was taken as 1,013.2 mb (760 mm Hg) and 21°C (70°F) respectively.

illustrates the typical cylinder valve interconnections and the points of mechanical disruption.

In consideration of the system configuration, the number of activated passenger oxygen masks and the damage sustained, the aircraft manufacturer conducted an examination and analysis of the passenger oxygen system availability during the period between the depressurisation and the landing at Manila. That work concluded that, on the basis of the remaining available oxygen volume and the design maximum leakage rates resulting from the system damage, oxygen would have continued to flow at usable levels to all activated masks, for approximately 65 minutes following the depressurisation event.

Figure 26: Typical appearance of the cabin after arrival in Manila. Note the passenger masks dropped and activated, and those dropped and not activated (arrowed)



Flight recorders

The aircraft was fitted with three flight recorders:

- cockpit voice recorder (CVR)
- flight data recorder (FDR)
- quick-access recorder (QAR).

The CVR and FDR are required by regulation to be installed on certain types of aircraft. Information recorded by the CVR and FDR is stored in 'crash-protected' modules.

The QAR is an optional recorder that the operator has chosen to fit to all their B747-400 aircraft. Information recorded by the QAR is not crash-protected. As the name suggests, QARs allow quick access to flight data whereas FDR's require specialist downloading equipment. The parameters that are recorded by an FDR are defined by regulatory requirements. However QAR systems can be configured by

an airline to record different and, in most cases, more parameters than the FDR system. Airlines routinely use QAR data for engineering system monitoring and fault-finding, incident investigation and flight operations quality assurance programs.

Recording system operation

CVR system

The CVR records the total audio environment in the cockpit area. This includes crew conversation, radio transmissions, aural alarms, control movements, switch activations, engine noise and airflow noise. The CVR installed in VH-OJK retained the last 2 hours of information in solid-state memory, operating on an endless-loop principle.

CVR systems are designed to operate even when the aircraft is on the ground with the engines shutdown. This allows investigators access to important crew conversation or checklist actions before the first engine is started for takeoff or after the last engine is shutdown after landing. The disadvantage is that valuable audio information is quickly overwritten following a non-catastrophic accident or serious incident, where there is a significant interval between the occurrence and when the flight is completed and electrical power is removed from the CVR.

FDR system

The FDR records aircraft flight data and, like the CVR, operates on an endless-loop principle. The recording duration of the FDR fitted to VH-OJK was 25 hours; the FDR typically records when at least one engine is operating and stops recording when the last engine is shutdown. The FDR installed in VH-OJK recorded approximately 300 parameters and used a magnetic tape as the recording medium.

QAR system

Like the FDR, the QAR records aircraft flight data. The QAR installed in VH-OJK stored data on a removable magneto-optical disk with a capacity of 230 Mb and approximately 500 recorded parameters. Airlines balance the logistics of handling large quantities of QAR disks with the benefits of obtaining the data as soon as possible after a flight has occurred. Typically, most airlines will leave a disk inserted in the QAR for several days until the aircraft returns to a suitable maintenance base.

The QAR system installed on VH-OJK was configured to enter a 'sleep' mode once a period of stable cruise had been detected. Once a climb or a descent was detected, the QAR would resume recording until a further period of cruise was detected. As B747-400 aircraft are typically used on long-range flights, using this sleep mode technique reduced the amount of data that was recorded per flight and increased the number of flights that could be recorded on a single disk. Worldwide experience over many decades has shown that the take-off and landing phases of flight have the highest risk and these periods are continuously recorded using this 'sleep' mode technique.

Recorder recovery

The CVR, FDR and QAR disk were removed from the aircraft in Manila under the control of the Australian Transport Safety Bureau (ATSB) and sent to the operator's safety department in Sydney. They were received on Sunday 27 July 2008. Permission was given by the ATSB for the operator to replay the QAR disk and a copy of the QAR data was provided to the ATSB.

The CVR and FDR were quarantined and sent to the ATSB technical analysis laboratories in Canberra. They were received on 28 July 2008. The CVR was downloaded on 28 July 2008 and the FDR was downloaded on 29 July 2008.

Results

CVR

The entire 2 hours of recorded audio was successfully downloaded by ATSB investigators in Canberra. Analysis of the audio showed that the oldest information retained by the CVR related to aircraft operation while cruising at 10,000 ft, after the emergency descent had already taken place. A comparison with the FDR information showed that the start of the CVR audio occurred 30 minutes and 41 seconds after the depressurisation event had occurred.

Of the 2 hours of CVR audio, 24 minutes covered flight time including the approach and landing at Manila. The remaining audio covered ground operations including the aircraft being towed from the runway to the gate and time with the aircraft stationary at the gate.

FDR

The tape was removed from the FDR by ATSB investigators in Canberra and downloaded. The FDR had recorded data from the following flights:

23 July 2008: Singapore – London

24 July 2008: London – Hong Kong

25 July 2008: Hong Kong – Manila

Continuous data from engine start on the ground in Hong Kong until engine shutdown on the runway in Manila was successfully recovered. The FDR data was used to produce a sequence of events and plots (Attachment D).

QAR

The QAR disk was replayed by the operator. As an empty disk had been installed in the QAR at Sydney on 23 July 2008, flight data from five flights was successfully recovered. The flights recorded were:

23 July 2008: Sydney – Melbourne

Melbourne – Singapore

Singapore – London

24 July 2008: London – Hong Kong

25 July 2008: Hong Kong – Manila

Analysis of the QAR data, in conjunction with FDR data, showed that the QAR recorded continuously from engine start on the ground in Hong Kong until 0212:28 UTC when, as expected, the QAR entered 'sleep' mode while the aircraft was in cruise at FL290. The depressurisation event occurred 4 minutes and 48 seconds later. Four seconds after the event, the QAR resumed recording data.

Sequence of events

The flight

The following sequence of events table was prepared from data obtained from the aircraft's flight recorders.

Table 6: Occurrence flight sequence of events

Time (UTC) (hh:mm:ss)	Time relative to event (hh:mm:ss)	Event:
01:22:12	-00:55:04	Takeoff at Hong Kong
01:42:30	-00:34:46	Aircraft reached top of climb FL290
02:12:28	-00:04:48	QAR entered 'sleep' mode and stopped recording
02:17:16	0:00:00	Depressurisation event
02:17:17	0:00:01	Autopilot (Right) disengaged
02:17:19	0:00:03	Cabin pressure warning commenced
02:17:20	0:00:04	QAR resumed recording data
02:17:38	0:00:22	Speed brake extended, engine thrust reduced
02:17:43	0:00:27	L & R isolation valves change to closed
02:17:54	0:00:38	Aircraft left FL293 on descent
02:17:57	0:00:41	A minimum cabin pressure of 5.25 psi was recorded ¹⁸
02:18:43	0:01:27	Autopilot (Centre) engaged
02:19:09	0:01:53	Autothrottle disconnected
02:22:50	0:05:34	Cabin pressure warning ceased
02:23:09	0:05:53	Aircraft descended through 11,000 ft
02:23:48	0:06:32	Aircraft altitude reached 10,000 ft
02:29:40	0:12:24	Captain's NAV SEL changed to right FMC
02:47:57	0:30:41	Start of CVR audio
02:56:11	0:38:55	Aircraft left 10,000 ft on descent
03:09:58	0:52:42	Autopilot (Centre) disengaged
03:11:56	0:54:40	Aircraft touched down at Manila
03:17:38	1:00:22	No. 3 engine shutdown on runway

¹⁸ This corresponds to a cabin altitude of 25,900 ft.

03:19:10	1:01:54	Remaining engines shutdown on runway
03:26:53	1:09:37	Park brake released for tow
04:01:12	1:43:56	Chocks on
04:51:06	2:33:50	CVR shutdown

Cylinder event

On the basis of the physical damage found with the aircraft forward cargo hold and cabin, it was evident that the number-4 passenger oxygen cylinder had sustained a failure that allowed a sudden and complete release of the pressurised contents. The rupture and damage to the aircraft fuselage was consistent with being produced by the energy associated with that release of pressure. Furthermore, it was evident that as a result of the cylinder failure, the vessel had been propelled upward, through the cabin floor and into the cabin space. Damage and impact witness marks found on the structure and fittings around the R2 cabin door showed the trajectory of the cylinder after the failure event.

With the exception of the damaged valve components, the failed number-4 cylinder body, or any part thereof, was not located within the aircraft after a thorough examination of the cabin, forward cargo hold and associated overhead and underfloor void spaces.

Table 7 presents an evaluation of the possible scenarios that may explain the absence of the cylinder.

Table 7: Missing number-4 cylinder – scenario evidence

Possibility	Evidence supporting	Evidence against
Cylinder ejected from aircraft during depressurisation event	Thorough search during investigation - cylinder not found on board. Rapid airflow could evacuate cylinder from cabin and/or hold.	Small opening in cabin floor – cylinder would not easily slip through.
Cylinder removed from aircraft after landing	Thorough search during investigation - cylinder not found on board.	Aircraft secured and access restricted after disembarking passengers. Cylinder large and visible to others if a passenger attempted to remove it.
Cylinder remains on board aircraft	Small opening in cabin floor – cylinder would not easily slip through.	Thorough search during investigation – cylinder not found on board Void spaces unlikely to accommodate size of cylinder without being visible or interfering with other aircraft systems.

Figures E1 – E7 (Attachment E) illustrate the likely trajectory of the cylinder after rupture, based upon the physical evidence found. The graphics represent a cross-sectional view through the aircraft at the position of the R2 main cabin door (STA 830).

Tests and research

Explosive residue testing

During the initial stages of the on-site investigation in Manila, an officer of the Australian Federal Police, with the assistance of the Philippine National Bureau of Investigation, conducted tests for the presence of explosive residue within the aircraft forward cargo hold and passenger cabin.

No indications of any residues of explosive compounds were detected in any of the examined areas.

Previous cylinder failures

To explore any historical experiences with the in-service failure of compressed gas cylinder/s, the ATSB has discussed the issue with several large manufacturers and users of transportable compressed gas containers, from both aviation and general industrial operations. On that basis, it appears that the VH-OJK cylinder event has been without precedent in the aviation arena, in terms of what is known about the nature of the failure and the aircraft damage sustained. Aviation oxygen cylinders have failed on-board aircraft previously, however all of the known events have been attributed to external influences, such as on-board fires or damage sustained during accident impacts.

Industrial oxygen and compressed gas cylinder failures have also been reported, however in each instance examined, the failures have been attributed to valve damage or to improper maintenance activity, resulting in excessive corrosion or material degradation. While the history of cylinder failure remains under examination, the characteristics of the occurrence event appear to remain unique in world-wide experience.

Oxygen gas analysis

During the inspection of the operator's oxygen cylinder maintenance and servicing facilities, records were provided of other DOT3HT-1850 cylinders that had been inspected and refilled around the same time as the failed cylinder SN: 535657. Two of those filled cylinders (SN: 681134 & 806422) were provided by the operator and submitted to the Defence Science and Technology (DSTO) Aircraft Forensic Engineering laboratories for the chemical analysis of the oxygen gas. Those cylinders had been inspected and hydrostatically tested the day following the failed cylinder.

The gas analyses from both cylinders were assessed against the requirements of MIL-O-27210F Type 1 '*Aviators' Breathing Oxygen*'. All results, with the exception of the moisture content, complied with the specification requirements. The moisture content results (36 and 34 ppm¹⁹ respectively) exceeded the specification limit of 7 ppm.

To further investigate this issue, the oxygen gas manufacturer was contacted and subsequently provided analytical certificates for the contents of the bulk transport

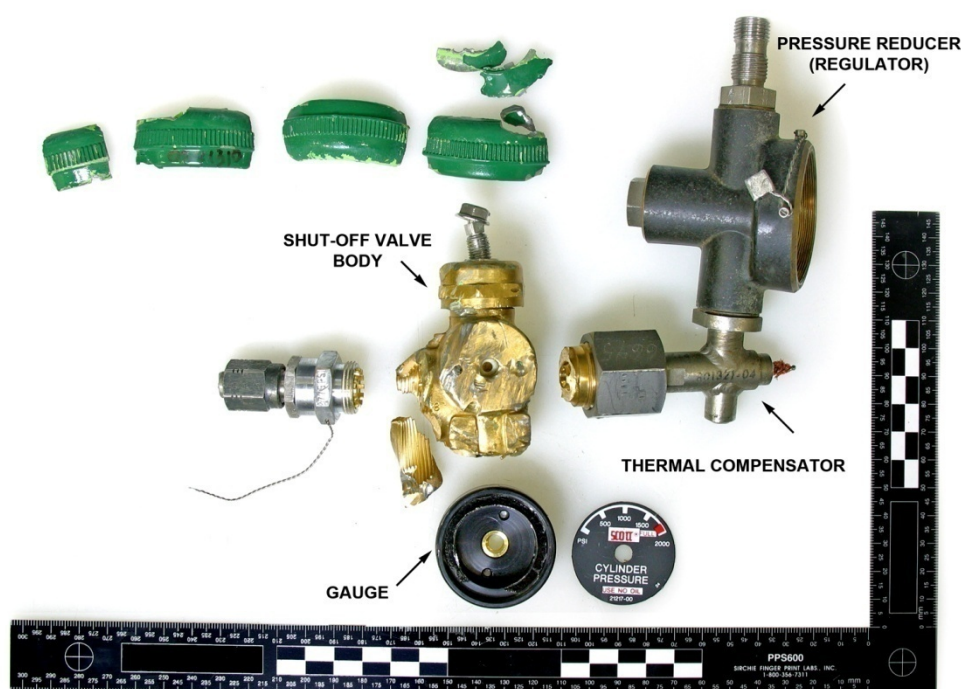
¹⁹ Parts per million.

containers from which the operator filled the aircraft cylinders. Those certificates reported a moisture content of less than 1 ppm – compliant with the specification requirements.

Valve components

While the entire body of the number-4 passenger oxygen cylinder had been lost from the aircraft, a number of damaged fragments and components from the valve assembly were recovered from the aircraft cabin, or remained attached to the pipe-work servicing the missing cylinder (Figure 27).

Figure 27: Cylinder number-4 valve and related components and fragments recovered



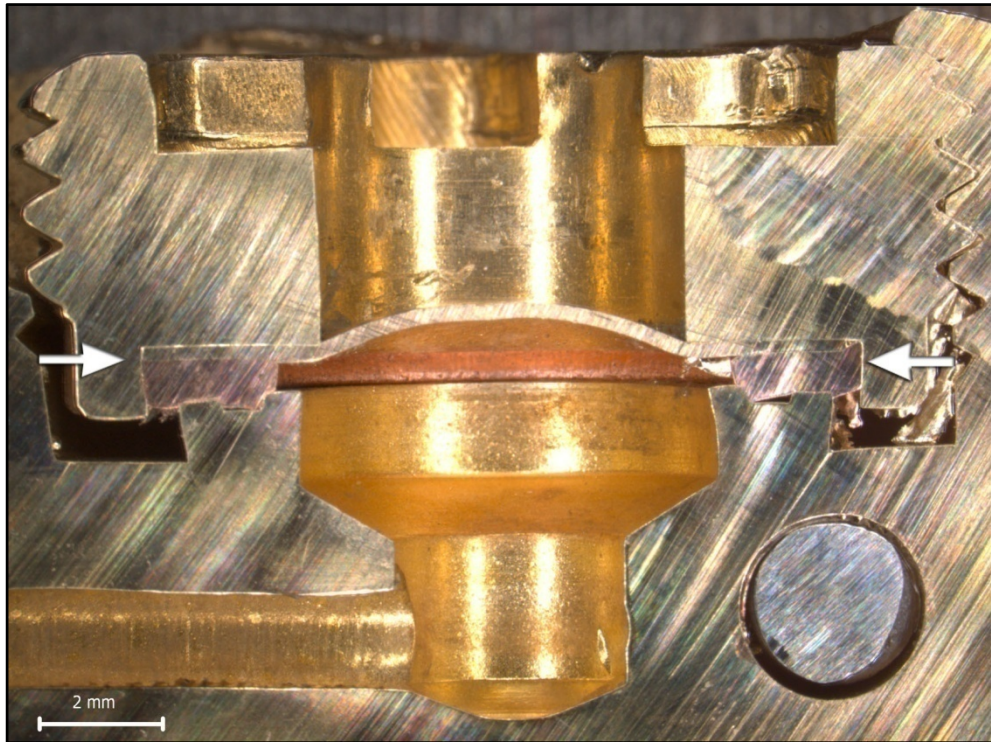
The ATSB conducted a detailed laboratory examination of the valve components, including a study of the principal fracture surfaces, the valve sealing surfaces and the condition of the internal galleries and chambers normally exposed to oxygen service. Axial sectioning of the valve body was required to facilitate inspection of the frangible (burst) disk and provide access to the internal parts. An identical valve assembly was also disassembled and sectioned to permit a direct comparison against the damaged items

Findings

- The valve was fully opened at the time of cylinder failure.
- Witness marks and fracture features exhibited by the valve body were consistent with blunt impact and tensile/bending forces.
- No evidence was found to suggest the valve assembly had been exposed to a significant overpressure condition. The frangible (burst) disk within the valve was intact (Figure 28) and comparable in appearance to other serviceable items.

- No evidence was found to suggest that a combustion event (i.e. an oxygen promoted fire) had initiated within, or in the vicinity of the valve body or interconnected components.

Figure 28: Transverse section through the frangible disk (arrowed) and retaining assembly from the number-4 cylinder. The outward curvature is typical of normal service.



Exemplar cylinders

The entire number-4 oxygen cylinder body was not located on board the aircraft, having presumably been lost from the aircraft during the rupture and subsequent depressurisation event.

In the absence of a subject for direct investigative analysis, the ATSB, with the assistance of the Boeing Office of Air Safety Investigation, initiated a program to identify other cylinders from the same 1996 production batch. Select cylinders from those identified were obtained by the ATSB to enable a general engineering study of the type, and to facilitate the identification of any metallurgical quality issues that may have affected the cylinder production at that time. The Boeing Company provided replacement cylinder/s to those operators that submitted cylinders to the ATSB for examination.

Engineering examination

Five part number 801307-00 cylinders from the same production batch as cylinder serial number 535657 were received by the ATSB – serial numbers 535652, 535626, 535598, 535667 and 535643. A program of engineering examinations and tests of those items was subsequently commenced and is ongoing, with the tests based around the original certification requirements of CFR Title 49 §178.44

'Specification 3HT seamless steel cylinders for aircraft use' and the visual inspection criteria provided in the US Compressed Gas Association document CGA C-8-2005 *'Standard for requalification of DOT-3HT, CTC-3HT and TC-3HTM seamless steel cylinders'*. In addition, 15 other cylinders are also held by the ATSB (including the 12 remaining from VH-OJK) and are being examined as part of the overall study.

External / internal examination

Twenty cylinders in total have been examined externally by eye, and internally using general illumination and a flexible video endoscope.

In general, all items presented only isolated light external surface abrasions, scrapes and rub marks, with localised paint removal and superficial corrosion in some areas (Figure 29). Damage to the underlying steel in those areas was not evident. The largest of the individual marks measured approximately 10 x 10 mm (0.4 x 0.4 in), although multiple such marks were sometimes evident in clusters or lines.

Figure 29: External surface marks on exemplar cylinder SN: 535598

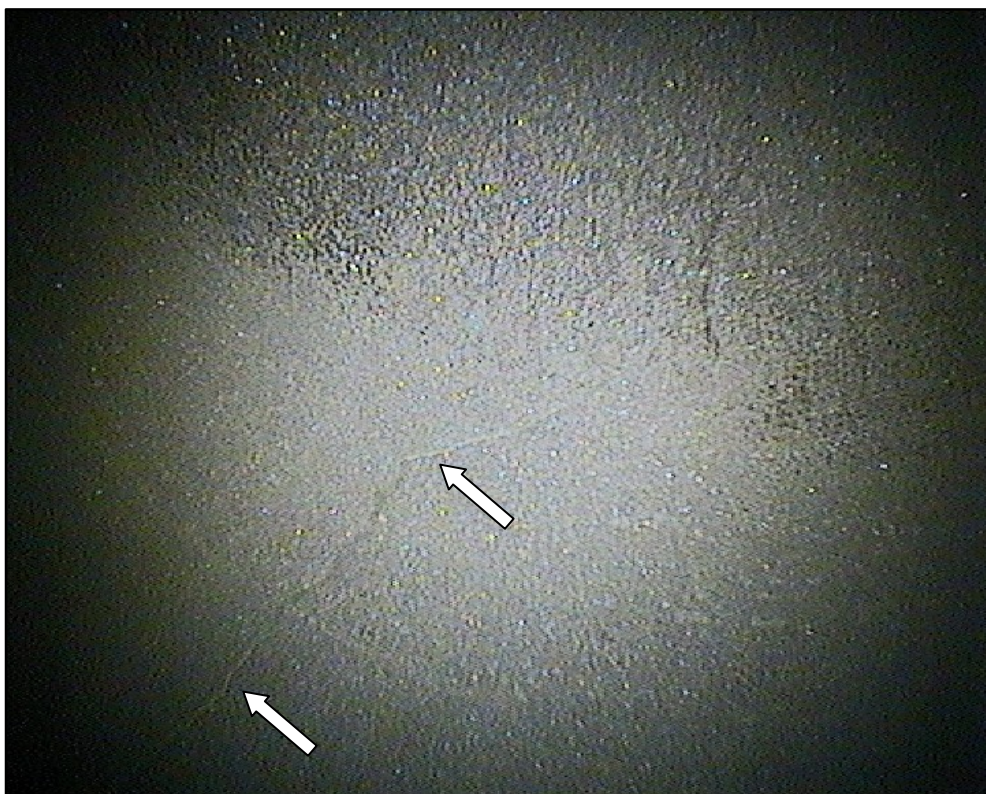


Internally, all cylinders were essentially free from any visible evidence of active pitting or general corrosion attack. Superficial corrosion staining and/or light surface deposits were evident in some cylinders (Figure 30), with the most visible areas around the upper dome and neck transition regions. One cylinder (SN: 535626) showed an irregular linear feature extending from the upper dome to part way along the cylindrical body (Figure 31). That cylinder was subsequently selected for sectioning and destructive examination to facilitate the characterisation of that feature and the general metallurgical condition.

Figure 30: Internal endoscopic view of the upper dome and neck region of cylinder SN: 535571



Figure 31: Linear feature observed inside cylinder SN: 535626 (arrowed)

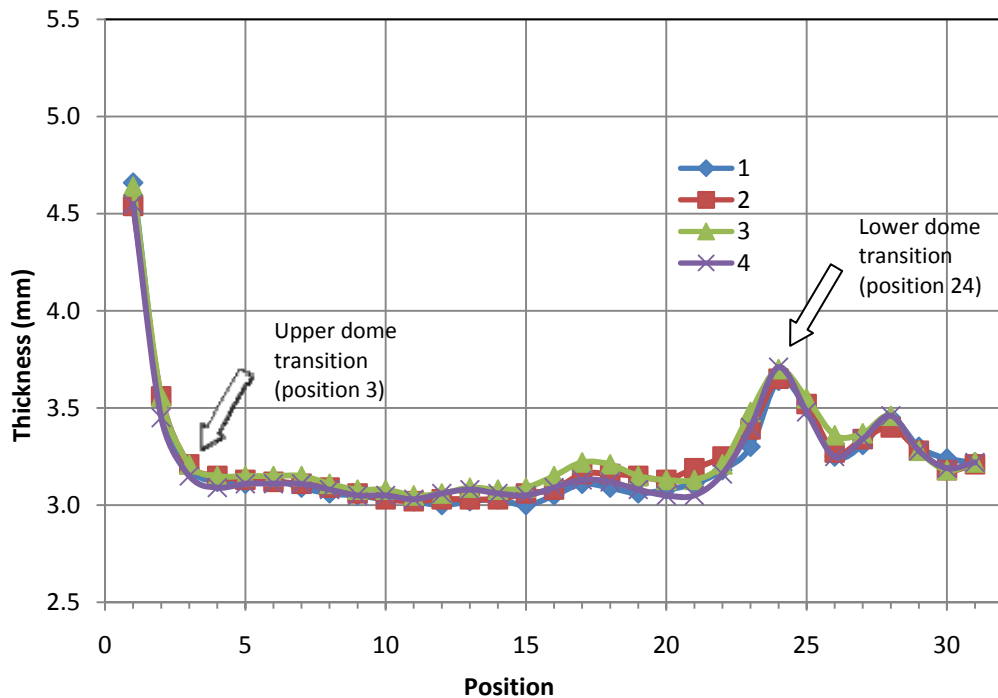


Non-destructive testing

Six cylinders, including the five from the SN: 535657 batch, were examined ultrasonically to ascertain the absolute values and uniformity of the wall thicknesses along the cylinder length. Each cylinder body was examined at 25 mm (1 in) intervals, along four longitudinal traverses spaced equally around the circumference. Each traverse commenced within the upper dome, at 50 mm (2 in) from the body transition, and was completed at the centre of the lower dome.

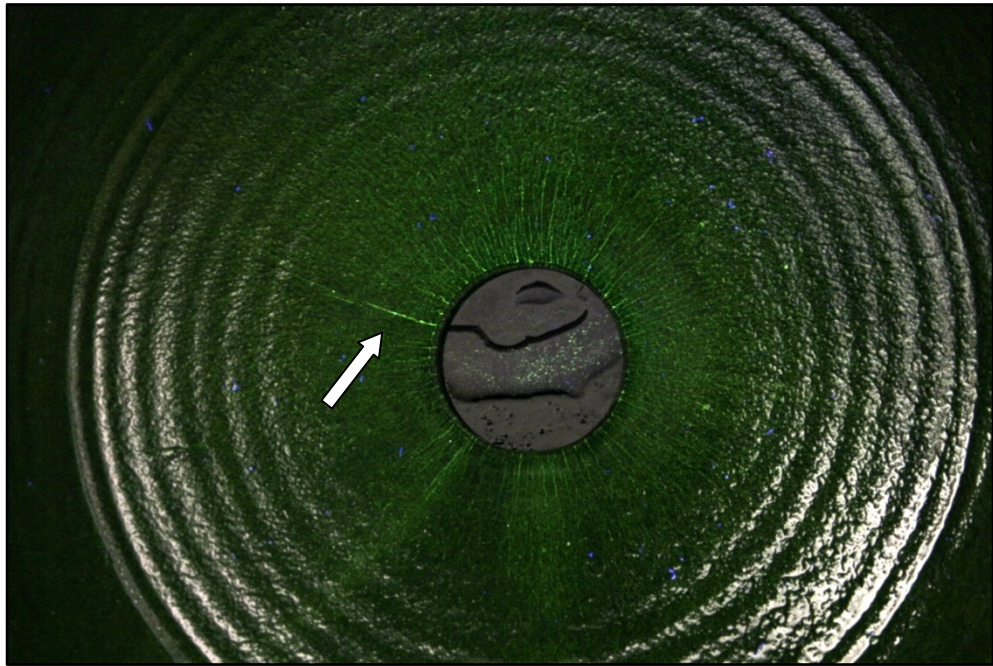
Of the cylinders examined, SN: 535667 presented the lowest nominal wall thickness, with a minimum recorded value of 3.0 mm (0.118 in); 0.13 mm (0.005 in) above the prescribed 2.87 mm (0.113 in) minimum wall thickness. Figure 32 presents the survey results for this cylinder graphically. In general, the minimum wall thickness was found within the central regions of the cylinder body, although the variability was minimal (typically ± 0.1 mm, 0.004 in) along the body length. The thickness measurements also highlighted the presence of a localised increase in thickness of around 0.5 mm (0.02 in) around the lower dome transition.

Figure 32: Thickness survey data for cylinder SN: 535667



After sectioning cylinder SN: 535626 to expose the internal surfaces, a fluorescent magnetic particle technique was employed to examine 100% of the internal surface area, including the linear feature observed during the endoscopic examination (Figure 31). While no evidence of crack-like features was observed within the cylinder body, multiple linear indications were detected radiating outward from the cylinder neck transition region (Figure 33). The longest of the indications extended for approximately 12 mm (0.5 in).

Figure 33: Linear indications extending from the internal neck bore of cylinder SN: 535626 (largest arrowed)



Material / microstructural examination

Prior to further sectioning for microstructural study, the internal surfaces of cylinder SN: 535626 were examined visually. It was noted that the internal surfaces at, and around the upper dome and neck transition, displayed a considerably coarser and irregular surface finish when compared with the general cylindrical and lower dome surfaces. A radial pattern of fissures and rivulet features was observed, becoming more prominent toward the neck (Figure 34). The entire surface in the region presented an oxidised or thick scale-like appearance. The linear feature observed endoscopically (Figure 31) was revealed to be a diffuse surface mark, with no characteristics of a surface flaw or other injurious defect.

A number of transverse sections were removed from the cylinder and prepared for microscopic study, encompassing the upper and lower dome transition regions and the material around the cylinder neck that exhibited the linear indications. The bulk cylinder microstructure (Figure 35) presented fine and uniform tempered transformation products (martensite / bainite), with a ferritic decarburisation²⁰ layer extending to around 0.2 mm (0.008 in) depth from all surfaces. The linear indications within the upper dome and neck presented as intrusive, oxide-filled flaws, with a characteristic envelope of decarburised material around the profile (Figure 36), consistent with their formation during the initial high-temperature forging and forming processes used to produce the cylinder. The largest of the features displayed a branched nature and extended to a depth of approximately 0.9 mm (0.035 in) beneath the normal surface plane. None of the intrusions showed any indication of crack growth from the tips or other extremities.

²⁰ Decarburisation is a high-temperature diffusion process where elemental carbon is lost from the surfaces of steels and other ferrous alloys.

Figure 34: Linear features on the internal surfaces around the cylinder neck

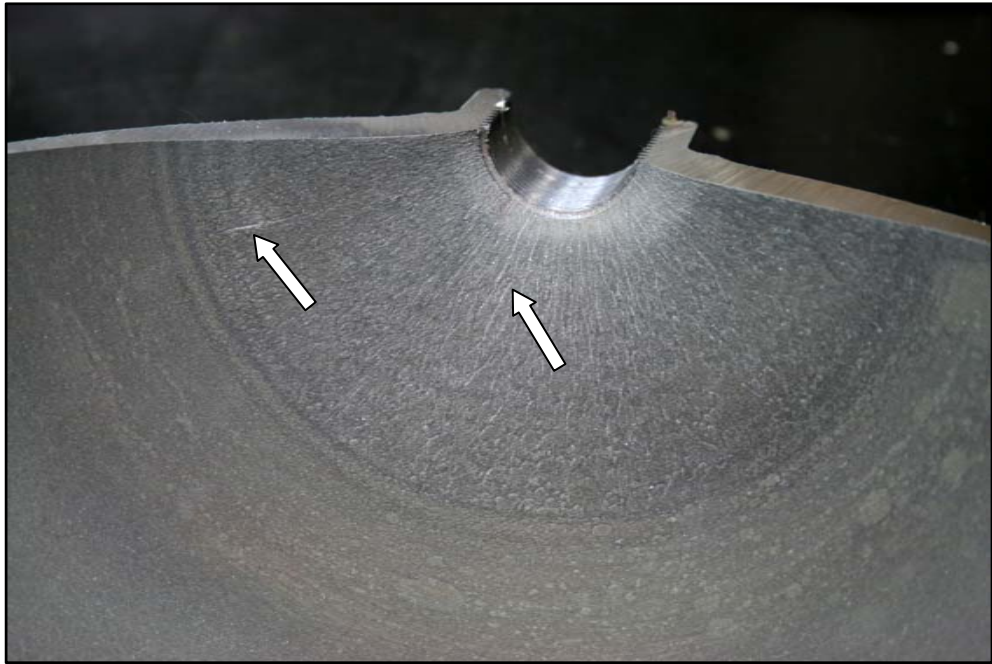


Figure 35: General cylinder material microstructure – tempered martensite / bainite

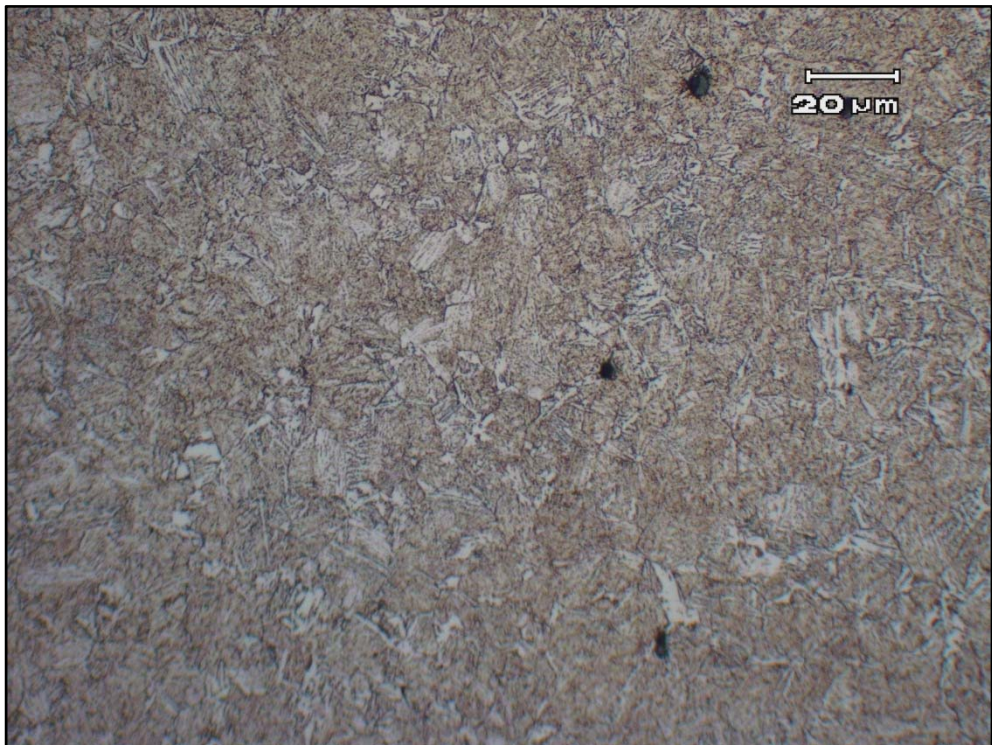
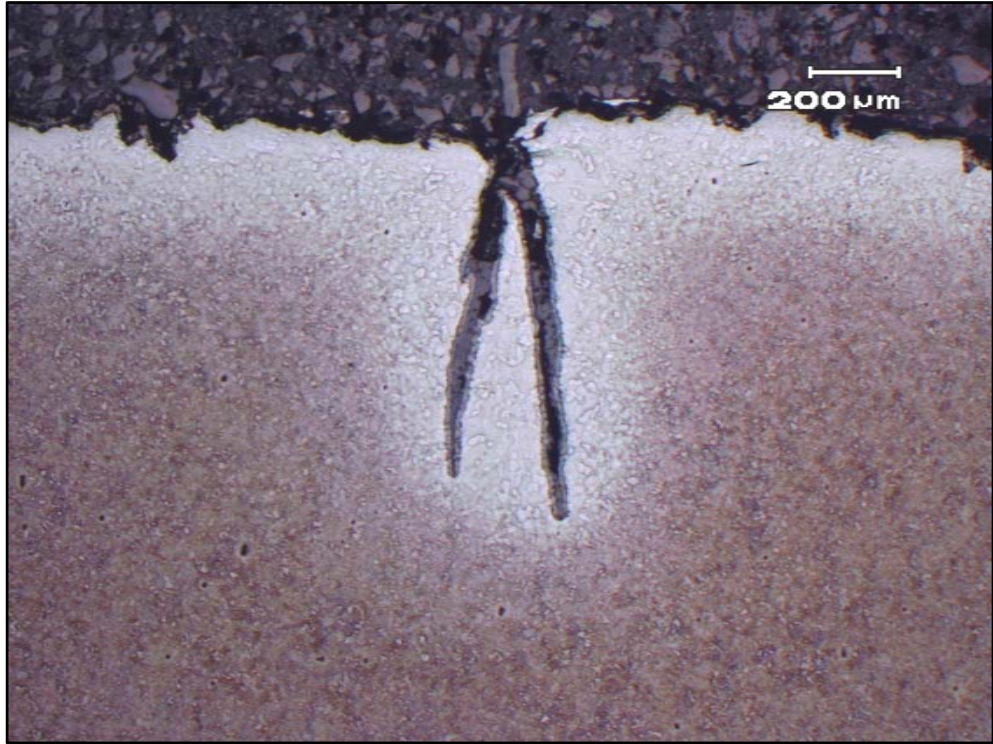


Figure 36: Largest of the internal surface intrusions identified around the cylinder neck transition



Mechanical testing

The cylinder production standard (US CFR Title 49 §178.44) required the demonstration of satisfactory material physical strength and ductility through the performance of material tensile and flattening tests. Suitable samples for these tests were removed from exemplar cylinder SN: 535652 and tested in accordance with the requisite standards by an accredited independent laboratory.

Specimens for the assessment of the tensile properties of the cylinder material were removed from the barrel section, in both longitudinal and transverse orientations. Additional specimens were also removed from the lower dome transition region; oriented radially with respect to the cylinder longitudinal axis (Figure 37).

Table 8: Tensile test results

Sample	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation A₈₅ (%)	Elongation A_{2"} (%)
Longitudinal – 1	996	1061	9	12
Longitudinal – 2	1002	1069	9	12
Circumferential – 1	774	1060	5 [#]	9
Circumferential – 2	806	1059	7	11
Circumferential – 3	845	1072	8	11
Transition – 1 [*]	1021	-	-	-
Transition – 2 [*]	982	-	-	-

Sample	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation A ₈₅ (%) ^a	Elongation A _{2"} (%) ^b
Transition – 3	890	1106	5 [#]	8
Transition – 4	871	1127	7	9
Requirements as per CFR 49 §178.44	-	1138 Max (165,000 psi)	6 min	-

- Fracture location was less than 25% of the original gauge length from a gauge mark, hence the elongation result may be unrepresentative.

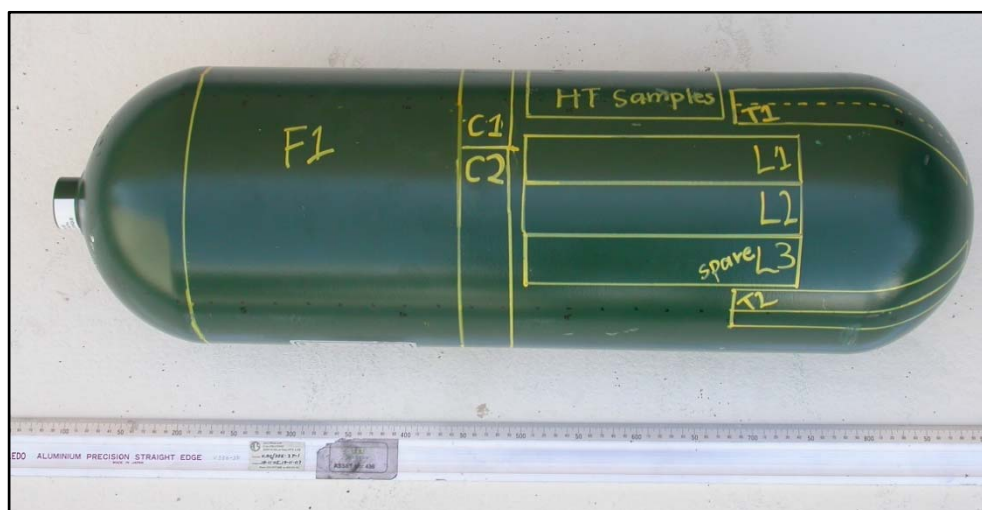
* - Samples fractured through the pinned end grip – two retests were performed.

a – elongation measured over an 85mm gauge length (as per §178.44)

b – elongation measured over a 2 inch gauge length

A single flattening test as described in section I of CFR Title 49 §178.44, was prepared and tested from the upper cylindrical section of the cylinder. When flattened between knife edges having a 60° included angle and 12.5 mm (0.5 in) edge radii, the specimen cracked longitudinally at a knife edge separation of approximately 60 mm (2.4 in). As such, the test did not comply with the requirements specified by CFR Part 49 §178.44 section (p)(1), which stipulated “flattening required without cracking to ten times the wall thickness of the cylinder” (28 mm / 1.13 in).

Figure 37: Cylinder SN: 535652 with locations of mechanical test specimens marked. L, T & C are the longitudinal, transition and circumferential tensile test specimens, F1 the flattening test specimen



Tempering temperature evaluation

Using samples removed from the cylinder body material, a series of increasing temperature heat-treatments and intermediary hardness tests were conducted to ascertain the temperature at which the cylinder material had been tempered during the original manufacturing process. The evaluation was based on the principle that heat treatments carried out *below* the original tempering temperature, will not significantly affect the material hardness, while heat treatments conducted *above* the original temperature will induce additional tempering, and thus a measurable reduction in hardness.

Table 8: Tempering test results

Sample heat treatment condition	Average hardness (HV₁₀)[#]	Relative hardness change
As-received (reference)	374	-
400°C soak for 1 hour	369	- 5
425°C soak for 1 hour	369	- 5
450°C soak for 1 hour	374	0
475°C soak for 1 hour	373	- 1
500°C soak for 1 hour	366	- 8
525°C soak for 1 hour	356	- 18

- Vickers hardness scale, 10 kg indenter load.

From the trial results, it was evident that the original cylinder tempering heat treatment had been conducted at a temperature around 500°C (932 °F). CFR Part 49 §178.44 section (g)(3) specified that tempering heat treatments must be conducted at a temperature above 454°C (850°F).

ONGOING INVESTIGATION ACTIVITIES

Engineering

The technical investigation into the potential factors that contributed to the oxygen cylinder failure is ongoing, with the following key areas of study:

- continuing examination of the exemplar cylinders from the same production batch as the failed item
- assessment of the results and findings of a finite element stress analysis and fracture mechanics assessment of the cylinder design that is currently in progress
- cylinder pressure tests, including pneumatic and hydrostatic rupture and cyclic pressurisation endurance tests
- exploration of cylinder defect and damage tolerance, based upon the findings of the fracture mechanics assessments and employing artificially flawed test cylinders.

Cabin safety/survival factors

The cabin safety / survival factors investigation will continue, employing the information gathered from the operating crew interviews and passenger surveys, to review the cabin crew procedures and determine whether any improvements or changes to those procedures would enhance safety.

The investigation will also continue to examine the serviceability and functionality of the cabin oxygen apparatus and other cabin safety equipment, cabin crew actions, and passenger actions and problems.

The ATSB has received responses from approximately 47% of those passengers to whom the survey was provided. Passengers who have received a survey, but have not yet responded are encouraged to do so. Replacement surveys are also available for those that may have misplaced or did not receive the original documents – please provide an email or postal address to the ATSB (aviation.investigation@atsb.gov.au) or phone +61 2 6257 4150 (from overseas) or 1800 020 616 (within Australia).

Flight recorders

Examination of CVR, FDR and QAR information is ongoing and will include the following:

- Analysis of CVR audio regarding crew actions, aircraft handling and crew/cabin communications during the approach and landing at Manila.
- Analysis of FDR and QAR data to produce a detailed sequence of events and assist in identifying secondary damage from the oxygen cylinder failure and the effects of that damage to aircraft systems and aircraft handling.
- A review of the operator's procedures for preserving a CVR recording following a serious incident or non-catastrophic accident.

SAFETY ACTION

Aircraft operator

On 27 July (2 days following the VH-OJK event), the aircraft operator, in agreement with the Civil Aviation Safety Authority (CASA), commenced a fleet-wide program of detailed visual inspections of its Boeing 747 oxygen system installations. The ATSB was advised that those inspections were completed by 1 August. The operator has also completed a preliminary internal review of the event, addressing the crew and passenger response, the emergency passenger oxygen system operation, supplementary passenger oxygen requirements, and the functionality of the depressurisation emergency announcement system operation. From that review, several changes have been introduced to cabin crew operating procedures and are due to be implemented by the end of March 2009.

- The introduction of a new non-normal depressurisation checklist, which will follow the format used by flight crew to manage their initial actions during a depressurisation.
- Depressurisation procedures will no longer differentiate between primary and assisting cabin crew.
- Once at a safe altitude and the flight crew have advised cabin crew to '*carry out follow-up duties*' the use of supplemental oxygen by cabin crew is no longer mandatory.
- The CSM will remain in a set location and assume the role of the communicator following a depressurisation. They will act as a central point of contact for cabin crew and the flight crew.
- Information and training materials produced from the occurrence review have been incorporated into the practical exercises for the cabin crews' initial and recurrent emergency procedures training programs.

The aircraft operator has also advised that their group safety department's report into the occurrence is nearing completion and will be provided to assist the ATSB investigation.

ATSB safety action

It is acknowledged that any corrective or precautionary action undertaken in response to a safety occurrence should be justifiable in terms of established or probable facts. However, in view of the nature of the depressurisation event and the implication of a possible mechanism or condition that could affect the structural integrity and safety of other oxygen cylinders used in the aviation environment, the ATSB draws attention to the following advisory notices, on the basis of prudence, until such time that the mechanism/s contributing to the cylinder failure on board VH-OJK are established and understood.

Safety advisory notice (AO-2008-053-SAN-006)

The Australian Transport Safety Bureau encourages all organisations performing inspection, testing, maintenance and repair activities on aviation oxygen cylinders, to note the circumstances detailed in this preliminary report, with a view to ensuring that all relevant procedures, equipment, techniques and personnel qualifications satisfy the applicable regulatory requirements and established engineering best-practices.

Safety advisory notice (AO-2008-053-SAN-007)

The Australian Transport Safety Bureau encourages other operators of transport category aircraft fitted with pressurised gaseous oxygen systems, to note the circumstances detailed in this preliminary report, with a view to ensuring that all oxygen cylinders, and cylinder installations, are maintained in full accordance with the relevant manufacturer's requirements, statutory regulations, and established engineering best practices.

Aviation research and analysis reports

The ATSB research and analysis section has published two reports intended as information bulletins for passengers and cabin crew of pressurised aircraft.

- Staying Safe During an Aircraft Depressurisation - Passenger information bulletin. Aviation research and analysis report AR-2008-075(1)
- Aircraft Depressurisation – Cabin crew information bulletin
Aviation research and analysis report AR-2008-075(2)

The bulletins have been written to provide passengers and cabin crew with an improved understanding of the potential effects of a depressurisation event on the individual, and to provide advice regarding actions that can minimise the risk of injury.

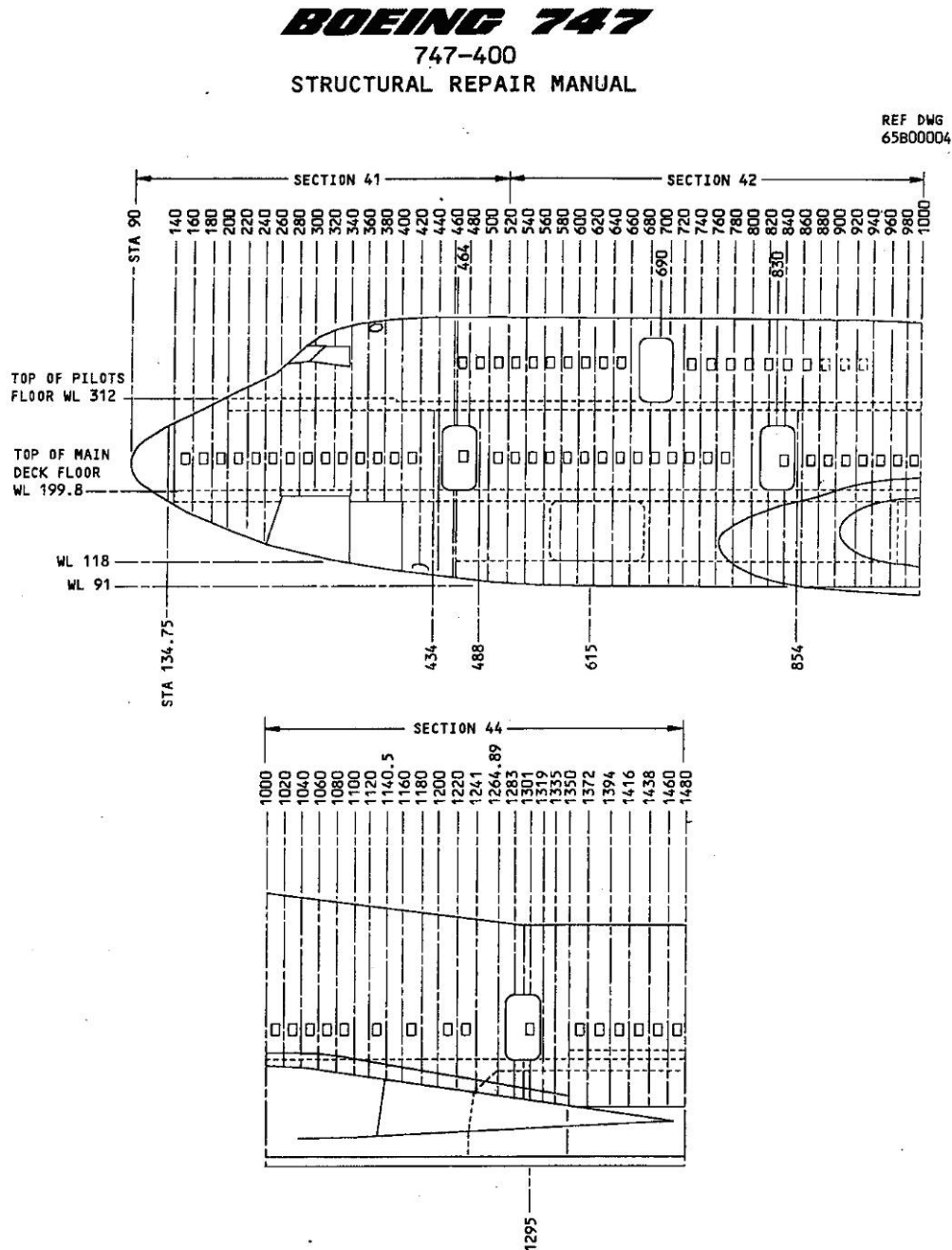
The information bulletins are available for download from the ATSB website at the following addresses:

Passenger bulletin: <http://www.atsb.gov.au/publications/2008/AR2008075.aspx>

Cabin crew bulletin: http://www.atsb.gov.au/publications/2009/AR2008075_2.aspx

ATTACHMENT A: AIRCRAFT STATIONS

Figure A1: Boeing 747-400 forward fuselage station diagram

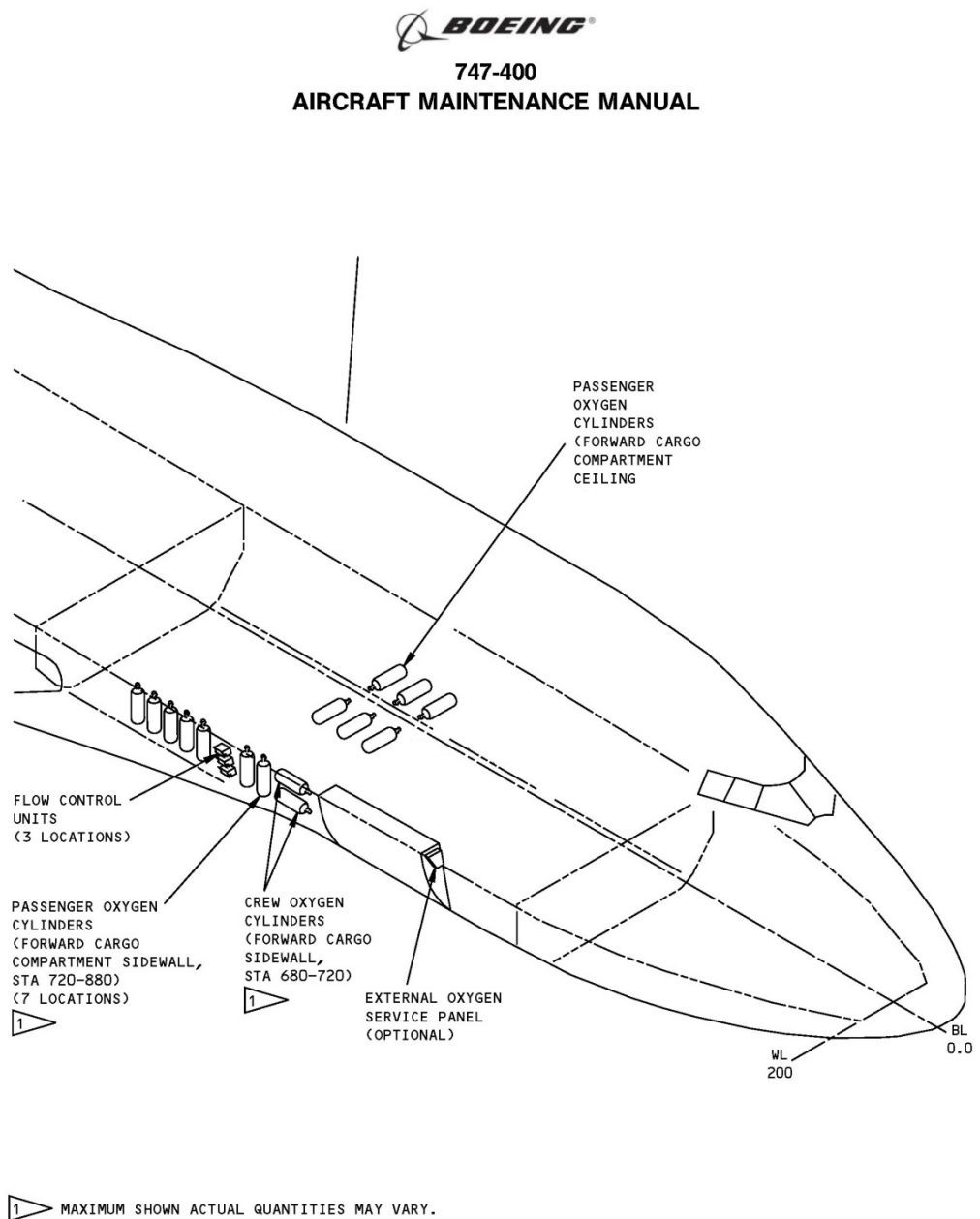


Fuselage Station Diagram
Figure 1 (Sheet 1)

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ATTACHMENT B: OXYGEN CYLINDER LOCATIONS

Figure B1: Typical cylinder locations in the Boeing 747-400 aircraft



Oxygen Supply System
Figure 1 (Sheet 2 of 2)/35-40-00-990-801-001

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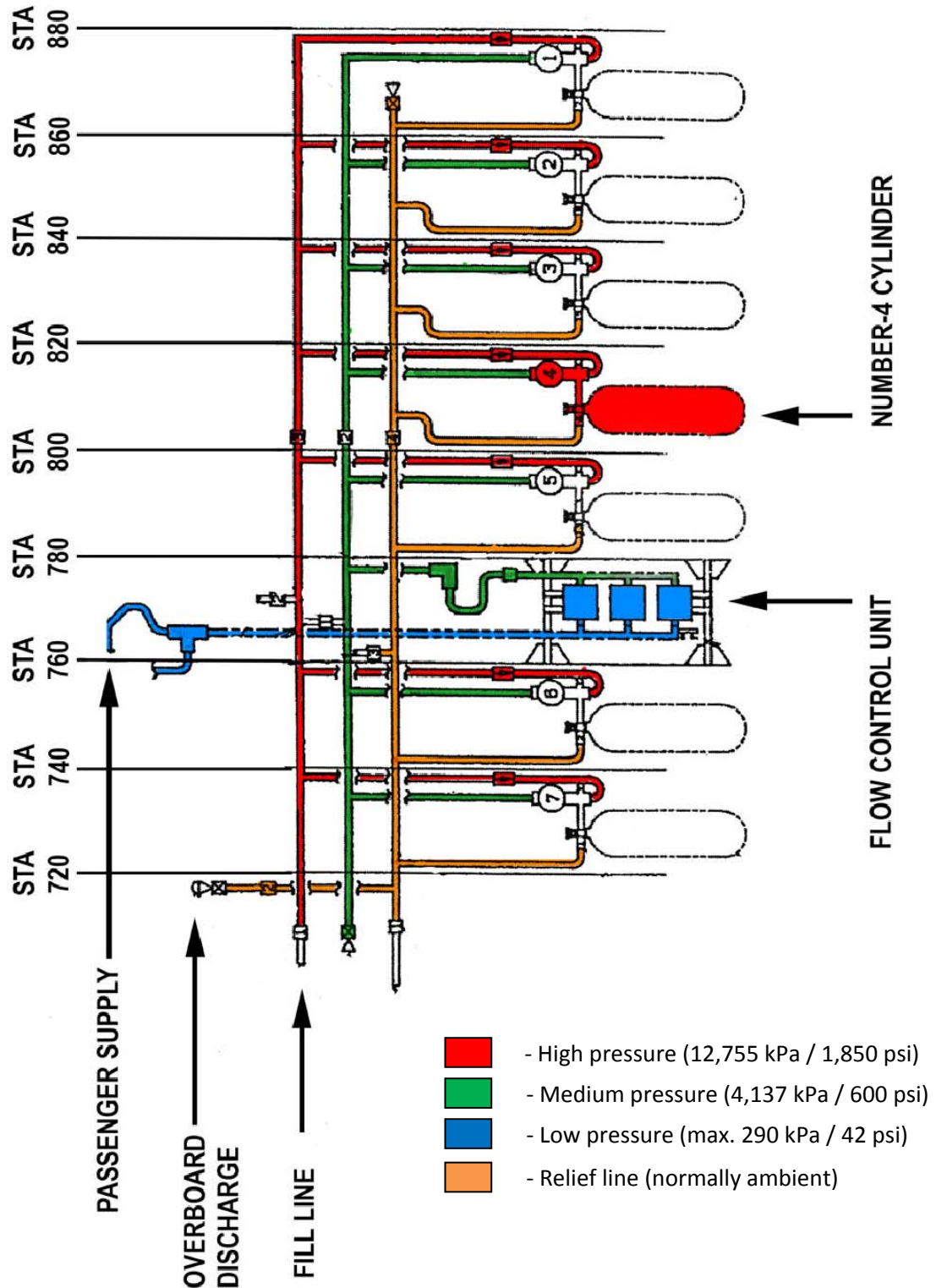
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Page 4
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ATTACHMENT C: PASSENGER OXYGEN SYSTEM

Figure C1: Schematic illustration of the forward cargo hold oxygen system installation.



ATTACHMENT D: FLIGHT DATA RECORDER PLOTS

Figure D1: Data plot for complete flight duration

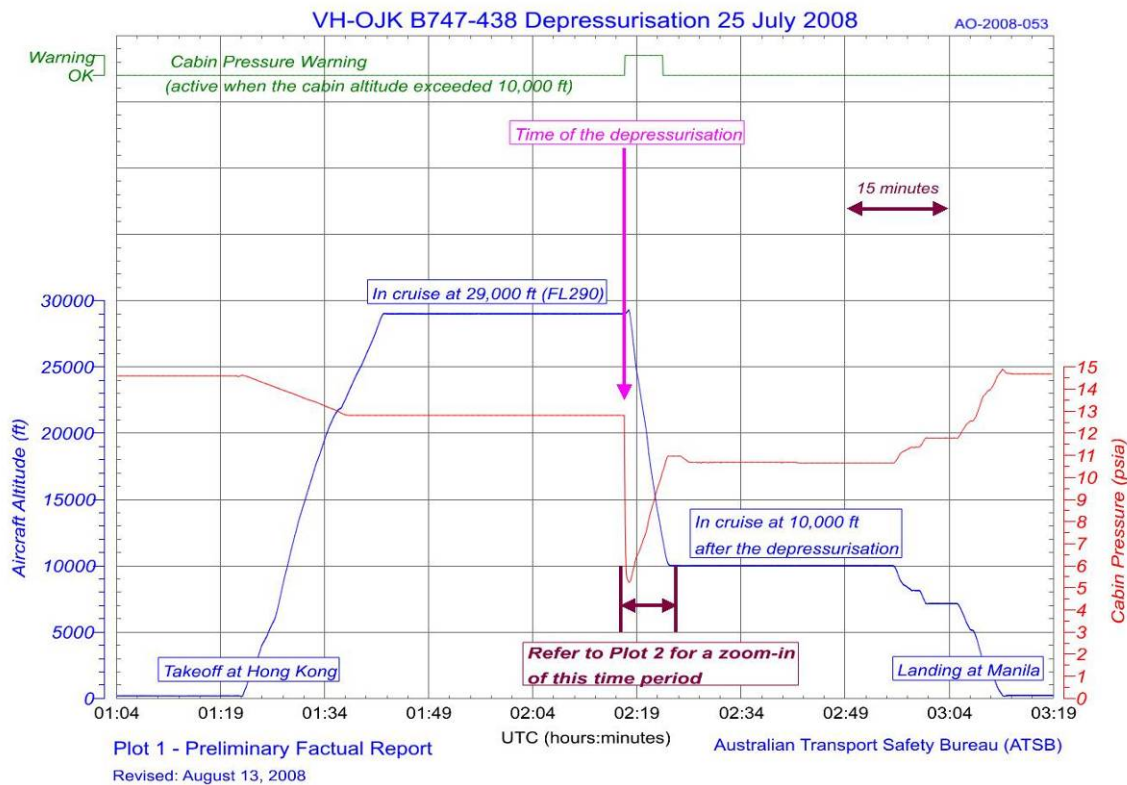
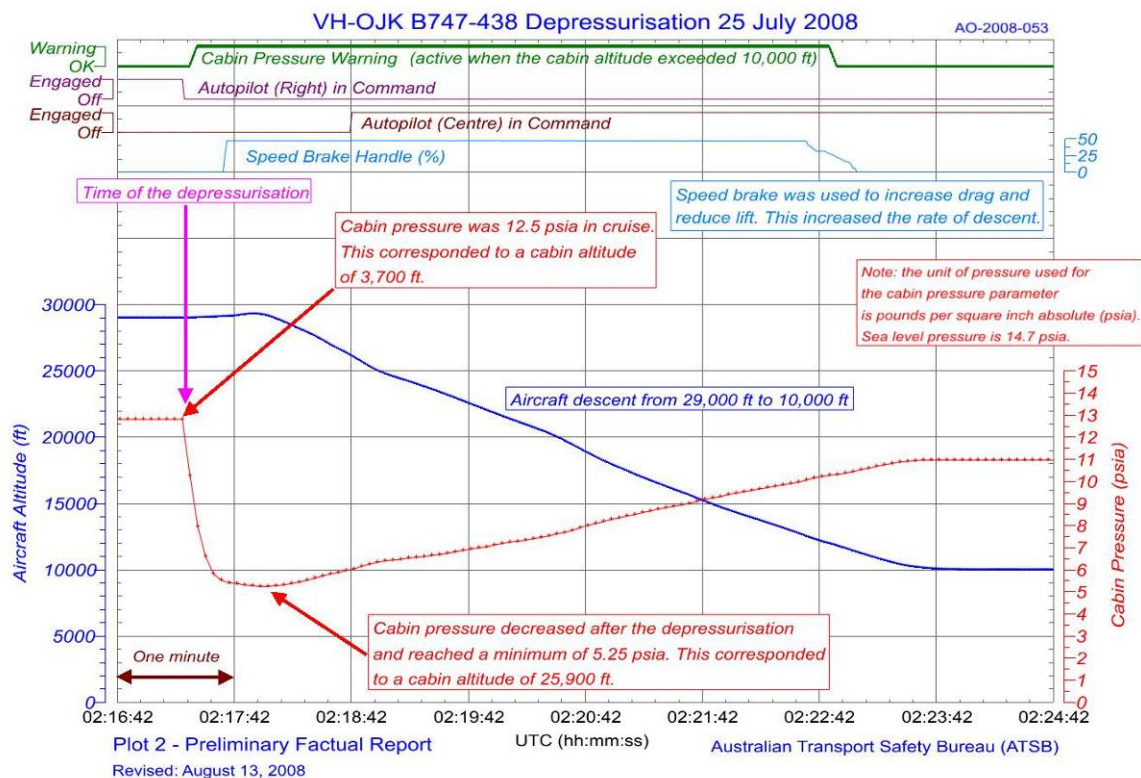
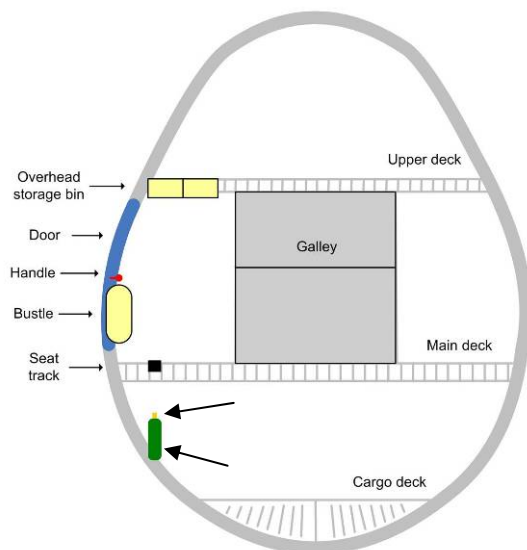


Figure D2: Data plot for the depressurisation event

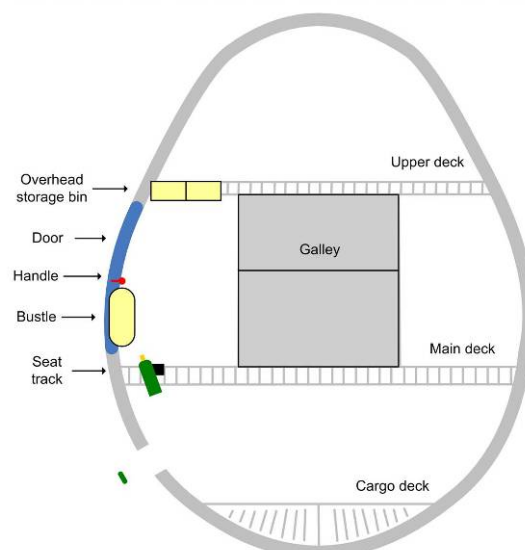


ATTACHMENT E: PROBABLE OXYGEN CYLINDER TRAJECTORY

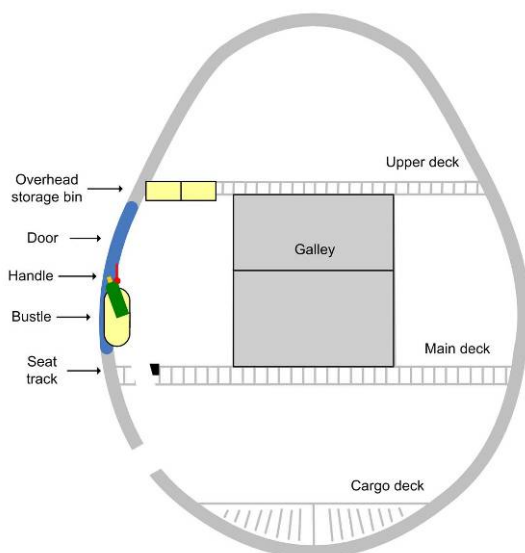
Figures E1 – E7: Cross-sectional view through aircraft fuselage at the R2 cabin door location



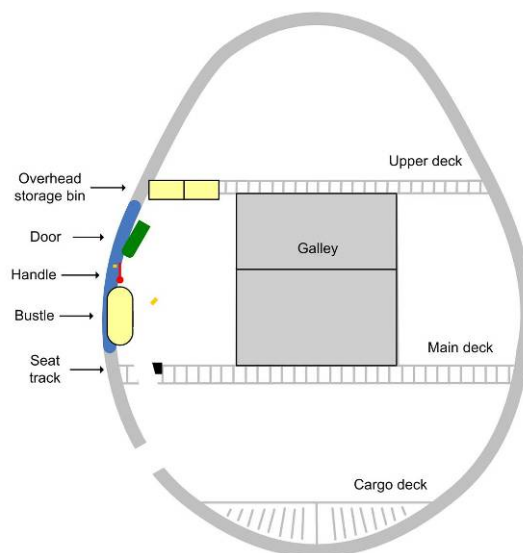
1. Normal arrangement (Oxygen cylinder and valve arrowed)



2. Cylinder failure produces fuselage rupture, with bulk of the cylinder length propelled upward through the cabin floor. See Figure 11.

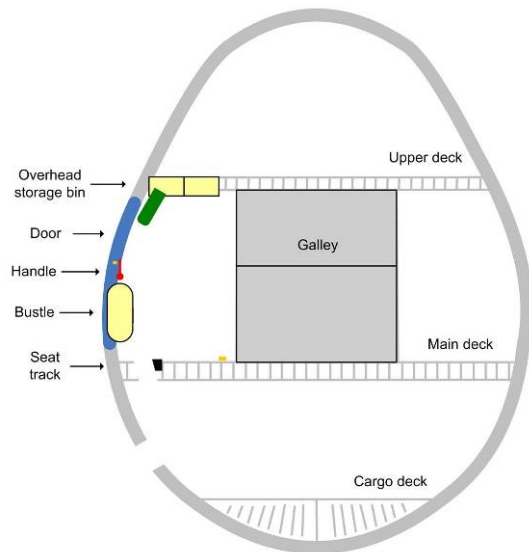


3. Cylinder impacts R2 door frame and internal door handle. See Figures 10 & 12.

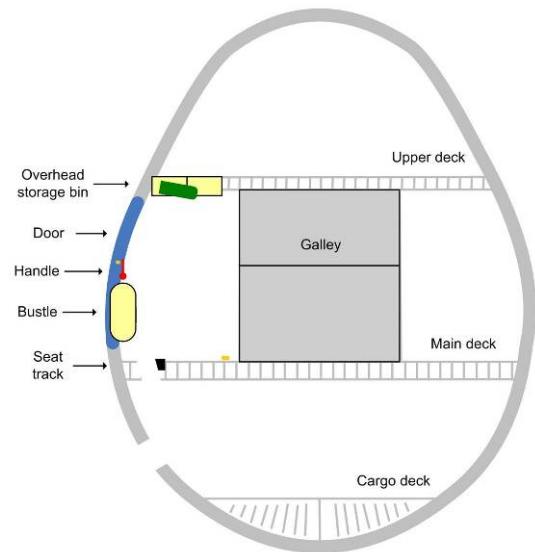


4. Door frame impact breaks off cylinder valve and causes cylinder to invert while continuing to travel upward.

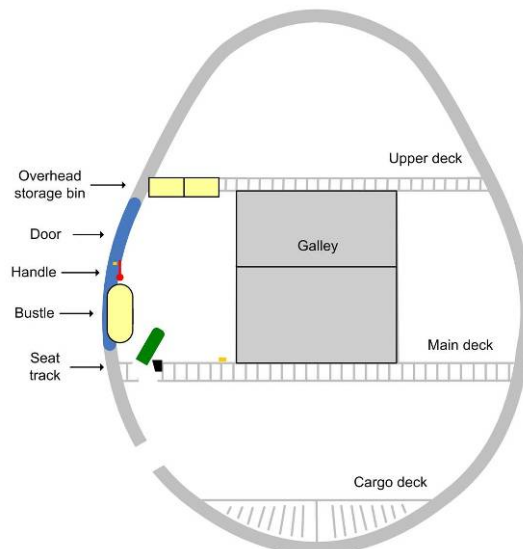
Probable oxygen cylinder trajectory (continued)



5. Cylinder impacts overhead panelling end-on, producing circular cut-out type damage. See Figures 14-16.



6. Still rotating cylinder impacts overhead storage bin, producing semi-circular crushing damage. See Figure 17.



7. Cylinder falls to cabin floor and exits the aircraft through the ruptured fuselage.