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ATSB TRANSPORT SAFETY REPORT
Aviation Occurrence Investigation AO-2008-053
Interim Factual No. 2

Depressurisation – 475 km north-west of Manila, Philippines – 25 July 2008

Overview of October 2009 report

The following report is provided as an update on the Australian Transport Safety Bureau's (ATSB's) investigation into the depressurisation of a Boeing Company 747-438 aircraft while en-route from Hong Kong to Melbourne, Australia on 25 July 2008. It is intended that this report be read together with the Preliminary Investigation Report published in August 2008 (ISBN 978-1-921490-65-1) and the first Interim Factual Report, published in March 2009 (ISBN 978-1-921602-21-4). Both reports are available from the ATSB website, at http://www.atsb.gov.au/publications/investigation_reports/2008/aair/ao-2008-053.aspx

This second interim report provides a summary of factual information that has been derived from the continuing investigation of this occurrence. 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 this report.

Figure 1: External damage sustained by the aircraft

Summary from March 2009 report

At 1017 local time (0217 UTC[1]) on 25 July 2008, a Boeing Company 747-438 aircraft, (registered VH-OJK) operating a scheduled passenger service between Hong Kong and Melbourne, Australia, sustained the sudden and forceful rupture of the forward fuselage in a location just in front of the right wing leading edge transition (Figure 1). At the time of the rupture, the aircraft was established at a cruising altitude of 29,000 ft and was approximately 475 km to the north-west of Manila, Philippines. There were 369 passengers and crew on-board.

The cabin crew reported that the rupture was accompanied by a 'very loud bang' and immediate indications of cabin depressurisation. Oxygen masks deployed from above the passenger seats shortly after the event, and most passengers began to use the masks soon after they dropped.

Responding to the depressurisation, the flight crew commenced an emergency decent and declared a MAYDAY on the Manila flight information radio frequency. At 1024 (0224 UTC), the aircraft was levelled at an altitude of 10,000 ft, where the use of supplemental oxygen by the passengers and crew was no longer required.

Ninoy Aquino International Airport, Manila, was chosen by the flight crew as a suitable diversion for the aircraft, which landed safely at 1112 (0312 UTC). The aircraft was subsequently towed to a terminal gate, where the passengers were disembarked normally. None of the passengers reported any physical injuries to the cabin crew, or to the operator's staff after arrival at Manila. A

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

later Australian Transport Safety Bureau (ATSB) survey of passengers found that some had experienced pain associated with the depressurisation, including ear discomfort and/or 'popping', temporary hearing loss and headaches. Many also reported high levels of anxiety and feelings of panic. Several passengers reported feelings of faintness, light-headedness and/or tremors; however, it was unclear whether those symptoms had resulted from hypoxic (oxygen deprivation) effects from the depressurisation, anxiety brought upon by the situation, or were the result of some other pre-existing condition.

An engineering inspection of the aircraft in Manila found that the fuselage rupture had occurred in a location coincident with the installed position of the number-4 passenger emergency oxygen cylinder; one of seven such cylinders installed as a bank along the right side of the aircraft's forward cargo hold. The number-4 cylinder was missing from the bank, with the associated oxygen service and feed lines fractured. Immediately above the normal location of the number-4 cylinder was a large, circular hole in the cabin floor, leading into the main cabin at a location just forward of the R2[2] door. Within the cabin, substantial damage had been sustained by the door frame and overhead panelling, and the door handle had been partly rotated toward the open position.

FACTUAL INFORMATION UPDATE

Ongoing investigation

It was readily apparent to the investigation that the principal contributing event was the sudden and forceful rupture of the number-4 passenger emergency oxygen cylinder. That failure had compromised the aircraft's pressure hull, leading to the immediate and rapid depressurisation of the cabin. Part of the aircraft's fuselage and the number-4 cylinder were lost from the aircraft during the depressurisation.

As such, the investigation has focused on the following key aspects of the occurrence:

- identification and investigation of the engineering issues that could have contributed to the cylinder failure
- review of the oxygen cylinder design, including compliance with specifications and the damage tolerance of the type
- examination of the aircraft's emergency and operational systems performance and behaviours in the context of the event
- evaluation of the cabin safety performance, including a review of crew procedures, systems behaviours and passenger actions
- review of the flight crew performance and procedures in the context of the event.

Cylinder engineering evaluation

The loss of the ruptured oxygen cylinder from the aircraft prevented its direct examination and failure analysis. In lieu therefore, a program of engineering assessments of five other cylinders obtained from the same production lot was undertaken, and has included:

- detailed external and internal visual examination
- non-destructive testing, including radiographic examination, wall-thickness testing and magnetic particle inspection
- material and microstructure characterisation
- material mechanical testing.

The Interim report published in March 2009 presented a summary of the outcomes of these tests. Subsequently, work has continued, and has included:

- monotonic hydrostatic expansion and rupture testing
- cyclic hydrostatic testing
- stress analyses and fracture mechanics assessments.

2 The R2 door is the second main cabin door on the right side of the aircraft.

Hydrostatic tests

To assess the compliance of the cylinder production lot with the requirements of the manufacturing specification (US Code of Federal Regulations, title 49, section 178.44 (49CFR178.44) - *'Specification 3HT seamless steel cylinders for aircraft use'*, a series of hydrostatic pressure tests were conducted on three of the exemplar cylinders. Two cylinders were subject to proof expansion and subsequent rupture tests; a third underwent a proof expansion test followed by a cyclic pressurisation program, a second proof expansion test, and a final rupture test. All tests were conducted as required by the 49CFR178.44 specification.

Expansion tests

Each cylinder was pressurised to a nominal test value of 3,083 psi (21,256 kPa) within an external water jacket. Displacement of water from the jacket into a burette assembly permitted the assessment (Table 1) of the volumetric expansion of the cylinder at the test pressure.

Table 1: Expansion test results

Cylinder	REE[1] (ml)	Expansion (ml)
535667	170.1	157.8
535643	168.0	152.2
535598 test 1[2]	169.1	160.2
535598 test 2[2]	169.1	154.2

[1] – Rejectable Elastic Expansion requirement - marked on cylinder.

[2] – tests conducted before (1) and after (2) program of cyclic pressure tests.

Rupture tests

Each cylinder was progressively pressurised within a containment room until failure occurred, with the peak pressure and failure mechanism (leak or burst) being recorded (Table 2).

Table 2: Rupture test results

Cylinder	Failure pressure (psi / kPa)	Failure mode
535667	4,400 / 30,337	Burst
535643	5,005 / 34,508	Burst
535598[1]	4,200 / 28,958	Leak

[1] – After cyclic testing program.

The minimum allowable rupture pressure prescribed by 49CFR178.44 was 4,111 psi (28,344 kPa), and all test cylinders exceeded that value. Figures 2 to 4 present the external appearance of the cylinders following rupture testing.

Figure 2: Rupture of cylinder 535667

Figure 3: Rupture of cylinder 535643

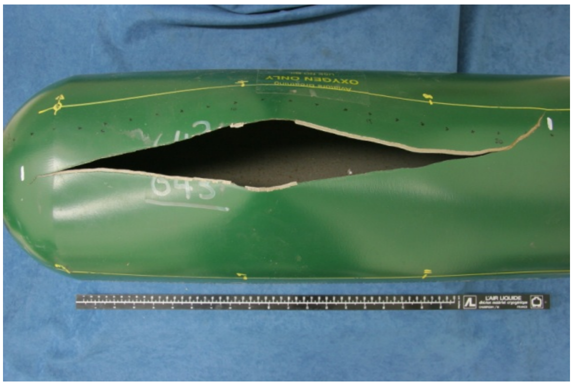
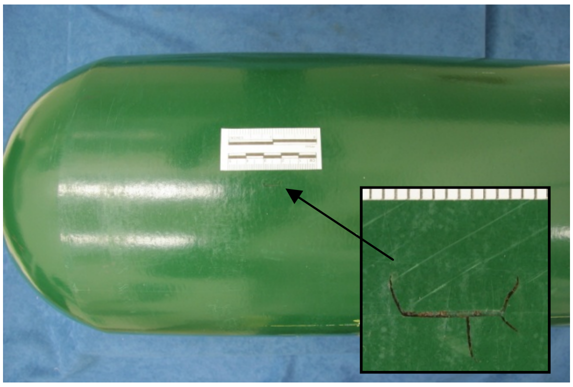


Figure 4: Rupture of cylinder 535598 (at arrow)



Cyclic tests

Cylinder 535598 was subjected to a program of repeated pressurisations from 0 to 1,850 psi (12,755 kPa) in accordance with 49CFR178.44. A total of 10,000 discrete pressure cycles were applied, over a period of 6 days (10 blocks of 1,000 cycles), at a nominal rate of six cycles per minute. After each block of cycles, the cylinder was visually examined for evidence of leakage or other anomalies, and after completion of the 10,000 cycles, the cylinder was subject to expansion and rupture tests as previously detailed.

At no stage during the program did the subject cylinder show any evidence of leaking, perforation or becoming structurally compromised in any way.

Stress analysis / fracture mechanics

To obtain indicative estimates of the critical flaw sizes[3] for failure of the 3HT1850 oxygen cylinder type in question, the ATSB retained the services of QinetiQ Aerostructures Pty Ltd, for the performance of a finite element analysis of the design, along with a residual strength analysis using linear elastic fracture mechanics (LEFM) techniques.

Finite element stress analysis

The finite element model (FEM, Figure 5) was prepared using data from engineering drawings sourced from the cylinder manufacturer. Values for the minimum cylindrical wall thickness (0.113 in / 2.87 mm), average internal cylinder diameter (8.75 in / 222.2 mm) and minimum lower hemisphere wall thickness (0.102 in / 2.60 mm) were obtained from the production test certificate for the cylinder lot.

The FEM analysis produced an average longitudinal cylindrical wall stress value of 36.3 ksi (250.3 MPa) and average hoop (circumferential) stress value of 72.6 ksi (499.9 MPa), for the 1,850 psi design service pressure of the cylinder. Both values compared favourably with the conventionally calculated values of 37.3 ksi (257.2 MPa) and 74.7 ksi (515.0 MPa) respectively.

Taking into consideration the allowable reduction in wall thickness within the lower hemisphere (90% of the minimum cylindrical thickness), the FEM analysis revealed the presence of elevated peaks in the longitudinal stress field associated with the transition region between the cylindrical and lower hemispherical sections (Figures 6 and 7). The peak longitudinal stress in this region was 45.9 ksi (316.5 MPa); a factor of 1.3 times the average longitudinal stress in the main body of the cylinder.

Figure 5: Finite element model of the oxygen cylinder

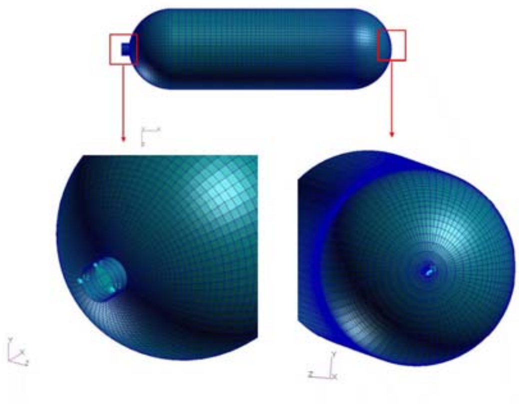


Figure 6: Stress distribution across the cylinder profile. Peak stresses are shown in red

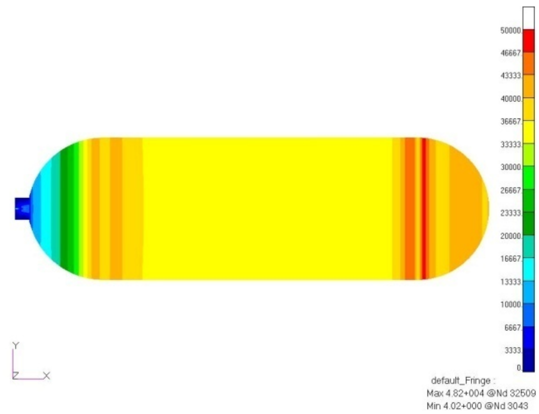
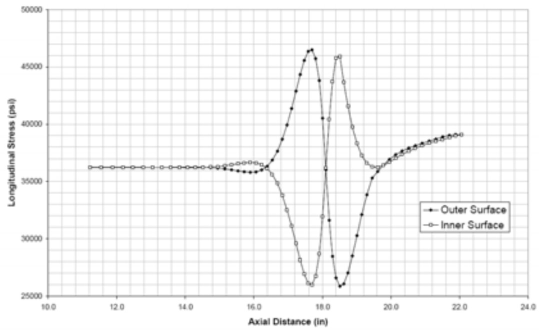


Figure 7: Stress distribution across the cylinder – lower hemisphere transition



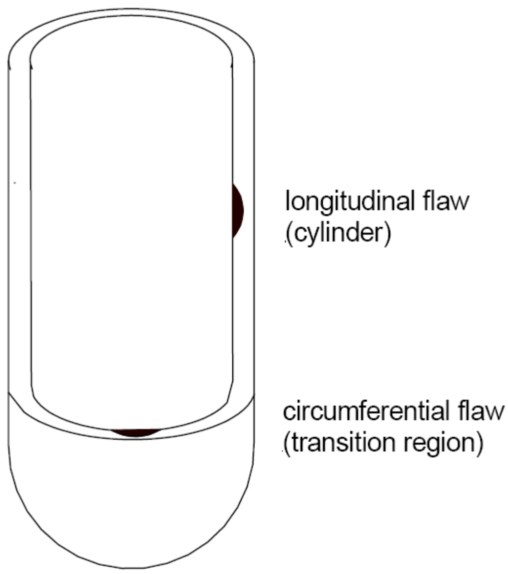
3 The *critical size* of a flaw is defined as the minimum size required to cause failure of the cylinder at a given stress (pressure) level.

Critical flaw size determination

Two potential locations were considered for the possible presence of critical semi-elliptical flaws within the failed cylinder (Figure 8):

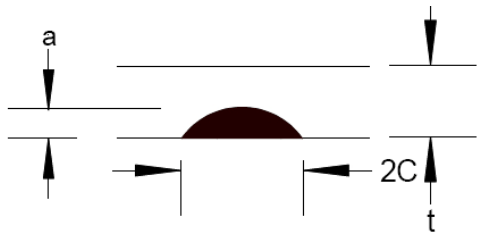
- inner surface longitudinal flaw within the cylindrical (main body) of the cylinder
- inner surface circumferential flaw within the transition region between the main body and the lower hemispherical end of the cylinder.

Figure 8: Cylinder flaw locations considered



Through the preparation of residual strength diagrams that demonstrate the relationship between flaw size and pressure vessel stress, a conservative representation of critical sizes for semi-elliptical flaws of various aspect ratios[4] was prepared for two nominal values of fracture toughness (K_{1C}) of the shell material (50 / 75 ksi$\sqrt{in}$).

Figure 9: Surface flaw schematic



4 The aspect ratio is the relationship between length and depth of the flaw and is normally expressed as the ratio of crack depth to half the crack length (i.e. depth/0.5xlength).

Table 3: Critical sizes for longitudinal flaws

			Flaw Aspect Ratio			
Loading	K_{1C}	Dimension	0.2	0.3	0.4	0.5
Test Pressure	50 ksi$\sqrt{in}$	A (in)	0.009	0.011	0.013	0.016
		C (in)	0.046	0.037	0.033	0.031
	75 ksi$\sqrt{in}$	A (in)	0.012	0.016	0.020	0.026
		C (in)	0.060	0.053	0.049	0.052
Working Pressure	50 ksi$\sqrt{in}$	A (in)	0.048	0.059	0.070	0.081
		C (in)	0.239	0.195	0.175	0.164
	75 ksi$\sqrt{in}$	A (in)	0.063	0.084	0.105	No Fail
		C (in)	0.318	0.279	0.263	

Table 4: Critical sizes for circumferential flaws at the lower transition region

			Aspect Ratio		
Loading	K_{1C}	Dimension	0.2	0.3	0.4
Test Pressure	50 ksi$\sqrt{in}$	A (in)	0.050	0.059	0.069
		C (in)	0.249	0.196	0.173
	75 ksi$\sqrt{in}$	A (in)	0.070	0.087	No Fail
		C (in)	0.350	0.291	
Working Pressure	50 ksi$\sqrt{in}$	A (in)	0.078	0.098	No Fail
		C (in)	0.390	0.325	
	75 ksi$\sqrt{in}$	A (in)	No Fail	No Fail	No Fail
		C (in)			

The analysis results illustrated the key role played by aspect ratio in establishing the critical flaw size, with lower aspect ratio (longer, shallower) flaws proving more critical. From the results presented in Tables 3 and 4, it was shown that the most significant (i.e. smallest) flaw that could present as critical to the integrity of the cylinder type, was a longitudinal defect with a depth of 0.048 in (1.22 mm) and length of 0.478 in (12.1 mm), when evaluated at the cylinder service pressure (1,850 psi) and using a limiting material fracture toughness of 50 ksi$\sqrt{in}$. It was noted by the analysts however, that the flaw sizes determined by this process were likely to be conservative, and should be supplemented by additional analyses using elastic-plastic fracture mechanics techniques (EPFM) and/or a physical test program on cylinders with artificially-produced flaws. The ongoing ATSB investigation will encompass an evaluation of the cylinder performance in the presence of machined external flaws – further detail is provided in the ongoing investigation activities section of this report.

Cabin safety / survival factors

Australian Transport Safety Bureau cabin safety / human factors specialists conducted a comprehensive investigation and review of events within the aircraft's cabin, from the time of the occurrence through to the diversion and landing in Manila. The investigation was supplemented by returns from a survey of passengers and interviews of the cabin crew.

In summary, it was found that the cabin crew had acted in a timely and appropriate way in responding to the occurrence and preparing the passengers and cabin for an emergency landing. Several issues were identified however, centred around:

- Cabin crew actions immediately after the depressurisation – movement around the cabin before being cleared to do so by the flight crew.
- Follow-up cabin crew actions – two cabin crew members became temporarily incapacitated during follow-up duties.
- Passenger address tape reproducer – the automatically-activated system for addressing passengers in the event of a depressurisation did not function, requiring cabin crew to remove their own masks to shout instructions for passengers to stay seated, fasten seat-belts and use the deployed oxygen masks.
- Not all passenger oxygen masks deployed – as a result, two passengers did not immediately start using oxygen and displayed symptoms of hypobaric hypoxia[5].
- Flight deck / cabin crew announcements – some passengers indicated problems with hearing or understanding announcements, and some were concerned regarding a lack of timely information passed onto them.
- Mask oxygen flow – many passengers expressed concern that oxygen was not flowing into the masks, as the re-breathing bag was not inflating[6] or they could not feel or hear the oxygen flowing.

Safety action taken by the aircraft operator in response to the occurrence has considered and addressed these issues.

Electrical systems

The oxygen cylinder failure and associated fuselage rupture damaged many electrical cables and cable bundles that were routed through the affected area. The investigation identified the functions associated with that wiring, and was able to assess the impact of the wiring damage on the aircraft systems.

A total of 85 individual wires were either severed or partially cut during the fuselage rupture. After allowing for duplicates and two unidentified wires, 52 discrete conductors were identified as being applicable to the following aircraft systems:

- 38 relate to the operation and function of the oxygen system (see page 18 of the previous Interim report).
- 3 served the forward cargo hold lights.
- 2 served the cargo area external lights.
- 1 served the right wing leading-edge flap drive primary electrical system.
- 1 served the right wing ground refuelling valve.
- 4 served the right wing outboard trailing-edge flap primary electrical and asymmetry protection systems.
- 1 served the right body landing gear anti-skid system.
- 2 served the potable water and drain line heaters.

While some of the system issues reported by the flight crew could be attributed directly to the wiring damage sustained, others (such as the faults exhibited by the left flight management computer and left VHF Omnidirectional Radio Range - VOR) were not directly related. Consultation with the operator's engineering staff determined that those systems may however, have been affected by a brief power interruption sustained during the initial cylinder failure and fuselage rupture event.

5 Hypobaric hypoxia – a deprivation of oxygen resulting from exposure to reduced atmospheric pressures.

6 Inflation of the mask bag is dependent upon the breathing rate of the user and the flow of oxygen into the mask.

ONGOING INVESTIGATION ACTIVITY

Mechanical testing

The program of mechanical testing conducted on the cylinder material will be concluded with an assessment of the shell impact toughness (both transversely and longitudinally). Further bend and flattening tests to assess the ductility limitations of the shell material are also being conducted.

Damage tolerance

The design of vessels for the safe storage of compressed gasses must incorporate measures to mitigate the risk of unstable fracture and the consequential forceful and destructive release of the contents. Fundamentally, the design must ensure that the cylinder will not fail by unstable fracture when exposed to injurious conditions, or in the presence of injurious flaws. Failure must demonstrably occur by stable (arresting) fracture – the traditional *leak before break* scenario.

To practically establish the leak / fracture boundary conditions for the DOT3HT-1850 cylinder type, and thus level of *damage tolerance*[7] provided by the cylinder design, a program of physical tests employing artificially-flawed cylinders is underway, based on the program of testing undertaken by an International Standards Organisation (ISO) working group (ISO/TC 58/SC 3/WG 14).

Environmental cracking

Like many metal alloys, the heat-treated AISI/SAE 4130 alloy steel comprising the cylinders is susceptible to environmental cracking mechanisms in the presence of a sustained tensile stress and certain environmental conditions. A survey of published literature is being undertaken to determine whether the alloy may be susceptible to cracking when exposed to the chemicals and materials used at all stages of the cylinders' operational lives (service/inspection/testing/cleaning).

SAFETY ACTION

The safety action undertaken by the ATSB and the aircraft operator in response to this occurrence was presented in the first Interim Factual report, and included:

- fleet-wide safety inspections of oxygen system installations
- revision of flight crew emergency procedures, including the introduction of a new depressurisation checklist
- revision of cabin crew emergency operating procedures to address the identified issues
- revision of the operator's policies and materials for training of cabin crew
- ATSB published information bulletins for passengers and crew of pressurised aircraft, providing information on the potential effects of a depressurisation event and actions that can minimise the risk or injury
- ATSB Safety Advisory Notices, encouraging operators of aircraft fitted with pressurised gaseous oxygen systems, and organisations providing maintenance and inspection services for those systems, to ensure that all relevant procedures, equipment, techniques and personnel qualifications meet the applicable regulatory and best-practice requirements.

7 Damage tolerance – the degree of physical damage that can be sustained by a component without causing the onset of failure.

MEDIA RELEASE

Oxygen bottle failure and depressurisation accident still under rigorous scrutiny

The Australian Transport Safety Bureau is continuing its rigorous and comprehensive examination of the circumstances surrounding the failure of an oxygen cylinder that led to the depressurisation of a Boeing 747 on a flight from Hong Kong to Melbourne in July last year.

The ATSB's second interim factual report on this accident, released today, indicates that to date there is no evidence of systemic safety problems with oxygen bottles of the type involved in the accident. Various tests have not been able to replicate the cylinder failure that initiated the accident.

The report provides details of the wide-ranging and ongoing technical examination of five oxygen cylinders obtained by the ATSB from the same manufacturing lot as the failed cylinder. The original cylinder was lost in the South China Sea in the course of the accident.

Analysis of the factual information and findings as to the factors that contributed to the accident remain the subject of ongoing work. Details will be included in the final report of the investigation.

To date, all pressure tests of the cylinders met or exceeded the relevant safety specifications, with recorded rupture pressures being over twice the maximum working pressure of the cylinders.

Other work is being carried out to determine the minimum size of mechanical flaws that could result in cylinder failure in service. The ongoing ATSB investigation will supplement that work with a program of rupture tests on cylinders that have had various sized 'artificial' flaws machined into the shell.

The ATSB expects to conclude the data gathering and analysis aspects of the investigation in early 2010, with a final report to follow.

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