Revisiting Aloha Airline Flight 243: Corrosion Engineer’s Stand point

Submitted by

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The Story of Aloha airline Flight 243

Introduction

1. From the Latin word of "Corrodere", the word of corrosion has been derived which means "gnaw into pieces". Despite the rapid pace of human society since last 3 centuries, the silent attack of corrosion has been a problem. From giant engineering structures till sewer pipe line, the battle between rust and run is on since the industrial revolution. Corrosion has been the main factors of many technological and structural disasters. From catastrophes of bridge collapse, pipe line explosion and aerospace structures, almost all of the industries have born the burst of this silent enemy. In preceding text, a similar catastrophe of fateful aloha airline flight 243 has been discussed in detail.

History of Aloha airline flight 243

2. According to (National Transportation Safety Board, 1989, p. 1), on April 28, 1988 a Boeing 737 from Hawaii based Aloha Airlines was scheduled for many interisland flights to different Hawaii destinations. From 0500 hours till 1100 hours, the aircraft had flown six interisland uneventful flights.

3. As per (National Transportation Safety Board, 1989, p. 2), at 1325 hours flight 243 was ready to depart from Hilo, Hawaii to Honolulu, Hawaii. Two pilots, three flight attendants and a Federal Aviation Authority (FAA) observer was the part of the flight

crew with 89 passengers on board. The departure and climb till cruise altitude were uneventful.

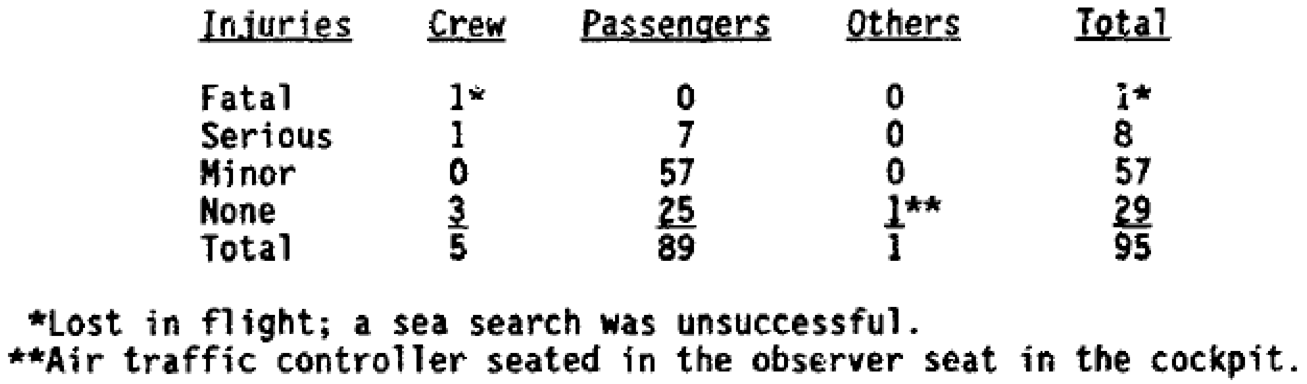
The Catastrophe Strikes

4. As per (National Transportation Safety Board, 1989, p. 2), as the airplane was leveled off to the cruising altitude of 24000 Feet AGL, both pilot heard a clap or whooshing sound followed by wind noise behind them. The captain of the aircraft observed that “there was blue sky where the first class ceiling had been”. The captain immediately took control and started the descent. Due to ambient noise in the cockpit, it was impossible to communicate.

5. At the onset of the decompression flight attendant no 1 was standing at seat row 5 and was swept away by the blowing wind from left side of the fuselage. The no 2 flight attendant was standing at the row 15/16 and was thrown to floor. She sustained few minor bruises. While no 3 flight attendant was standing at row 2, she was struck by the debris and thrown to floor. She sustained serious head injuries.

6. According to (National Transportation Safety Board, 1989, p. 3), the first officer radioed to the Honolulu air traffic controller about the emergency and also informed the alternate Maui airport air traffic control for an emergency landing. The aircraft was becoming uncontrollable below the speeds of 170 Knots and flap retraction above 5. The captain decided to maintain the speed and flap retraction to attempt a landing on Maui Airport. The landing gears were selected down but no indication of nose landing gear was acknowledged by the flight crew. However visual check from the air traffic

control confirmed the lowering of nose landing gear. The aircraft landed at 1358 hours on Maui Airport. The Causalities details is Illustrated below.



Injuries	Crew	Passengers	Others	Total
Fatal	1*	0	0	1*
Serious	1	7	0	8
Minor	0	57	0	57
None	3	25	1**	29
Total	5	89	1	95

*Lost in flight; a sea search was unsuccessful.
**Air traffic controller seated in the observer seat in the cockpit.

Figure 1: Details of Causalities of Airline Flight 243 (Source: (National Transportation Safety Board, 1989, p. 5)

Damage Details of the Airplane

7. As per (National Transportation Safety Board, 1989, p. 5), a major portion of upper crown skin and structure of section 43 separated in flight causing an explosive decompression of the cabin. From NTSB stand point, explosive decompression in this case refers to violent expansion and noise from cabin air released under pressure rather than the effect of a chemical explosive device. From (National Transportation Safety Board, 1989, p. 5) point of view, the damaged area extended from aft of main cabin entrance door, rearwards about to 18 feet to the area just forward of the wing and from left side at the cabin floor level to the right side window level. The airplane was worth at an estimated cost of 5 million US dollars. As a result of accident it was determined as damaged beyond economic repair and was dismantled and sold in scraps and parts. The visual illustrations of the damage are depicted below in the figures.

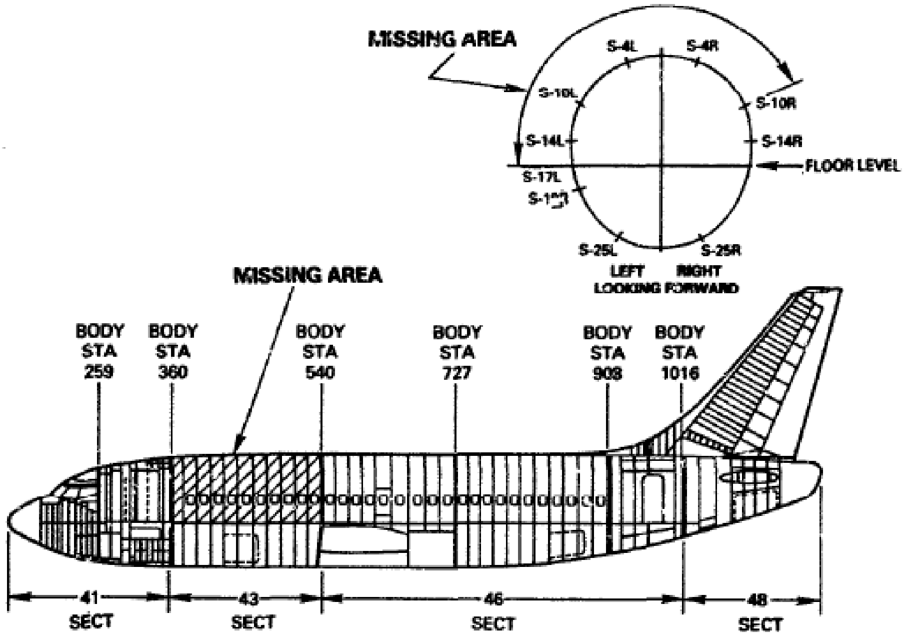


Figure 2: Schematics of Damage Cause to Aloha Airline Flight 243 (Source: (National Transportation Safety Board, 1989, p. 6)

Figure 3: Damage to the right hand side of Fuselage of Aloha Airline Flight 243

Figure 4: Damage to the Left Hand Side of Aloha Airline Flight 243

Figure 5: Front view of Damaged Aloha Airline Flight 243 fuselage

Visual Examination

8. As per (National Transportation Safety Board, 1989, pp. 8-10), the skin of the aircraft from body station 360 till body station 540 was peeled from the structure in down and aft direction. The direction of damage on aircraft station is illustrated below in the figure.

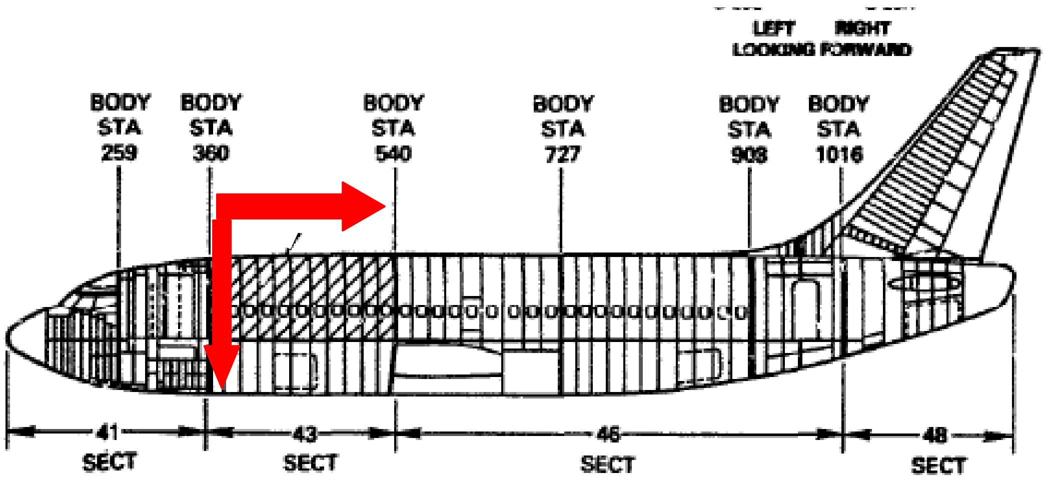


Figure 6: Damage Direction between Body station 360 & 540

9. According to (National Transportation Safety Board, 1989, p. 9), indications of pre-existing cracks were found in lap joints of S-10L forward of body station 540 and on side of each rivet holes in body station 360 butt strap near S-7R. All other fractures adjacent to the separation area were typical of overstress application.

10. As per (National Transportation Safety Board, 1989, p. 10), fracture surface and the immediate areas surrounding the separation perimeter were generally corrosion free. However, areas of corrosion and dis-bonded surface were noted in joints at body station 360 and 540.

History of the Airplane

11. According to (National Transportation Safety Board, 1989, p. 12), the mishap aircraft N73711 was a Boeing 737-297 with serial number 20209. It was manufactured in 1969 as production line number 152. It was equipped with two Pratt & Whitney JT8D-9A engines. The airplane was delivered to Aloha Airlines on 10 May, 1969. The Aloha Airline was operating eleven jets, all of them were Boeing 737s with flight cycles of 60000 or more.

12. As per (National Transportation Safety Board, 1989, p. 12), at the time of accident, the jet N73711 has accumulated 35496 flight hours and 89680 flight cycles (Landings). The airplane was the 2nd highest in number of operating cycles. The actual operating flight cycles of the airplane was less than the stipulated number, as the airplane never reached the maximum pressure differential of 7.5 PSI. The maintenance log books of the airplane did not revealed any discrepancy prior to the accident.

The Boeing 737 Lap Joints Problem and its Dis-Bonding Issues

13. According to (National Transportation Safety Board, 1989, p. 13), the fuselage structure of Boeing 737 comprises of four sections. The section 41, 43 and 46 formulates the most of pressurized area. These sections are joined with section 48 by butt joints forming the complete fuselage. The section wise distribution of the Boeing 737 structure is illustrated below.

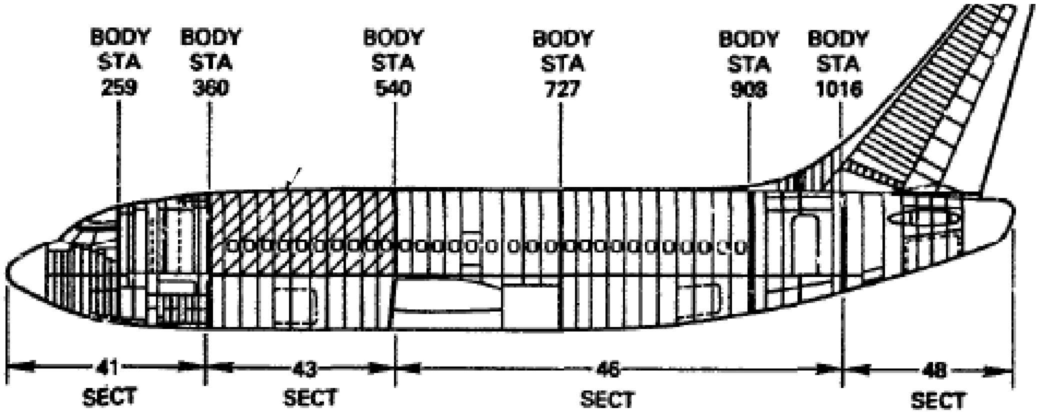


Figure 7: Section wise distribution of Boeing 737 Fuselage (Source: **(National Transportation Safety Board, 1989, p. 6)**

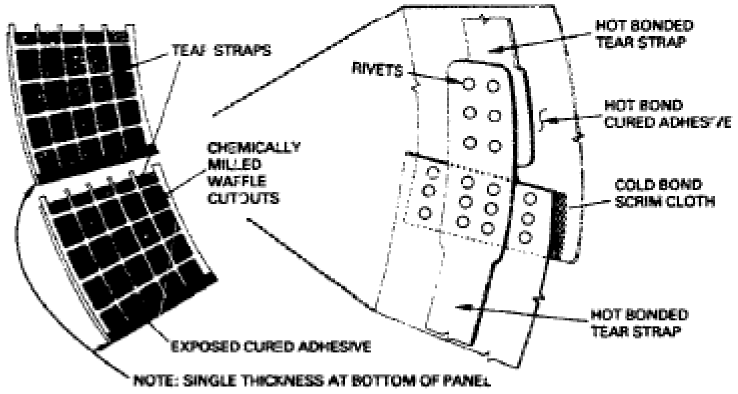
14. The sections are constructed of circumferential frames and longitudinal stringers that are covered by formed aluminum skin panels that are riveted to the underlying structure. Each skin panel on the lobe of section 43 is the length of entire section that is 18 Feet. Adjacent skin panels are joined together by overlapping the panel about 3 inches over the lower panel. The joint area is fastened with three rows of rivet and a bonding process.

15. As per (National Transportation Safety Board, 1989, p. 14), in Section 43 the skin panel lap joints exists at S-4L & R, S-10L & R and S-14L & R at the upper lobe. Similarly lap joints exist at S-19 L & R and S-26 L & R at the lower lobe. The upper lobe skin panels in section 43 are fabricated from two complete sheets of 0.036 inch thick aluminum that are joined together using a hot bonding process. An acid etch is used to prepare the surfaces of sheets before bonding. The inner sheet is then masked and then chemically milled leaving the waffle doublers that provides circumferential tear straps at each 10 inch intervals. On the early production model (till serial number 291),

the doubler sheet was milled away chemically at lap joints location. While for production serial number 292 and onward, the doubler sheet was retained to provide an extra thickness. For earlier production serial number (1-291), the fuselage skin lap joints were cold bonded. The cold bond process used an epoxy impregnated woven scrim cloth to join the single thickness 0.036 inch skin panel together. The joints were mechanically fastened by three rows of counter sunk rivets. The metal surface to be bonded was etched to ensure cleanliness and prepare the surface for suitable bonding. The epoxy used was reactive at room temperature and was kept in storage with dry ice and was warmed till room temperature before use.

16. According to (National Transportation Safety Board, 1989, p. 14), the cold bond process was intended to provide structural efficiency, manufacturing cost advantage and overall reduction in weight over traditionally riveted thick skin panels. Fuselage pressurization load was intended to be transferred through the cold bond rather than the rivets, thus overall not having any impact on fatigue life of the structure. A comparative lap joint construction for production serial number 1-291 and 291 onwards is illustrated below in the figure.

LINE NUMBER 1-291



LINE NUMBER 292 & AFTER

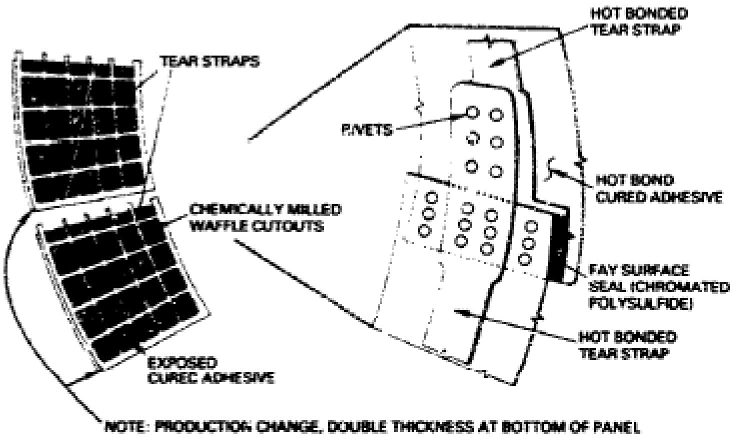


Figure 8: Comparison fuselage structure for production serial number of Boeing 737 fuselage (Source: **(National Transportation Safety Board, 1989, p. 15)**

17. As per (National Transportation Safety Board, 1989, p. 18), the laboratory coupon tests and Quonset hut test of full scale fuselage model conducted by Boeing revealed no abnormality regarding the reliability of the cold bonded lap joints. However, the early service history records of Boeing 737 revealed that difficulties were encountered during this bonding process. From Boeing's point of view the problem of bonding degradation was either due to presence of condensation in scrim cloth or due

to premature curing of the bond. The presence of such discrepancies can trigger corrosion which can get worst during service due to accumulation of water on these vulnerable sites. The cold bond production process was dis-continued in 1972. The riveted joints were replaced by using chromated polysulfide sealing compound without any bonding. The production process was implemented from production serial number 292 onwards. From Boeing's point of view, the dis-bonding caused direct transfer of fuselage hoop stresses to the counter sunk rivet holes and ultimately triggers fatigue crack initiation and propagation. In cylindrical fuselage like 737 the amplitude of circumferential hoop stresses is greater than the longitudinal stresses, the crack propagation takes place perpendicular to the direction of hoop stresses. In case of Boeing 737, the fatigue cracks were expected to initiate in the outer layer of skin and not to the underlying skin panels due to absence of counter-sunk holes. Random cracking of lap joints were reported by Boeing 737 users. The rate of crack propagation was dependant on degree of dis-bonding, accumulation of full pressurization cycles and environment of operation. The reports of cracks appearance is illustrated in a historic time line in figure illustrated below.

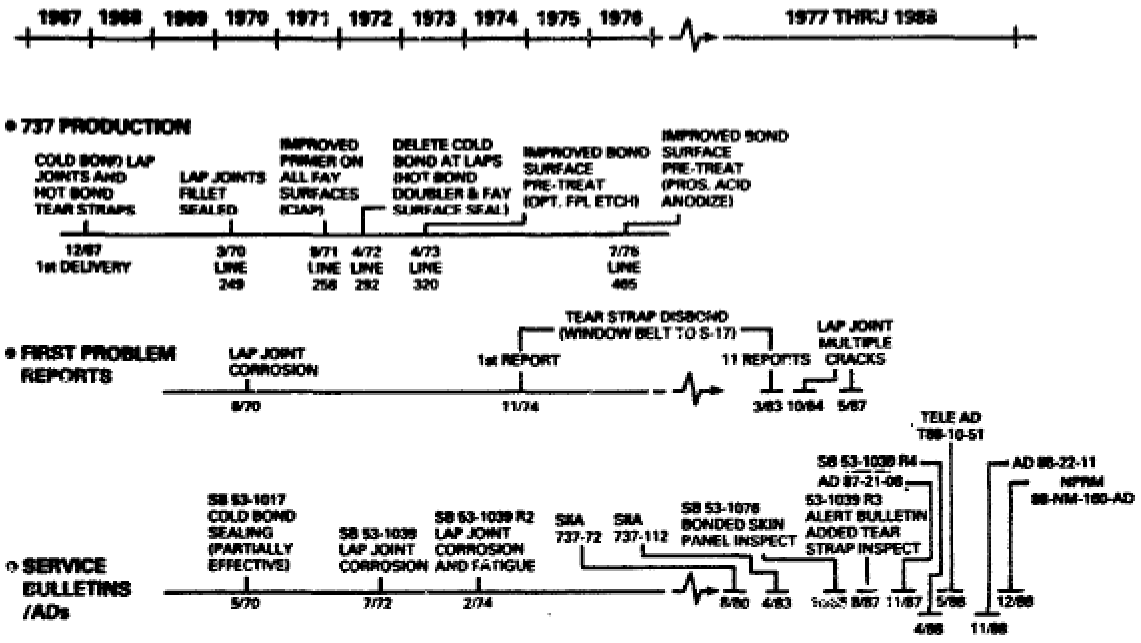


Figure 9: Historic Time line of Lap joints crack appearance on Boeing 737 fuselage

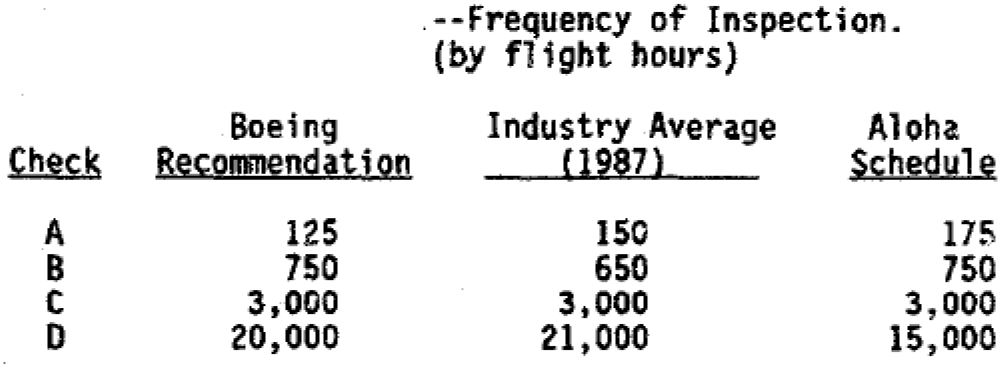
(Source: **(National Transportation Safety Board, 1989, p. 19)**

18. According to (National Transportation Safety Board, 1989, p. 20), Boeing issued several service bulletins (SB’s) to address the issue. The earliest of which was issued in May 13, 1970 under the heading of “Sealing of Cold Bonded structure for Corrosion Protection” bearing SB 737-53-1017. A follow up SB, bearing number SB 737-53-1039 was issued on July 19, 1972 which addressed the area of lap joint corrosion and repair in the first 291 produced planes. In 1974, a revision was issued which stated, “In most instances these areas are identified only after corrosion caused exterior bulges, cracks on missing fasteners” and prolonged operations with de-lamination (dis-bonded) would lead to fatigue cracking. The details of corrosion and fatigue inspections were also stipulated. However, the Federal Aviation Authority (FAA) never classified it as mandatory. In 1987, the status was upgraded to alert and was to be complied before

30000 landing or next 250 landings by the FAA. It is pertinent to note that these instructions laid emphasis on S-4L & R particularly. As per these directives, eddy current non destructive testing (NDT) was to be performed on the suspected areas.

Aloha Airline Maintenance Record

19. The maintenance schedule of Aloha Airline as per Boeing recommendations and other operators is illustrated below in the figure.



--Frequency of Inspection.
(by flight hours)

Check	Boeing Recommendation	Industry Average (1987)	Aloha Schedule
A	125	150	175
B	750	650	750
C	3,000	3,000	3,000
D	20,000	21,000	15,000

Figure 10: Frequency of Maintenance of Aloha airlines and others (Source: **(National Transportation Safety Board, 1989, p. 22)**

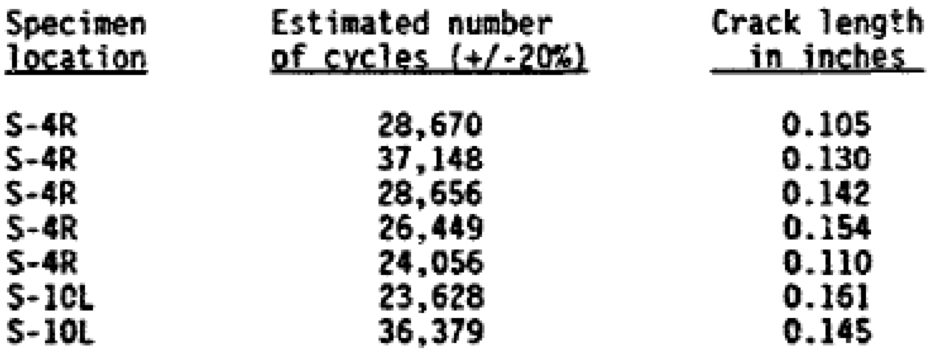
20. As per (National Transportation Safety Board, 1989, p. 23), from maintenance record of Aloha Airlines, it was found that the airplane had undergone its A,B,C and D level checks in 1987 and 1988. The D checks which deals with the fuselage skin and framing was complied in 1987. A similar kind of D check regarding the inspection of fuselage splices and stringers was complied in 1981. The D check inspection included an FAA approved ¼ sampling which meant that D level checks have to be carried out on ¼ airplanes of the fleet. In case of adverse findings, rest of the fleet has to be inspected. In case of no abnormality at the normal 15000 hours if no adverse finding

has been found the same inspection has to be complied on 30000 hours. As per Aloha airlines maintenance records, no adverse findings were recorded.

21. According to (National Transportation Safety Board, 1989, p. 24), once visual inspection of airplane exterior was carried out. Considerable evidence of corrosion on fuselage of the fleet was recorded. Swelling and bulging of skin, dished fastener heads, pulled and popped rivets, blistering, scaling and flaking paints were observed on lap joints of almost every plane. Aloha airline failed to produce any evidence of in pace corrosion control program. As per Boeing's instructions, extensive application of corrosion inhibitors compounds, fasteners reapplication, airplane washing and buffing and brightening of unpainted surface was a part of corrosion control program at specified intervals.

Metallurgical Investigation

22. According to (National Transportation Safety Board, 1989, p. 30), the lap joint sample S-4R between BS 360 and 420 was found having extensive fatigue cracking. The longest crack was found to be of 0.27 inches. The entire cold bonded lap joint had become dis-bonded. Light to moderate and severe corrosion was noticed on different areas. The lap joint of S-4L from BS-727 to 747 and 847 and 867 also showed fatigue cracking in the skin adjacent to rivet holes. The laboratory examination further revealed that only a crack larger than 0.08 inch can be detected by stipulated eddy current contrary to Boeing's claim of 0.04 inch. Boeing also performed the striation counts on seven crack samples. The data acquired from these counts is illustrated below in the figure.



Specimen location	Estimated number of cycles (+/-20%)	Crack length in inches
S-4R	28,670	0.105
S-4R	37,148	0.130
S-4R	28,656	0.142
S-4R	26,449	0.154
S-4R	24,056	0.110
S-10L	23,628	0.161
S-10L	36,379	0.145

Figure 11: Number of cycles observed on different stringers (Source: **(National Transportation Safety Board, 1989, p. 31)**

23. The typical lap joints and appeared crack are illustrated below in the figure.

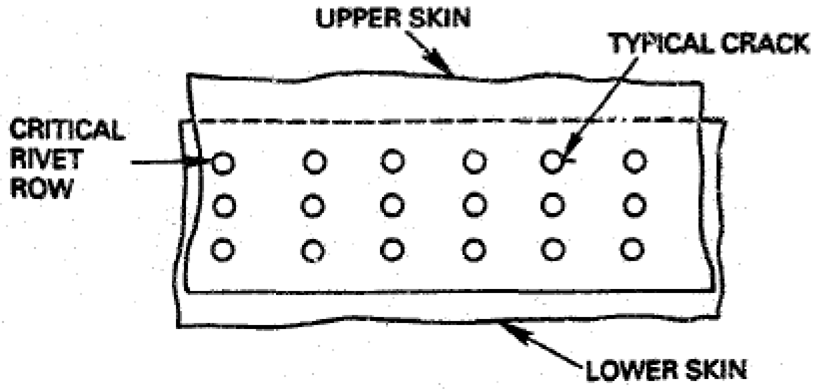


Figure 12: Typical Crack Appearance on Lap joint (Source: **(National Transportation Safety Board, 1989, p. 32)**

The typical crack origination site on the lap joint has been depicted below in the figure.

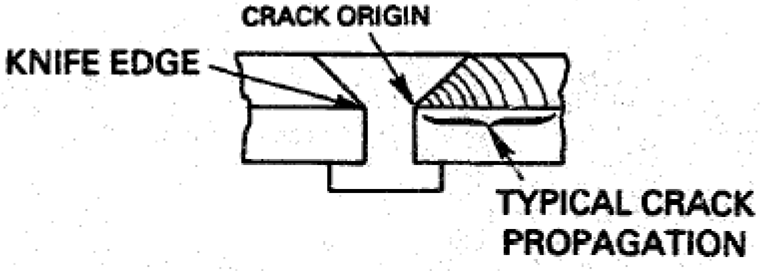


Figure 13: Typical Crack origination site on Lap joint (Source: **(National Transportation Safety Board, 1989, p. 32)**

NTSB Analysis

24. According to (National Transportation Safety Board, 1989, p. 47), the accident sequence initiated with the separation of the pressurized fuselage skin. This separation led to an explosive decompression which further caused the separation of upper lobe of section 43 of the cabin. The post accident examination of the structure revealed that the remaining intact structure did not contain the origin of the failure. The main exhibit was not recovered despite the extensive sea and ground search. The origins of failure were deliberated on the basis of remaining structure and the air worthiness history of the airplane. The available evidence suggested that the origin of the fuselage separation was initiated from lap joint S-10L near BS-440. NTSB also concluded that the tear strap dis-bonding also resulted in failure of expected controlled decompression of the airplane which was anticipated by designers. The multiple sit damage (MSD) also resulted in multiple cracks. The dis-bonding of cold lap joints would result into transfer of loads

directly to the counter sunk rivets holes. The presence of knife edge in these rivet holes would result in to a stress concentration area making it susceptible to fatigue cracking.

25. According to (National Transportation Safety Board, 1989, pp. 52-55), the Aloha airline maintenance program did not realize the effect of flight cycle accumulation. The maintenance program was based on flight hour's accumulation rather than the flight cycle accumulation. The maintenance program was further limited by time and man power constraints and maintaining the operational status of the fleet. Moreover the complied service bulletins of Boeing by Aloha airline did not had the documentary evidence for compliance of NDT. The conduct of NDT on such portions of fuselage was also difficult.

26. According to (National Transportation Safety Board, 1989, pp. 58-59), the corrosion control program of Aloha airline was not as aggressive as it should have been. The maintenance personnel's seems to be unaware of the criticality of corrosion on lap joints, tear straps and its adverse consequences. The maintenance record established the fact that corrosion problem was detected by Aloha maintenance personnel and the corrective actions were deferred without any sound reason.

27. As per (National Transportation Safety Board, 1989, pp. 73-74), the probable cause of accident was failure of Aloha airline maintenance program to detect the presence of significant dis-bonding and fatigue damage which ultimately led to the failure of lap joint at S-10L and the separation of fuselage upper lobe. FAA also failed to ensure the mandatory compliance of Boeing's alert service bulletin regarding corrosion and dis-bonding of lap joints.

Corrective-preventive measures

28. As per (National Transportation Safety Board, 1989, pp. 74-77), the FAA should identify those operators which had significant difference in flight hour's operation time and flight cycle accumulation. They may be provided by the needed assistance for maintenance programs. The programs of NDT certification and periodic skill demonstration may be revised. FAA should also monitor the Boeing 737 jet fatigue issues of lap joints. FAA should also develop model program for corrosion control for airline operators. Full scale fatigue testing for at least two economic life cycles may be included for future certifications and all those jets in operation may also be subjected to subject testing's.

29. NTSB also advised Aloha airline to revise its maintenance from cycle point of view instead of flight hours. Aloha airlines were also advised to initiate an aggressive corrosion control program. Aloha was also advised to upgrade its technical division on professional grounds.

Aviation Industry after Aloha Incident

30. The Aloha airline incident was considered as a game changer for the airline industry. The vulnerability of earlier production Boeing 737's lap joint is area under debate for decades after the accident. Boeing has incorporated many modifications and steps to enhance and beef up the weak area. However, as per (Norris, 2011), on April 4 ,2011 Boeing issued a service bulletin to all airline operators for inspecting the lap joints on planes built between 1993-2000. The life cycle of 175 affected planes is greater than 30000 flight cycles. Boeing expected cracks appearance at around 60000 flight cycles. According to (Boylan, 2011), the inspection was triggered by an in-flight fracture of

fuselage skin panel on South West Airline Flight 812. As per (Dubios, 2011), Boeing has further reduced the inspection cycle to 30000 flight cycles.

Figure 14: South West Airline Flight 812 with fractured skin on fuselage (Source: **(Boylan, 2011)**

31. The recurrence of the problem despite many corrective actions after the Aloha airline incident has triggered a new debate. The core topics of debate would raise questions on the failure mechanism of the Aloha airline flight 243 and further to the steps to avoid the future recurrence. It has been felt imperative to re-visit the findings and conclusion of Aloha airline Flight 243. Special emphasis has to be laid on the failure mechanism and it’s in depth analysis. The contradictory theory of fluid hammer may also be taken into account to ascertain its contribution in the failure.

Synthesis

The Contradictory Fluid Hammer Theory

32. The disaster of Aloha airline flight 243 has opened new debate on the fail safe design of Boeing 737. As per Boeing's claims a small hole in the fuselage would result into a controlled decompression of the airplane. The controlled decompression would not allow an explosive decompression and enhances the chance of survivability of passengers. For this purpose, the tear straps are incorporated throughout the whole fuselage structure. These tear straps allows the controlled decompression. The biggest question in case of Aloha airline flight 243 was regarding the functionality of Boeing's tear strap mechanism. From NTSB point of view, the fatigue cracks within the skin also cause fracture of tear straps, thus impeding their function to act as controlled decompression points. However, as per (Stoller, 2001), a Hawaiian steam engineer Matt Austin had others ideas regarding the crash of Aloha airline flight 243 and failure of Boeing's Tear strap mechanism. Austin is a former Hawaiian boiler expert and runs a consultancy business.

33. According to (Austin, 2001), the failure of Aloha airline flight 243 was due to what he termed as a fluid hammer theory. Austin has derived his hypothesis on the basis of a blood stained picture from the NTSB investigation. The blood stained photograph that formulates the basis of Austin's theory is illustrated below.

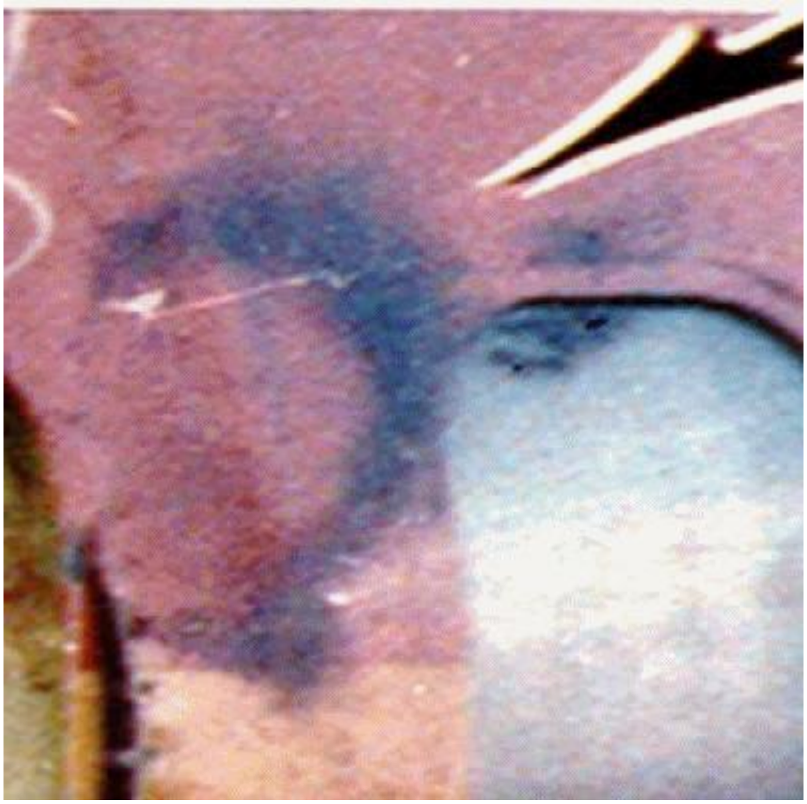


Figure 15: Blood Stains photograph that forms the Basis of Austin's fluid hammer theory (Source: **(Austin, 2001)**)

34. According to (Austin, 2001), these blood stains are a tell tale story of what might had happened at Aloha airline flight 243. These stains were actually the silhouette of the only casualty of the flight, C B Lansing's skull. From Austin's point of view, these stains are not explained properly in the inquiry and are misunderstood. Due to these reasons the NTSB investigation cause is out rightly wrong. From Austin's point of view, the separation sequence started at BS 500 instead of BS 340. The flight attendant standing at row 5 was sucked in the tear opening, blocking the controlled decompression. This blockage led to the increase of the pressure inside the hull and eventually its failure. A pictorial illustration of Austin's theory is illustrated below.

Figure 16: Illustration of Austin's theory showing trapped Lansing at the onset of separation

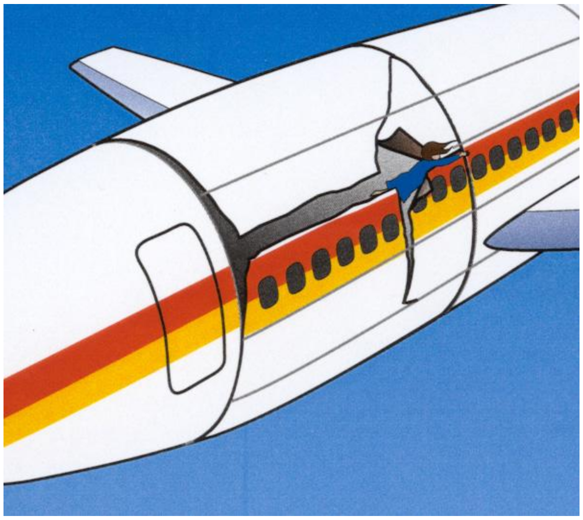
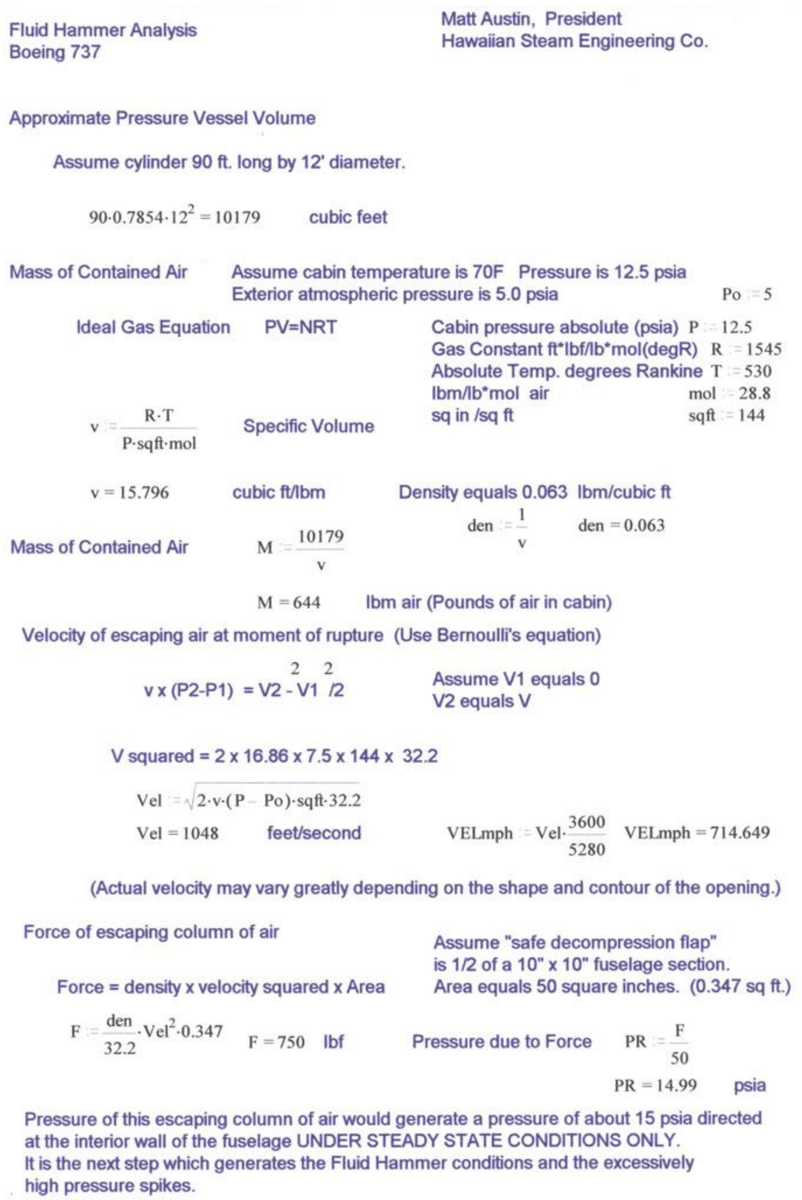


Figure 17: Sequence II of Austin's theory indicating rupture of upper lobe of section 43

35. Austin's fluid hammer comes from the boiler's back ground. It looks much appealing in explaining the failure of tear strap mechanism. But NTSB had shown not

much interest to buy Austin's idea. The calculation performed by Austin to validate his fluid hammer theory is illustrated below in the figure.



Fluid Hammer Analysis
Boeing 737

Matt Austin, President
Hawaiian Steam Engineering Co.

Approximate Pressure Vessel Volume

Assume cylinder 90 ft. long by 12' diameter.

$90 \cdot 0.7854 \cdot 12^2 = 10179$ cubic feet

Mass of Contained Air — Assume cabin temperature is 70F Pressure is 12.5 psia
Exterior atmospheric pressure is 5.0 psia $Po := 5$

Ideal Gas Equation PV=NRT

Cabin pressure absolute (psia) $P := 12.5$
Gas Constant ft*lbf/lb*mol(degR) $R := 1545$
Absolute Temp. degrees Rankine $T := 530$
lbm/lb*mol air $mol := 28.8$
sq in /sq ft $sqft := 144$

$v := \frac{R \cdot T}{P \cdot sqft \cdot mol}$ Specific Volume

$v = 15.796$ cubic ft/lbm

Density equals 0.063 lbm/cubic ft

$den := \frac{1}{v}$ $den = 0.063$

Mass of Contained Air $M := \frac{10179}{v}$

$M = 644$ lbm air (Pounds of air in cabin)

Velocity of escaping air at moment of rupture (Use Bernoulli's equation)

$v \times (P2-P1) = V2^2 - V1^2 /2$

Assume V1 equals 0
V2 equals V

V squared = 2 x 16.86 x 7.5 x 144 x 32.2

$Vel := \sqrt{2 \cdot v \cdot (P - Po) \cdot sqft \cdot 32.2}$

$Vel = 1048$ feet/second

$VELmph := Vel \cdot \frac{3600}{5280}$ $VELmph = 714.649$

(Actual velocity may vary greatly depending on the shape and contour of the opening.)

Force of escaping column of air

Assume "safe decompression flap"
is 1/2 of a 10" x 10" fuselage section.
Area equals 50 square inches. (0.347 sq ft.)

Force = density x velocity squared x Area

$F := \frac{den}{32.2} \cdot Vel^2 \cdot 0.347$ $F = 750$ lbf

Pressure due to Force $PR := \frac{F}{50}$

$PR = 14.99$ psia

Pressure of this escaping column of air would generate a pressure of about 15 psia directed at the interior wall of the fuselage UNDER STEADY STATE CONDITIONS ONLY.
It is the next step which generates the Fluid Hammer conditions and the excessively high pressure spikes.

Figure 18: Calculation performed by Matt Austin

Analyzing Fluid Hammer Theory

36. Before going further into details of NTSB investigation, it has been felt imperative to analyze the Mat Austin's fluid hammer theory. It is pertinent to note that the calculations performed by Austin are as per the ideal gas law. From a static structure like boilers, these calculations may stand valid, but from an aeronautical stand point there synthesis is felt imperative.

37. According to (Mccormick, 1995, p. 26), the flow around an aerofoil is two dimensional. As per (Megson, 1999, p. 220), the aircraft structures are designed to take two types of loads, the ground loads and air loads. These loads can be further classified into surface loads like aerodynamic and hydrostatic pressure and body forces due to gravitational and inertial effects. According to (Swnginnis, 2003, p. 332), the aircraft structures directly exposed to dynamic pressure could be damaged as the dynamic pressure of the air stream is converted into static pressure pressing inward on the structure. In case of Aloha airline flight 243 once the separation started due to cracks and skin peeling off, it opened a hole which allowed gust of high velocity winds. This high velocity winds when entered the cabin becomes stagnant and according to (Swnginnis, 2003, p. 341), the sum of static pressure and dynamic pressure are equal for an incompressible flow. The conversion of this huge dynamic pressure into static pressure also increased the applied stress from within the fuselage structure. Moreover these gust loads would have acted as impact loads on the internal structure. The value of these loads probably had exceeded the limit loads of fuselage design. As fuselage structures are not supposed to be accommodate any aerodynamic loads. Already weakened structure by multiple cracks and corrosion gave way while the structure

having sufficient strength stood by. The rupture of the fuselage should not have any impact on the lift. The lift distribution profiles on the aircraft fuselage are zero. However, the subsequent damage caused by the debris might have damaged others lift generating surfaces. That probably explains that why the aircraft still remained controllable even after such a structural disintegration. The reason for difficulties above the speeds of the 170 Knots might have been due to the reduced differential or hole in structure probably would have disturbed the laminar flow. The local turbulence above 170 knots might have caused the controllability difficulty in higher speed regimes. The fateful exit of C B Lansing had been probably due to this gust of wind. During her exit in a turbulent flow, her head might have made contact with the left side of fuselage causing the blood stained appearance of the side.

38. Mat Austin theory might have stand validated for a boiler or static system. But impact loads due to gust of wind entering inside the fuselage from the initial rupture could have been the sole cause of the structural dis-integration despite the presence of tear straps.

Metal Fatigue or Corrosion Fatigue

39. According to (Schijve, 2004, p. 7), if a specimen is subjected to cyclic loads, a microscopic fatigue crack could nucleate and grow till a macroscopic level, the final cycle of fatigue crack could lead to fracture. From metal fatigue point of view, it is pertinent to note that Boeing 737 had undergone the fatigue test and fatigue life estimation. In case of Aloha airlines, the mishap aircraft had flown 89680 flight cycles. Although the full pressurization (means a differential pressure of 7.5 psi) may not have been applied on all the cycles, thus lowering the number of actual cycles operated.

Boeing had designed 737 for an economic life of 51000 flight hours and 75000 cycles. The limit was further reduced to 60000 cycles after the crack reports on the structure. The lowering of limits also could not stop the incident of South West Airline flight 812. The recent reports of cracks are under a limit of 30000 flight cycles which is far below then the prescribed limit. These recent problems raises the questions that either the Boeing's fatigue test of 737 has some serious issues or the problem exist somewhere else. We will make an attempt to certify Boeing's tests. According to (D.Y.Jeong, 1995, p. 28), the pressure profile on the 737 fuselage is illustrated below in the figure.

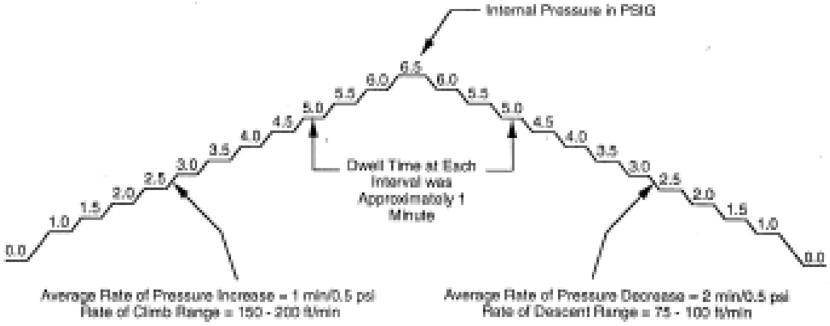


Figure 19: Pressure Profile on Boeing 737 fuselage (Source: **(D.Y.Jeong, 1995, p. 28)**)

40. According to the experiments conducted by (D.Y.Jeong, 1995, p. 30), the highest strain rate was experienced by top row of rivets. The graphical presentations of his results are illustrated below in the figure.

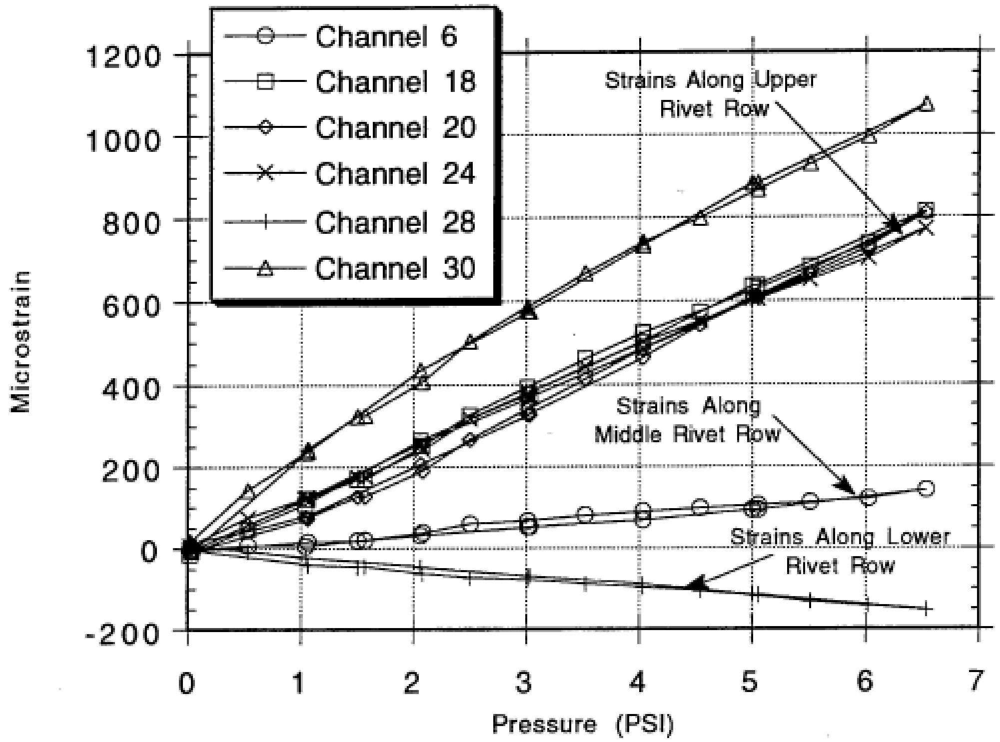


Figure 20: Strain rate of row of rivets on lap joint (Source: **(D.Y.Jeong, 1995)**)

41. This independent data indicates that Boeing's claims of vulnerable area are correct and the top most row of rivets is the susceptible one in case of fatigue cracking. According to (R.J.H.Wanhill, 1999, p. 19), there is no primary association between corrosion and fatigue. Severe corrosion did not result in multiple site damage (MSD). However (Craig L. Brooks, 1998, pp. 14-12) suggests that the corrosion has propounding effect on structural life. It can degrade the structural capabilities. His experimental result also indicates the reduction in critical length of the crack under aging effects. The graphical representations of his observations are illustrated below.

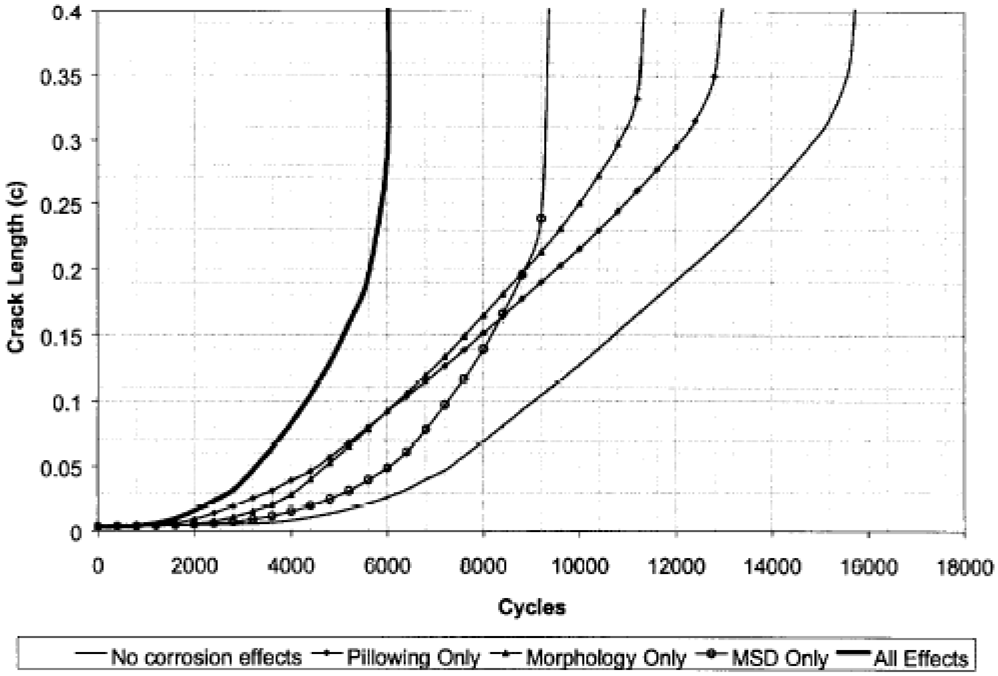


Figure 21: Effect of Corrosion on crack length (Source: **(Craig L. Brooks, 1998, pp. 14-10)**)

42. It is evident from these results that the presence of corrosion had degraded the structural capability to a considerable amount. The presence of corrosion is highly dependent on the operating environment. In controlled laboratory environment the tests may be misleading unless the operating environment is not simulated accurately. Aloha airline flight 243 was operated in a marine environment. As per (R.S.Treseder, 2002, p. 146), the environment of Hawaii had an average PH of 8-8.3 with salinity between 34.6-35, the content of dissolved oxygen in the environment is 6-14 ppm having a temprature of 24-28 degree centigrade. The environment of Hawaii is one of the aggressive as compared to other international marine environment. The absence of this environment or a closer environment could lead to erroneous results. All these arguments indicate

that corrosion can degrade the fatigue life. Now it is imperative to find a corrosion mechanism that can explain the catastrophe of Aloha airline flight 243.

A Corrosion Engineer's investigation of Aloha flight 243

43. According to (Roberge, 2007, p. 34), corrosion failures are environmentally context specific. As per (American Society of Materials, 1995, p. 1427), Aluminum is a thermodynamically reactive metal but formation of a 1 Nano meter oxide film makes it useful for the industrial application. The pourbaix diagram of Aluminum is illustrated below.

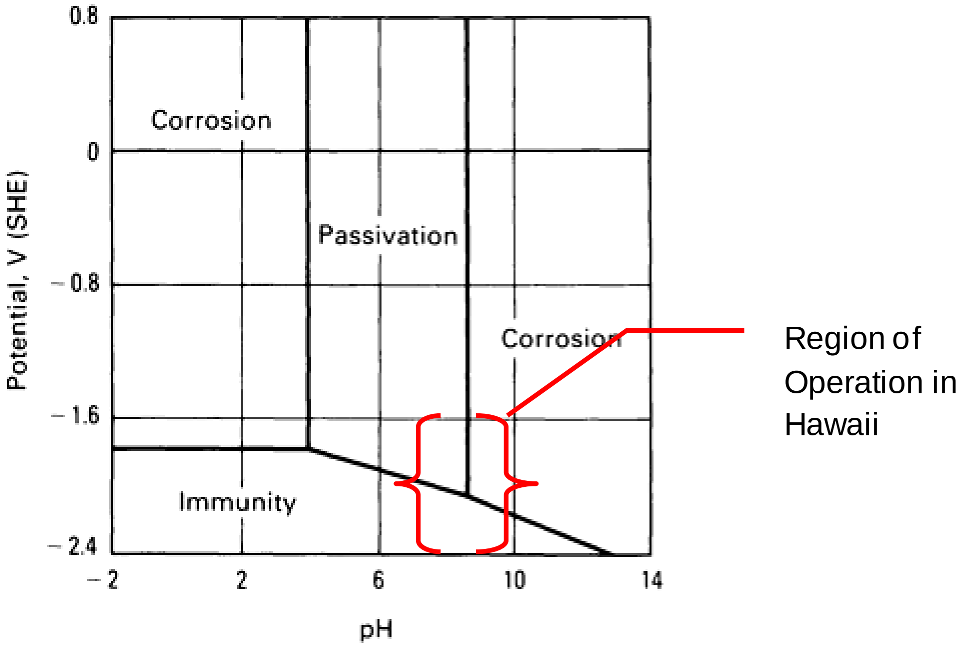


Figure 22: Pourbaix Diagram of Aluminum (Source: **(American Society of Materials, 1995, p. 1428)**)

44. According to (Vargel, 2004, p. 113), uniform corrosion is observed in aluminum in high acidic or alkaline media. The problem arises due to solubility of thin oxide film. The operating environment of Aloha flight 243 was almost neutral with PH range between 8-

8.3. Henceforth the chance of uniform corrosion in case of Aloha airline flight 243 seems remote.

45. As per (Vargel, 2004, p. 113), Aluminum is prone to localized or pitting corrosion in near neutral environment. Pitting corrosion occurs when the metal is put into permanent or intermittent contact with aqueous media. Experience shows that pitting corrosion occurs during first week of exposure. Pitting corrosion is known to be developed with Chloride ions. The operating environment of Aloha airline flight 243 had a pretty higher concentration of salinity. The high content of salinity means higher concentration of chloride ions making it more susceptible for corrosion. The mechanism for pitting corrosion in Aluminum is illustrated below.

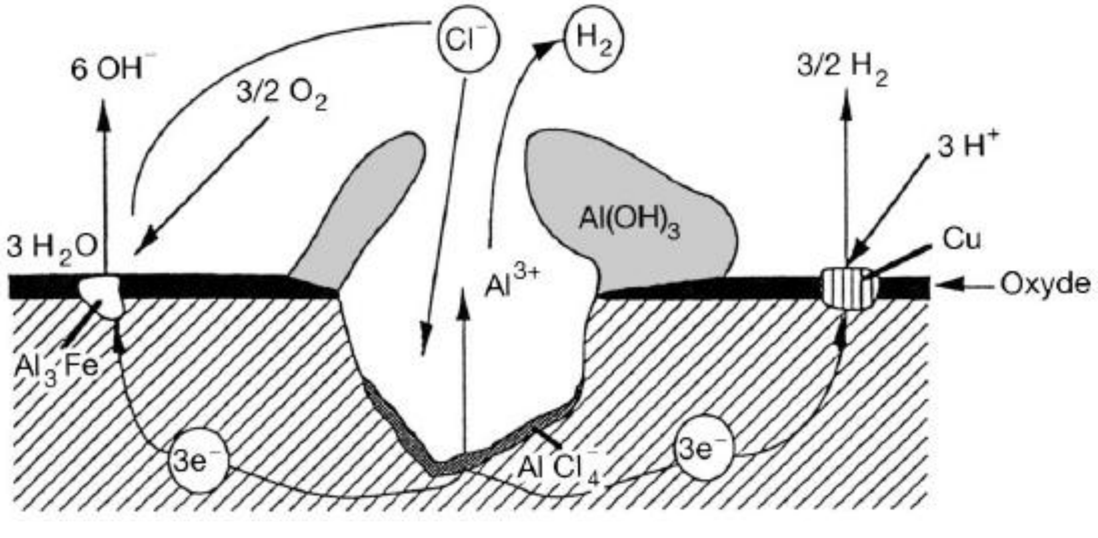


Figure 23: Pitting Corrosion mechanism in Aluminum alloys (Source: **(Vargel, 2004, p. 116)**)

46. According to (Vargel, 2004, pp. 117-118), the rate of pitting corrosion decreases with time. The pitting corrosion can be assessed using three criteria's, which are the

density (number of pits/area), rate of deepening and probability of pitting. The rate of deepening is more important than the density. As the deepening pit would determine the service life of the structure. As per (Vargel, 2004, pp. 123-127), the corrosion propagates either by intergranular means or by transgranular means. The transgranular corrosion starts from a pit. There is not relationship between intercrystalline corrosion and corrosion pit diameter. The intercrystalline corrosion can also propagate from minute and superficial pits. In case of Aloha airline flight 243, the fuselage is composed of Aluminum alloy 2024. In case of aluminum alloy 2024, the hardening phase Al_2Cu hardening phase would have a potential of 640 my. This phase would have copper atoms in vicinity, the copper depleted zone would have a potential of 750 mv which is anodic to grain boundaries. The pictorial illustration of the phase distribution is illustrated below.

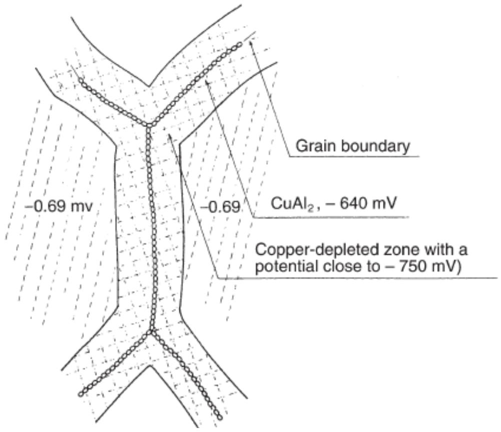
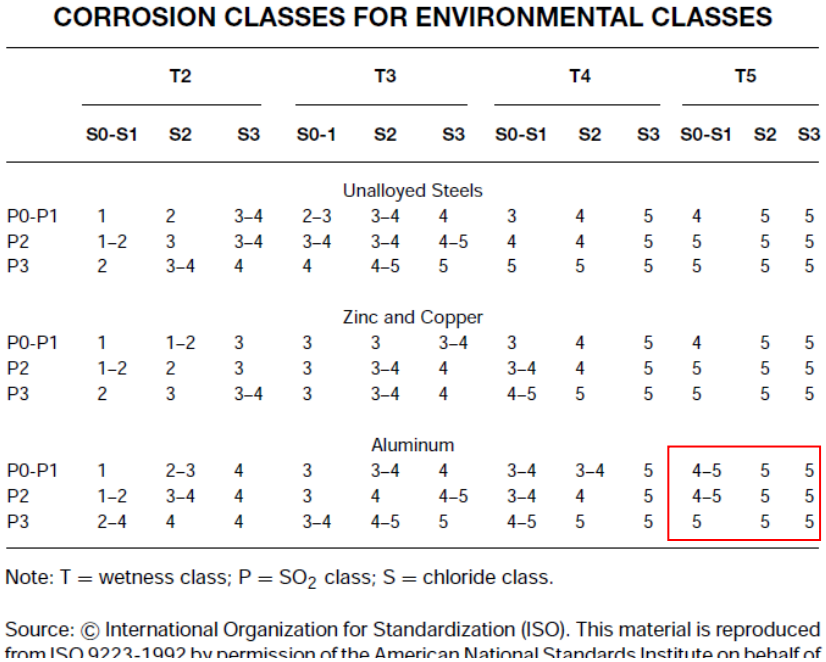


Figure 24: Precipitation of a cathodic phase on grain boundaries (Source: **(Vargel, 2004, p. 125)**

47. The arguments presented above are supplemented by (Federal Aviation Administration, 1998, p. 27), which states that the pits could acts as nucleation sites for

crack nucleation. Moreover (Federal Aviation Administration, 1998, p. 86) also reported that specimen operated in salt environment had the lowest number of failure cycles approximately 38000, far less than the anticipated metal fatigue cycles. (Federal Aviation Administration, 1998, p. 89) has also reported that case of hydrogen embrittlement is not reported in case of Aluminum alloys.

48. The lap joint issue of the Boeing 737 fuselage scrim cloth issue can also be explained from the corrosion stand point. The presence of condensation or water droplet could be cause for initiation of corrosion but it solely depends on time of wetness by the water droplets. As per (R.S.Treseder, 2002, p. 129), the classification of corrosion as per the time of wetness is important. For an indoor storage condition, a time of 10 hours/year has been stipulated for degree of wetness. For operations in tropical environment 5200 hours/year has been stipulated. The scrim cloth condensation may have cause earlier initiation of localized corrosion or uniform corrosion. It is pertinent to note that the corrosion of Aluminum as per wetness time is illustrated in the figure below.



CORROSION CLASSES FOR ENVIRONMENTAL CLASSES

	T2			T3			T4			T5		
	S0-S1	S2	S3	S0-1	S2	S3	S0-S1	S2	S3	S0-S1	S2	S3
					Unalloyed Steels							
P0-P1	1	2	3–4	2–3	3–4	4	3	4	5	4	5	5
P2	1–2	3	3–4	3–4	3–4	4–5	4	4	5	5	5	5
P3	2	3–4	4	4	4–5	5	5	5	5	5	5	5
					Zinc and Copper							
P0-P1	1	1–2	3	3	3	3–4	3	4	5	4	5	5
P2	1–2	2	3	3	3–4	4	3–4	4	5	5	5	5
P3	2	3	3–4	3	3–4	4	4–5	5	5	5	5	5
					Aluminum							
P0-P1	1	2–3	4	3	3–4	4	3–4	3–4	5	4–5	5	5
P2	1–2	3–4	4	3	4	4–5	3–4	4	5	4–5	5	5
P3	2–4	4	4	3–4	4–5	5	4–5	5	5	5	5	5

Note: T = wetness class; P = SO_2 class; S = chloride class.

Source: © International Organization for Standardization (ISO). This material is reproduced from ISO 9223-1992 by permission of the American National Standards Institute on behalf of

Figure 25: Classification of Corrosion severity with respect to Aluminum wetness time

(Source: **(R.S.Treseder, 2002, p. 131)**)

49. It is pertinent to note that even prolonged exposure to moderate or low concentration chloride would lead to maximum moderate corrosion. Aloha airline flight 243 was operating in an aggressive environment of chloride class S1 and prolonged exposure of aluminum would lead to very high corrosion. It can be concluded that probably the condensation of scrim cloth is not the sole reason for corrosion on lap joints. The prolonged operations in aggressive environment further aggravated the corrosion of lap joints and ultimately lead to corrosion fatigue. The sealant used by Boeing in production serial number after 291 was chromate polysulfide. In a moist environment the electrochemical properties with the presence of chloride ions also need a detailed study from corrosion stand point.

Aloha Airline Flight 243 failures from a Corrosion engineer stand point

50. From a corrosion engineer point of view, the failure of Aloha airline is probably resulted due to formation of pits on fuselage skin. These pits under an aggressive environment nucleated inter-crystalline fatigue cracks. Under a complex mechanism of fatigue crack propagation and stress corrosion (during operation due to tensile loads exerted by pressurized fuselage) eventually resulted in formation of MSD. The cracks joined up over a period of time and once reached critical length resulted into catastrophic failure.

Preventive measures to avoid recurrence

51. The case of Aloha airlines and its preventive measures are further bifurcated into different levels. The classification of these preventive measures is carried out from manufacturer and operators point of view.

Preventive Measure for Boeing's manufacturing

52. Boeing may like to consider sealing of the lap joints by using either a sealant or some rubber covering. The configuration used by Boeing in lap joints is susceptible to moisture accumulation and stagnation conditions which can trigger localized corrosion. During the design of these protective covers/sealing, a curvature may also be given to these surfaces to enable a better water drainage. The lap joints used on Boeing and their proposed protective covering point is illustrated below.

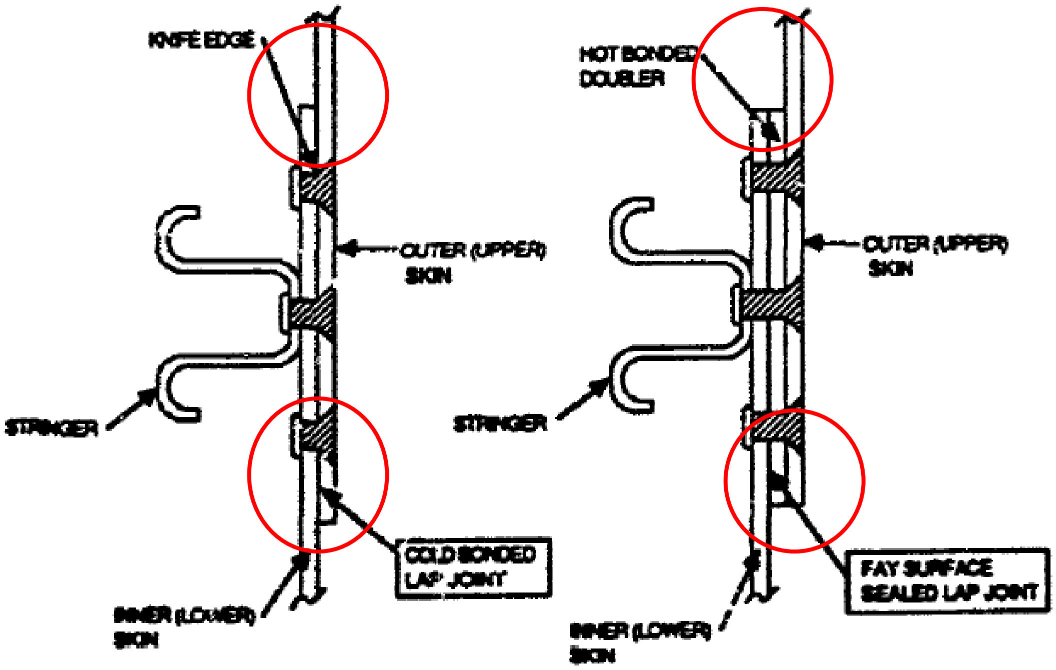


Figure 26: Boeing Lap joint design and proposed point of protection

53. Boeing may also like to study the chemical stability of chromate polysulfide in a moist/medium corrosive environment. The chemical stability of polysulfide in presence of chloride ions and other environmental species also needed to be reviewed.

54. Surface finish process for hot bonding also needed to be reviewed. An option of anodized aluminum skin may also be considered if mechanical limits permit.

55. Corrosion and corrosion fatigue tests may also be conducted for long duration in harsh chloride, So_x, NO_x environment with full scale modeling. The duration of test as per (Baboian, 2005, pp. 687-692) is vitally important for establishing susceptibility to pitting or localized corrosion. The material fatigue assessment and corrosion fatigue

assessment (in accordance with environmental operation) may be conducted separately.

Preventive Measure for Airline Operators

56. Corrosion is a specialist job and needs specialist to analyze it. Corrosion specialist may be made a permanent part of maintenance teams at MRO's and FBO's.

57. Maintenance Crew must be given education regarding aspects of corrosion in different environments. They must be cautioned and briefed properly to conduct maintenance in aggressive environment.

58. Independent checks by third agency may also be planned to verify the proficiency of crew.

59. Vigilance during maintenance may be emphasized again and again to detect corrosion.

Conclusion

60. Crash investigation is one of the toughest jobs in the globe. Extracting results from rubble and heaps of debris is always a tough ask. Most of the investigations always suggest the probable cause of failure. It is very hard to find exactly what happened. The case of Aloha airline flight 243 occupies a very high rating in the history of aviation industry. An attempt has been made to analyze the case from corrosion engineering point of view. The effort does not mean any undermining of the conducted investigation by NTSB. It may just opened horizon for a new possibility which is not much debated or considered in the investigation circles.

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