NATIONAL TRANSPORTATION SAFETY BOARD
OFFICE OF AVIATION SAFETY
WASHINGTON, D.C. 20594

October 29, 2018

POWERPLANTS GROUP CHAIRMAN'S FACTUAL REPORT

NTSB ID No.: DCA18IA092

A: INCIDENT

Location:	Honolulu, Hawaii
Date:	February 13, 2018
Time:	1200 Hawaiian standard time
Aircraft:	Boeing 777-222, N773UA, United Airlines flight 1175

B: POWERPLANTS GROUP

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Group Chairman:	Gordon J. Hookey National Transportation Safety Board Washington, D.C.
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Member: Kate Keogh
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Member: Al Mendez
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Member: Monal Merchant
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Member: Kirby Boyce
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Member: Neil Bell
International Brotherhood of Teamsters
San Francisco, California

C: SUMMARY

On February 13, 2018, about 1200 Hawaiian standard time (HST),[1] a Boeing 777-222 airplane, N773UA, operated by United Airlines as flight 1175, experienced an in-flight separation of a fan blade as well as the inlet duct and fan cowls of the No. 2 (right) engine, a Pratt & Whitney (P&W) PW4077, during cruise flight enroute to the Daniel K. Inoyue International Airport (HNL), Honolulu, Hawaii. While the airplane was in level cruise flight at flight level (FL) 360,[2] the flight crew heard a loud bang that was followed by a violent shaking of the airplane that was followed by warnings of a compressor stall.[3] The flight crew shut down the engine, declared an emergency, and proceeded to HNL for a single-engine landing without further incident, landing at about 1237 HST. The 364 passengers,[4] 2 pilots, and 8 flight attendants board deplaned normally at the gate and there were no injuries. The airplane was operating as a regularly scheduled flight in accordance with the provisions of 14 *Code of Federal Regulations* (CFR) Part 121 from the San Francisco International Airport, San Francisco, California (SFO) to HNL.

The examination of the No. 2 engine at HNL by members of the Powerplants Group revealed one fan blade was fractured transversely across the airfoil just above the blade fairings. The blade's fracture surface was flat with elliptical-shaped marks across the internal ribs and along the convex surface of the airfoil. The adjacent fan blade was fractured across the airfoil about 24-inches above the fairings. The examination of the airplane revealed a small hole along with several dents and gouges in the fuselage adjacent to the No. 2 engine. There were also several dents in the right wing and the right-hand horizontal stabilizer.

The metallurgical examination of the fractured fan blade was accomplished at P&W's Materials Laboratory in the presence of members of the Powerplants Group as well as an NTSB

[1] 1200 HST is 2200 universal coordinated time (UTC).
[2] FL 360 is 36,000 feet mean seal level based on an altimeter setting of 29.92 inches of mercury (Hg).
[3] A compressor stall that is also referred to as a compressor surge is an interruption of airflow through the engine that can be caused by damaged airfoils in the compressor or turbine, deterioration, airplane pitch or yaw movements, or throttle movements, and are typified by loud bangs and/or flames from the inlet and/or tailpipe.
[4] One of the people listed as a passenger was a United Airlines 777 first officer who was occupying a flight deck jumpseat. Refer to Section 5.1.

metallurgist. The examination revealed a fatigue fracture that had initiated from a subsurface origin on the interior surface of the hollow core fan blade. The origin of the crack was in an area where the basal planes of the crystals were all similarly aligned and were almost perpendicular the localized stress field when the fan blade was formed. The examination also revealed that the fan blade's material conformed to the specified titanium alloy's requirements.

The installed set of fan blades, including the fractured fan blade, had undergone two overhauls at which time the blades underwent a thermal acoustic imaging (TAI) inspection. At the initial TAI in 2010, there was a small indication at the location of the origin of the crack. The review of the records from the 2015 TAI show that there was a larger indication in the same area as where there was an indication in 2010 and from where the crack originated. At the time of each TAI, the inspectors attributed the indication to a defect in the paint that was used during the TAI process and allowed the blade to continue the overhaul process and be returned to service. The training that was provided to the inspectors was primarily on-the-job training (OJT). The review of the TAI process revealed several issues with the inspectors' training as well as with the inspection facility that could adversely impact the inspection. P&W has advised that it was working to correct those issues. The Federal Aviation Administration (FAA) Engine Certification Office (ECO) issued a Notice of Proposed Rulemaking that would mandate the accomplishment of initial and repetitive TAI inspections on PW4000 112-inch fan blades.

D: DETAILS OF INVESTIGATION

1.0 Engine information

1.1 Engine description

The engines on the airplane were P&W PW4077 turbofans. The PW4077 is a dual-spool, axial-flow, high bypass turbofan engine that features a 1-stage 112-inch diameter fan, 6-stage low pressure compressor (LPC), 11-stage high pressure compressor (HPC), annular combustor, 2-stage high pressure turbine (HPT) that drives the HPC, and a 7-stage low pressure turbine (LPT) that drives the fan and LPC. (Figure 1) According to the FAA's Type Certificate Data Sheet No. E46NE, the PW4077 engine has a takeoff thrust rating of 79,960 pounds and a maximum continuous thrust rating of 70,960 pounds, both of which are at standard day conditions.[5]

[5] Standard day temperature and pressure conditions are 59° Fahrenheit (15° Celsius) and 29.92 inches (1013.25 millibars) of Hg, respectively.

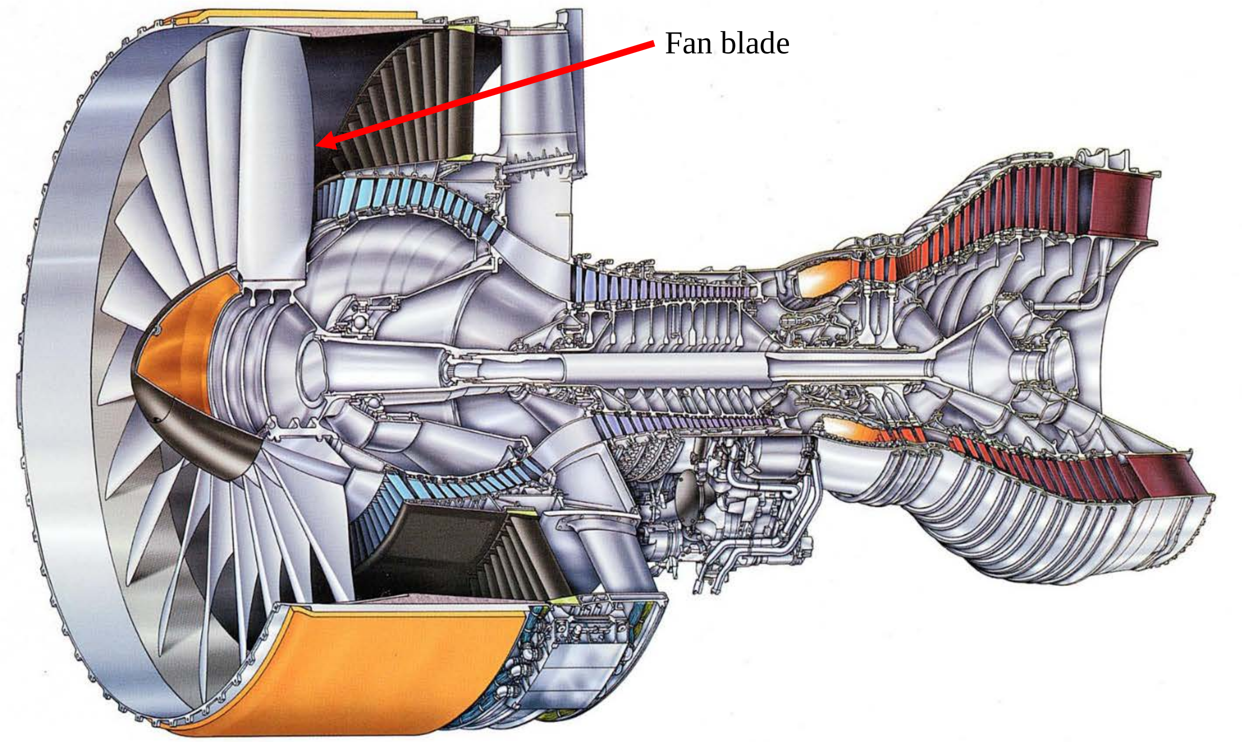

Figure 1: Cross section of a PW4077 engine. (P&W)

1.2 Engine history

According to United Airlines' maintenance records, the No. 2 engine on the airplane was serial number (SN) P777049. The records show that at the time of the incident, the No. 2 engine had accumulated 77,593 hours time since new (TSN) and 13,921 cycles since new (CSN) and 8,579 hours and 1,464 cycles since the last overhaul. The No. 2 engine was installed on the airplane at SFO on October 18, 2015, at an airplane time and cycles since new of 81,144 hours and 14,875 cycles, respectively. The engine had operated 8,579 hours and 1,464 cycles since it had been installed. The engine was manufactured on February 20, 1996.

The No. 1 (left) engine on the airplane was SN P777103. The records show that at the time of the incident, the No. 1 engine had accumulated 59,473 hours TSN and 10,814 CSN and 1,214 hours and 256 cycles since the last overhaul. The No. 1 engine was installed on the airplane at SFO on October 5, 2017, at an airplane time and cycles since new of 88,509 hours and 16,085 cycles, respectively. The engine had operated 1,214 hours and 254 cycles since it had been installed. The engine was manufactured on August 9, 2000.

2.0 Fractured fan blades

2.1 Fan blade description

The PW4000 112-inch engine fan blade is a hollow core, wide chord airfoil made of a titanium alloy. The PW4000 112-inch engine's fan blade is about 40.5-inches long from the base of the blade root to the tip of the airfoil and about 12.5- and 22.25-inches wide at the blade root and blade tip, respectively. A PW4000 112-inch fan blade can weigh a maximum of 34.85 pounds. (Photo No. 1)

Photo No. 1: View of exemplar PW4000 112-inch fan blade. (P&W)

2.2 Fan blade No. 11

2.2.1 On scene examination of fan blade

The fan blade in position No. 11[6] was fractured transversely across the airfoil about 1.44-inches above the fairing at the leading edge and slightly below the surface of the fairing at the

[6] Blade slot No. 1 was identified as the blade between two blade retaining lugs that had small circles that were dot peened onto the front face of the lug. The remaining blades were identified in accordance with gas turbine engine convention to number in a clockwise direction as viewed from the rear.

trailing edge. The fracture surface along the concave side of the airfoil had a sawtooth pattern that was about 45° to the surface of the airfoil. (Photos Nos. 2, 3, and 4) The fracture surfaces on the five internal ribs were flat and had elliptical-shaped marks. The fracture surface along the convex side was primarily smooth except at the leading and trailing edges where the fracture surfaces were at an approximate 45° angle to the surface of the airfoil. The elliptical-shaped marks did not appear to break out to the concave surface of the airfoil. The flat fracture surface did appear to break out onto the convex airfoil surface between ribs Nos. 1 and 5. The internal ribs were not separated. (Photo No. 5) There was a discolored area on the aft convex side corner of rib No. 4. There appeared to be a ratchet mark[7] within the discolored area. (Photo No. 6) The blade's dove tail root was intact. The contact surfaces of the blade root had some visible wear. There was also wear on either side of the airfoil that corresponded to the edges of the spacers that were between the blades. The base of the blade root was marked with ASSY 55A901 that had been crossed out and reidentified as 55A801. The blade root was also marked with the blade's serial number, CBDUAT7364, that corresponded to the serial number for blade No. 11 in the engine's maintenance records.

Photo No. 2: View of front of engine showing the two fractured fan blades, Nos. 10 and 11.

[7] Ratchet marks are the step-like junctions between adjacent fatigue cracks that propagate and link up.

Photo No. 3: View of No. 11 fan blade showing fracture surface.

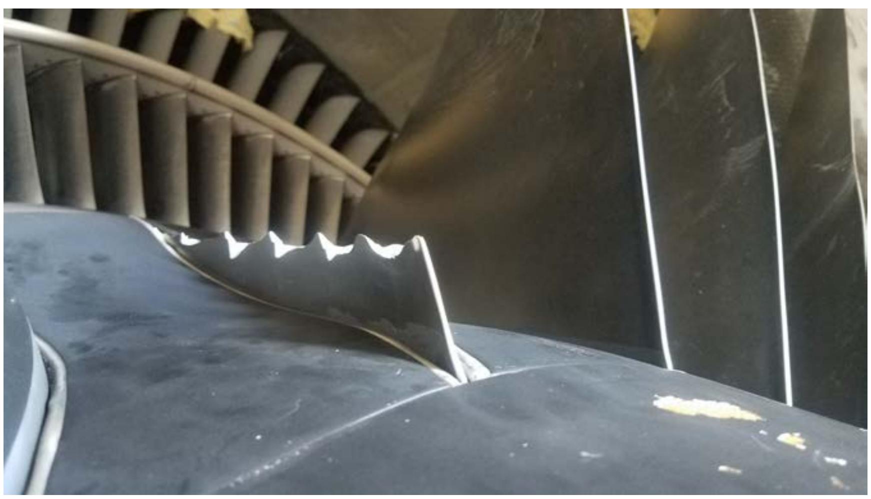

Photo No. 4: View of No. 11 fan blade showing sawtooth fracture pattern and the fracture surface being at about a 45° angle to the airfoil. (Boeing)

Photo No. 5: View of fracture surface showing elliptical marks and the internal ribs not being split. (Boeing)

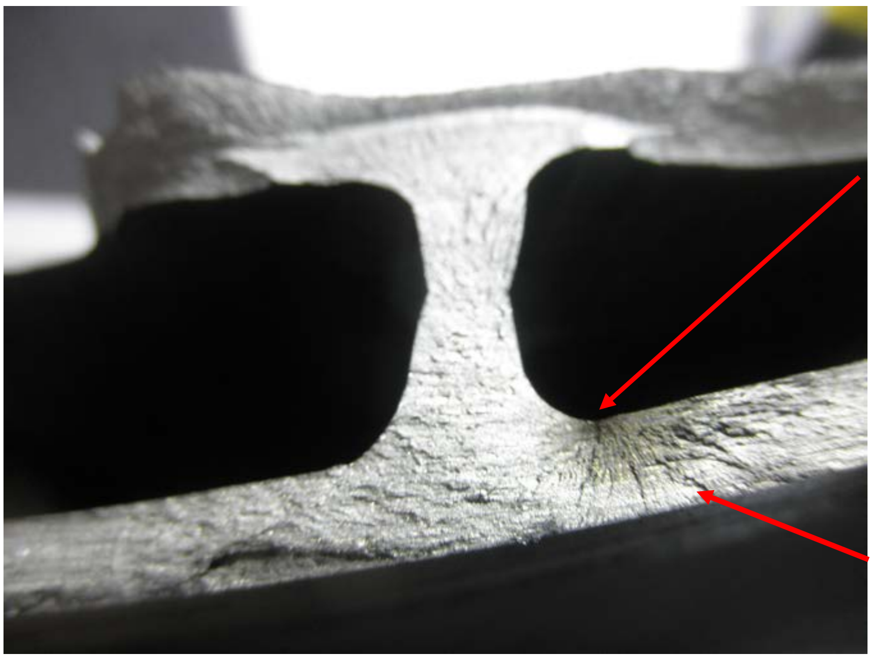

Photo No. 6: Close up view of fracture surface showing discolored area and ratchet mark radiating from an interior surface of the fan blade.

There was a piece of fan blade found up against the leading edges of the fan exit guide vanes at about 4 o'clock.[8] (Photo No. 7) This piece of fan blade was about 15-inches wide chord wise and 23-inches long radial that had a fracture surface on the inner end that corresponded to the fracture surface on blade No. 11. (Photo No. 8) There was a 2-inch wide radial by 1.5-inch deep chordwise gouge in the leading edge that was about a 50° angle to the axis of the engine. (Photo No. 9) At the outer end of the blade, the leading edge was curled in the direction of rotation and the trailing edge was bent opposite the direction of rotation. The

[8] All references to position or directions, as referenced to the clock, will be as viewed from the rear, looking forward, unless otherwise specified.

internal ribs at the inner end were all split. At the outer end of the blade piece, there was a chordwise rib internal to the blade that was also split.

Photo No. 7: View between fan blades showing fragment of fan blade No. 11 against fan exit guide vanes. (P&W)

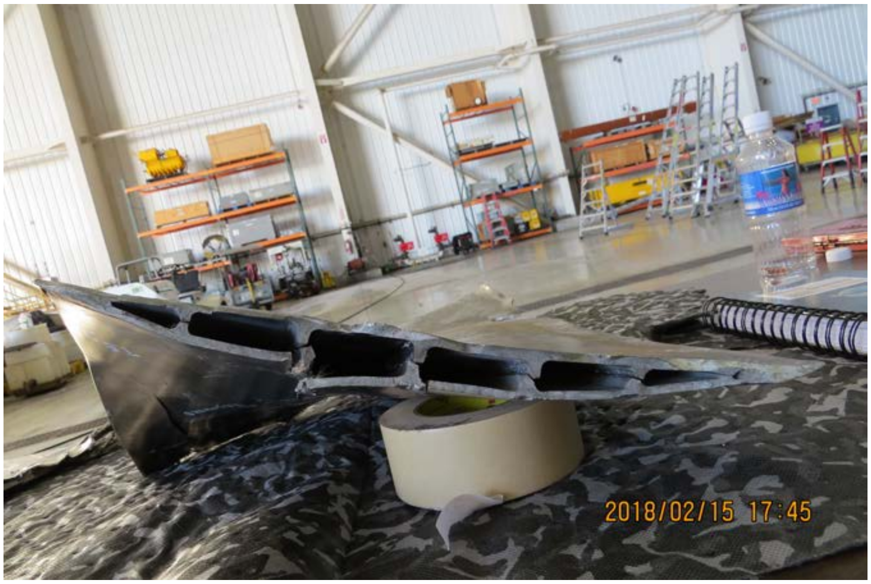

Photo No. 8: View of fracture surface on fragment from fan blade No. 11 showing how it corresponded to fracture surface on inboard end of blade. (P&W)

Photo No. 9: Fragment of fan blade No. 11 recovered from fan exit guide vanes. (P&W)

2.2.2 Metallurgical examination

Both of the fractured fan blades, Nos. 10[9] and 11, were removed from the No. 2 engine at HNL and shipped directly to P&W Materials Laboratory, East Hartford, Connecticut for metallurgical examination in the presence of an NTSB metallurgist as well as members of the Powerplants Group.

The metallurgical examination revealed that fan blade No. 11 had the airfoil separate transversely from the root section about 4.5-inches from the root bottom at the leading edge and about 8-inches from the root bottom at the trailing edge. The examination revealed a low cycle fatigue (LCF) fracture that had originated about 6.7-inches outboard from the blade root bottom on the interior wall of cavity FA adjacent to the airfoil's convex wall and the internal rib separating cavities EA and FA.[10] The origin of the fatigue was subsurface, about one or two

[9] For the details on fan blade No. 10, refer to section 2.3.
[10] The PW4000 112-inch fan blade has a hollow core, but the interior of the blade is made up of a labyrinth of horizontal and vertical ribs that form cavities. Each cavity is identified alphabetically with two letters. The first letter is the location from the leading edge to the trailing edge and the second letter is from the inner most cavity outboard towards the blade tip. Cavities EA and FA would be the fifth and sixth cavities back from the leading edge in the first row above the blade root.

grains deep within an area that had been smeared by secondary rub damage. Near the origin, the surface finish of the internal cavity exceeded the specification by 4μ-inches. The examination revealed that all of the other geometric features that were reviewed were within the specified limits. The examination also revealed that the fan blade's material conformed to the requirements for the specified titanium alloy. The recovered pieces of fan blade No. 11, the root section and a piece of the airfoil, weighed 24.6 pounds in comparison to 33.6 pounds for an exemplar fan blade.

The examination of the area of the fatigue origin with a field emission scanning electron microscope revealed several micro-textured regions of faceted growth where there were multiple contiguous grains with a similar orientation of the basal plane that were within 30° of perpendicular to the local stress field. The depth of the faceted growth was about 0.032-inches. Between 0.032 and 0.155-inches, there were approximately 5,500 striations of stable LCF growth. The fatigue progressed forward, aft, through the airfoil's convex wall, and across the span wise rib between cavities EA and FA. Beyond the stable LCF zone was an area of unstable fatigue progression. However, in the area of unstable fatigue growth, there was no evidence of any high cycle fatigue. The examination of the interior of the FA cavity where the fatigue crack originated did not reveal any indications of alpha case[11] or sparks or hot metal impingement.[12] The examination also showed that the bonded joint between the convex and concave sides of the airfoil did not have any indications of any voids, contamination, or lack of bonding.

The entire fan blade set, including blade No. 11, underwent an overhaul that included a TAI inspection in July 2015, 1,464 cycles prior to the event.[13] Back counting the striation count revealed the approximate size of the crack would have been about 0.094-inches deep.

For further details, refer to P&W Materials & Process Engineering Metallurgical Investigation Final Report Metallurgical Investigation of Fan Blades No. 11 and No. 10 from PW4077 Engine 777049, dated October 9, 2018. (Attachment 1)

2.2.3 Previous TAI

Fan blade No. 11 had undergone two TAI inspections in July 2015 and March 2010.

The review of the TAI from July 2015 revealed an indication in the area where the metallurgical examination identified the LCF fracture. Based upon a review of the image from the 2015 TAI, P&W process engineers estimated the size of the crack at that time was about 0.09-inches. The log sheet for the July 2015 TAI shows that there were several zones that had indications. For the zone where the crack occurred, the record of the inspection was annotated 'paint.' During the interview of the inspector who had conducted the 2015 TAI, while he

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[11] Alpha case is an oxygen-enriched surface condition in titanium and titanium alloys that were exposed to air or oxygen when heated. Alpha case is hard and brittle and tends to create microcracks that can progress to larger cracks.

[12] Sparks or hot metal impingement were caused by a production machining operation that had been identified as the cause of a previous PW4000 112-inch fan blade tip separation.

[13] For the overhaul of the fan blades that were completed in August 2015, the TAI was accomplished in July 2015.

attributed the indication to a discrepancy with the paint, he could not recall the specific issue that led to the annotation.

The review of the March 2010 TAI revealed that there was a TAI indication, albeit much smaller, at the same location as the indication in the 2015 TAI. The log sheet for the March 2010 TAI shows that there were several zones that had indications. For the zone where the crack occurred, the record of the inspection was also annotated ‘paint.’

2.2.4 Manufacturing history

The PW4000 112-inch fan blade has a hollow core airfoil. The blade is made from two titanium-alloy flat plates that have the airfoil’s external and internal features machined out. The airfoil halves then undergo dimensional and material inspections prior to being bonded together. The bonded halves undergo further machining and another material inspection prior to being formed into the fan blade’s final shape. After the blade is formed into the final shape, the blade’s root is machined as are the leading and trailing edges and the blade tip. The blade then undergoes a visual and another material inspection before undergoing several surface finish treatments. The blade then undergoes a dimensional inspection and a final inspection.

The No. 11 fan blade, SN CBDUAT7364, was manufactured in June 1994. The fan blade’s production record shows that there were four profile tolerances that were noted to be nonconforming during inspection. These nonconformances were: a ±0.003-inch profile that was out of tolerance by +0.0018 inch, a ±0.002-inch profile that was out of tolerance by -0.009 inch, a ±0.0025-inch profile that was out of tolerance by -0.0008 inch, and a ±0.0015-inch profile that was out of tolerance by -0.0012 inch. The manufacturing records show that all of the nonconformances were accepted without rework.

2.2.5 Fan blade maintenance history

According to United Airlines maintenance records, the No. 2 engine’s fan blades had stayed together as a complete set since their entry into service on November 7, 1995. According to United’s maintenance records, the fan blades had been installed in four other engines prior to being installed in the incident engine at the time of the engine’s last overhaul. The records show that the fan blades had accumulated 76,704 hours and 14,129 cycles since new.[14] There was no history of any damage such a bird strike or foreign object damage to any of the fan blades.

The fan blades were last overhauled by P&W on August 14, 2015.

United Airlines’ maintenance program for the fan blades is governed by United’s FAA-approved Engine Maintenance Program that is based on P&W’s PW4000 112-inch Maintenance Planning Document. The fan blades were maintained based on the PW4077 being operated at the full takeoff rated thrust condition.

[14] The PW4000 112-inch fan blade is not a life-limited part.

The records show the following work was accomplished to the fan blades:

(1) Wet lubrication (vibration/galling) that is to be done every 608 days. This was last accomplished at Hong Kong on March 30, 2017.

(2) Inspection of fan blades every 600 flight hours. This was last accomplished at HNL on January 19, 2018.

(3) On condition inspection for leading and trailing edge damage when the fan blades have accumulated more than 2,000 cycles and the engine is in the shop. This was last accomplished on August 14, 2015, at P&W.

(4) The fan blades are removed and sent to P&W for overhaul (heavy maintenance) when they have accumulated more than 5,000 cycles and the engine is in the shop. This was last accomplished on August 14, 2015, at P&W.

2.2.6 PW4000 112-inch fan blade overhaul process

The overhaul of a PW4000 112-inch hollow core fan blade consists of an incoming inspection to verify the PNs and SNs against the accompanying paperwork. Parts of the fan blade are masked. A coating is removed from the blade root. The fan blade is then cleaned. The fan blade undergoes a fluorescent penetrant inspection (FPI)[15] that is followed by a visual inspection. The fan blade's airfoil is painted in preparation for the TAI. The blade then undergoes the TAI. (For further information on the TAI, refer to Section 3.1) Following the TAI, the paint is removed from the airfoil. The leading edge of the fan blade is restored and the fan blade then undergoes several inspections. The fan blade then receives several surface finish treatments. The fan blades are then moment-weighed[16] and undergo a final inspection.

2.3 Fan blade No. 10

2.3.1 Condition

The fan blade in position No. 10 was fractured transversely across the airfoil about 24-inches above the spacers. (Photo No. 10) The fan blade's leading edge had some minor dents on

[15] FPI is a nondestructive inspection method of detecting cracks and other surface anomalies. The inspection consists of applying or immersing the part in a low-viscosity penetrating fluid containing fluorescent dyes to a component and allowing the fluid to penetrate into any surface defects. Excess penetrant is removed, and a "developer" is applied that acts as a blotter to draw the penetrant out from any surface defects that will luminesce when viewed under an ultraviolet light.

[16] For rotor balance purposes, turbine engine fan, compressor, and turbine blades may be pan or moment- weighed. An airfoil's moment-weight is the mass (weight) of the airfoil times the distance from the engine's centerline to the center-of-gravity of the airfoil.

the leading edge. The concave side of the airfoil had a cross hatch mark on the surface indicative of the fan blade's internal structure and there were two large dents with airfoil surface split adjacent to the dent. The fracture surfaces on the end of the blade were coarse and grainy and they were at an approximate 45° angle to the surface of the blade.

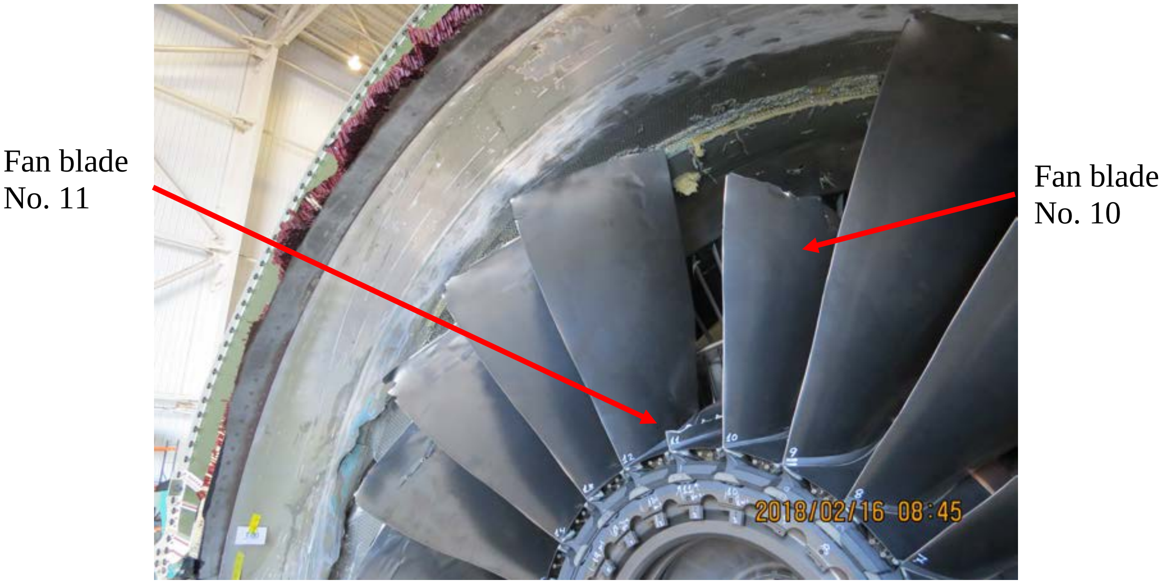

Photo No. 10: View of fractured fan blades Nos. 10 and 11. (P&W)

The base of the blade was marked with ASSY 55A901 that had been crossed out and reidentified as 55A801. The blade root was also marked with the blade's serial number, CBDUAT7363.

There was an approximately 10-inch by 12-inch piece of fan blade airfoil that was found against the fan exit guide vanes that had some partial markings that corresponded to fan blade No. 10. The piece was heavily battered. All of the fracture surfaces were at an approximate 45° angle to the surface of the airfoil.

2.3.2 Metallurgy

The examination of fan blade No. 10, which was the trailing fan blade to the blade No. 11 that separated, revealed that it had a transverse fracture through the airfoil about 23 to 27-inches above the blade root bottom. The examination of the fracture surface showed that the fracture was due to shear/tensile overstress. The examination of cavity FA, the cavity in fan blade No. 11 where the crack originated, revealed no evidence of a material discrepancy, fatigue progression, or alpha case. There were two identifiable pieces of fan blade No. 10 recovered that weighed a total of 28.7 pounds. An exemplar fan blade weighed 33.6 pounds.

For further details, refer to P&W Materials & Process Engineering Metallurgical Investigation Final Report Metallurgical Investigation of Fan Blades No. 11 and No. 10 from PW4077 Engine 777049, dated October 9, 2018. (Attachment 1)

2.3.3 Maintenance history

The fractured fan blade, as well as all of the other fan blades in the set, underwent two overhauls at P&W. The P&W facility is a 14 CFR Part 145 repair station, Air Agency Certificate No. WA2R259L, with Limited Powerplant and Limited Airframe Ratings.[17] The shop has ratings for various engines[18] including the PW4000 series for the maintenance and alteration of non-rotating and rotating parts, assemblies, and modules in accordance with current air operator/air carrier or manufacturer's approved data or data approved or acceptable to the [FAA] Administrator.

The first overhaul was in March 2010 when the fan blades had 49,878 hours TSN and 9,157 CSN. The second overhaul was in August 2015 when the fan blades had accumulated 68,125 hours TSN and 12,665 CSN. The FAA Form 8130-3, Airworthiness Approval Tag, for returning the fan blades to service after the 2010 and 2015 overhauls of the fan blades are attached, Attachments 2 and 3. The 8130 for the August 2015 overhaul only lists 20 fan blades, however, a rotor balance build sheet included all 22 fan blades.

The records of the fan blades' 2010 and 2015 overhauls show that the visual inspections did not identify any discrepancies.

2.4 Other PW4000 112-inch fan blade fractures and cracks

According to P&W, there were two previous PW4000 112-inch fan blade fractures. In October 2008, a fan blade fractured following a bird strike. P&W reported that about 30 percent of the blade tip was released. In April 2010, a fan blade fractured in the mid span area due to some chemical milling contamination that left a brittle oxide from where a crack initiated.

P&W also reported that between December 2004 and the time of the United event at HNL, there have been five PW4000 112-inch fan blades found to be cracked. There was one crack that was reported to have been detected visually and the remaining four cracks were found during the TAI inspection.

[17] A limited rating for powerplants and airframes issued to a repair station is for the performance of maintenance on particular makes and models of powerplants and airframes. The limited airframe rating is for the inspection of the Sikorsky S-76 helicopter's upper gearbox housing.
[18] The other engine ratings are for the P&W JT9D, JT8D-200, PW1000G geared turbofan, PW2000, and PW6000; International Aero Engine V2500; and Engine Alliance GP7000.

3.0 Thermal acoustic imaging inspection

3.1 Description

A thermal acoustic imaging (TAI) inspection process is used to detect internal and external cracking in hollow core fan blades. The TAI process used to inspect the PW4000 112-inch fan blade is proprietary to P&W. Sound energy is utilized to generate an excitation of the fan blade's internal and external structure. The sound energy excitation will cause relative movement between each side of a contacting discontinuity that will cause frictional heating. The frictional heat generated by the movement of each side of the discontinuity is detected on the surface of the fan blade by a thermal sensor. The convex and concave surfaces of the airfoil are divided into zones. The computer controlled thermal sensor takes an image of each zone. After both sides of the fan blade have been completely scanned, the images are processed by a computer that are then displayed on a monitor for the inspector to evaluate. The computer has the capability to enhance the image to assist the inspector in evaluating any indications. Certain types of indications may require the inspector to reinspect the area, which may require repainting of the fan blade and repeating the TAI process. If a fan blade has an indication that the inspector is not able to clearly evaluate, the inspector is to forward the images along with the fan blade to a Process Engineer for further evaluation and possibly further non-destructive testing such as ultrasonic and/or x-ray inspection.

The instructions to accomplish the TAI are contained in Non-Destructive Inspection Procedure (NDIP) 1065. NDIP-1065 was originally issued on September 27, 2005. The NDIP was revised in June 2017. Revision A modified the NDIP format, provided notes about hearing, calibration, system environment, test blade check period, and added a set up requirement. Revision A also provided new acceptance criteria for indications noted at the blade tip. The NDIP was revised again with Revision B that was issued in March 2018. Revision B added detailed examples of acceptable and rejectable indications as well as a flowchart of the evaluation process.[19] Revision C that was issued in April 2018 incorporated evaluation section updates and updated the flowcharts. Revision D that was issued in June 2018 incorporated feedback from a review of the process. The NDIP Revisions B, C, and D were all issued after the United Airlines incident in HNL.

3.2 Inspectors

P&W had three TAI inspectors.[20] The inspector on 2nd shift was the one that inspected the United Airlines incident fan blade. There is also an inspector on 1st shift plus another 1st shift inspector who is assigned to another part of the shop, but is available as a backup.

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[19] The revision pages on Revision B and C state the reason for Revision B was to add examples of acceptable/rejectable indications as well as a flowchart of the evaluation process. But the revision page on Revision D states that Revision B was a complete revision.

[20] P&W has reported that they have trained and qualified additional TAI inspectors since the United fan blade separation incident occurred.

3.2.1 2nd shift TAI inspector

The 2nd shift TAI inspector was the one who had accomplished the last TAI on the incident fan blade in 2015. He was interviewed by members of the Powerplants Group on March 21, 2018.

The 2nd shift inspector has been a P&W employee for about 34 1/2 years. His current job description is a lead NDT [non-destructive test] inspector. He holds an FAA repairman's certificate. He has always worked in NDT. He started with P&W's manufacturing operations in NDT. He worked on FPI, magnetic particle inspection (MPI),[21] etch, x-ray, and ultrasonic inspection (UTI)[22] at P&W's Southington, Connecticut facility. He transferred to P&W's West Palm Beach, Florida facility to work on x-ray inspections. He was still certified in NDI [non-destructive inspection] and he got to work on the RL-10 rocket engine and the space shuttle main engine. He returned to Southington in about 1992 to work on automated eddy current inspection (ECI)[23] primarily on military programs. He transferred to P&W's Middletown, Connecticut facility doing the same work when Southington was closed. He transferred to P&W's East Hartford, Connecticut facility in 1998 to work on the hollow core fan blade manufacturing in C-building. In 2008, he transferred from C-building to M-building and CTRP [Connecticut rotating parts]. After CTRP, he transferred to CTSC [Connecticut small components]. All of the transfers were at his request except the transfer from CTRP to CTSC that was at the company's request. He asked for the transfers to advance his career and to expand his experience. He had wanted to get into the QR [quality review] crib. Prior to working for P&W, he had NDT experience at a drop forging company and with the Arizona Department of Transportation.

He is certified in the following inspection disciplines: FPI, TAI, UTI, and ECI, at the reader level. His FPI certification was a Level 2, but he thought with the changes in the classification system that he thought he may be a Level 1S. At one time, he had Level 3 certifications in etch and FPI. He had taken a test and had a lifetime certification. He usually does two or three different inspections per shift. He may start doing a TAI and then go do another inspection. He works on the 2nd shift by himself. He is the only NDT inspector on the 2nd shift. He used to think it was an honor to do all of that work, but he sometimes thinks it is a burden. Of the 34 years that he has worked at P&W, 27 of those years were working on 2nd shift. He had shifted to 1st shift three times that were all at the company's request. The requests

[21] Magnetic particle inspection, MPI, is a non-destructive inspection method of detecting cracks and other defects in ferromagnetic materials such as iron or steel. The inspection consists of magnetizing the part with high amperage direct current electricity thus creating magnetic lines of flux, then applying or immersing the part in a liquid containing ferromagnetic particles in suspension. The ferromagnetic particles align themselves with the magnetic lines of flux on the surface of the part forming a pattern. If a discontinuity is present in the material on or near the surface, opposing magnetic poles form on either side of the discontinuity and the pattern is disrupted, forming an "indication." The indication assumes the approximate size and shape of the surface projection of the discontinuity; however, indications are more visible when the defects are approximately perpendicular to the magnetic lines of flux.

[22] Ultrasonic inspection is a nondestructive testing method in which high-frequency sound waves are projected into a solid object to detect and locate subsurface flaws.

[23] Eddy current inspection, ECI, is a nondestructive testing technique using electromagnetic induction to detect surface and subsurface defects in conductive materials. A magnetic field is induced into a conductive material. Any defect in the material will change the magnetic field that will be identified by measuring the change of impedance in the detection coil.

were made because at those times, they did not have the work flow that required an NDT inspector on 2nd shift and it was shut down. He could not remember if 2015 was when one of those shift changes had occurred.

To do the TAI, the only training the inspector received on the PW4000 blades was OJT. The company still does not have any formal training for the PW4000 fan blades. There was a one-time Level 1 formal training class for the TAI that was focused on the GTF [geared turbofan] engine.[24] He was not able to attend because he was needed to inspect PW4000 fan blades. Most of the NDT training is provided by Hellier that is an NDT test company in New London, Connecticut. Hellier's main office is in New London and that is geared towards nuclear.[25] There is one in Texas that is geared to the oil refineries. And there is one in California that is geared towards aerospace. Hellier does not offer training on the TAI that is used on the PW4000 112-inch fan blades. There was no one from P&W's NDE [non-destructive engineering] group that provided training. He received OJT from another inspector. Most of the TAI training was 'institutional knowledge.' There was a set number of hours that he thought was about 100 hours, or 100 parts, that he would inspect, and the other inspector would overinspect. He was given a written exam that he thought was mostly on general knowledge or theory. He was then given a practical exam that consisted of running a part and telling them what he saw. There is a recurring retest requirement that varies depending upon the level of his certification. Level 2 is every 2 or 3 years and Level 1S is every 5 years. The last time he was recertified was about 2 years ago. He receives an annual test that he last received was in February 2018.

The TAI training that he received never provided any reference material on what to look at. He was provided with some photos, but he said that they were very distorted. He did receive a study guide when he started the OJT that was about the steps to power up the machine and included what he said were fuzzy images of what the indications were supposed to look like. When showed a picture of an image, he now knew to rescan the part. The indication could be a piece of foreign material, a chip, a steel shot peening bead, a paint issue. The paint they originally used back in 2010 was good, but it would flake off when the humidity was high. They changed paint vendors and the paint was better, but they couldn't do anything with it. The paint was very fragile and could be removed easily. They would then have to send it out to be repainted. If he saw an indication, he would get his drop light and do a visual inspection to see if there was anything in the paint such a piece of grit that got into the paint or if the paint gun had spit out a droplet.

He thought he could do about six to eight parts a shift. Sometimes he operates both machines and he could do 12 to 14 blades per shift. He had never seen a blade where every image was a pass. Back in the 2015 timeframe, most of the images were marked as fails. Now, they are getting that down to about 10 to 12 fails on a fan blade. When he gets a fail on an image, he will look at the fan blade and then run his hand over the surface to feel for a piece of

[24] The PW1000G series engine, the geared turbofan, has fan blades that are TAI inspected as part of the manufacturing process. The GP7200 engine used on the A380 also has hollow core fan blades, but those engines have not yet accumulated enough time to require the fan blades undergo a TAI inspection.

[25] New London, Connecticut is homeport to several U.S. Navy submarines and nearby Groton, Connecticut is the location of General Dynamics Electric Boat Division that builds submarines.

grit. There is a color palette that they can use for the GTF fan blades to enhance the image, but they are not to use it for the PW4000 fan blades. He has a procedure that he follows when an image comes up that is marked failed. He will click on the failed image icon and the image will come up on the screen. Then if he clicks on the extreme image icon, it will show the image from the start to finish of the time period. The camera takes a video of the sector when the machine is vibrating the part. When the color in frame 68 turns red, that is the optimum time to read the image. When they first started doing GTF fan blades, they were shown how to use the color palette although they never received any formal training. They were not trained to use the color palette on the PW4000 fan blades. On the PW4000 fan blades, they are looking for service defects whereas on the GTF fan blades, they are looking for manufacturing issues.

The supervisor assigns the work. If the supervisor does not assign any work, as a lead person, he can look around to identify what needs to be done first. They get a lot of overtime because of the workload. Back in the 2015 timeframe, he thought that they had a 22 fan blade set backlog. He gets about 1 to 1 1/2 hours of overtime per day and then up to 6 hours on Saturdays. When the workload increases, the overtime could go up to 4 hours per day and then a double shift, or 12 hours, on Saturdays. The overtime is voluntary. He did not work the longer overtime hours.

He did not think the NDIP was very good. He thought the NDIP Revision A was not as good as the original that he didn't think was very good. He was not asked to provide any input for the NDIP. The person that wrote the NDIP did not have any NDT certification. He thought the NDIP had a lot of gaps and that the procedure was written for the lab rather than the shop. When he was in manufacturing, they worked to process sheets that he thought would be better. He said that they do not work to process sheets. All of the work instructions are on the computer. His machine only has one computer. If someone was using the other machine, he could not have the work instructions open. He would like to have written documents available to be used. There were no reference photos. There was no guidance on the disposition of the indications. When he inspected the blade in 2015, they did not have any instructions, on the computer or written, on how to disposition any indications. He thought that there were other blades that had indications that he thought might have been paint or debris on the inside. He said that the 2015 indication did not act like a crack. He generally does not get any feedback on blades that he had rejected on whether it was cracked or not. There are fan blades that he had done several times, but he never received any feedback from engineering on whether the indication was good or bad.

The blades are painted prior to him getting them for the TAI inspection. The paint comes off the fan blade easily. They were permitted to touch up the paint. But when trying to touch up the paint, the paint would come off and they would end up having to repaint the whole blade. He only does the inspections, he did not do the painting. The four painters in the fan blade cell do not do any inspections.

When he was shown an image from the NDIP and asked about images that appeared on both sides of the fan blade, he stated that the instructions said to measure the indication. But he further stated that they had no way to measure the size of the indication. As long as the indication was on both sides of the fan blade, the indication would be considered to be acceptable. If the indication was only on one side of the fan blade, it needed further evaluation. He would look at it and then rescan it. If the indication repeated, he would have the fan blade repainted and then rescan it again. If the indication still repeated, he would send it to Manufacturing Process Engineering (MPE) for evaluation. In the previous two weeks, he had sent about 18 to 20 blades for repaint and then 10 to 12 of those blades were sent to MPE for further evaluation. He said that there was one machine that they would get indications on one particular zone that he thought was a reflection from the machine.

The inspector stated that he thought the room where the TAI is accomplished could have been set up better. He said that late in the afternoon when the sun sets, the sun shines directly on the blade. He had asked to get a shade to block the sun that he thought caused false indications. He thought it was too bright in the room. He said that they have recently added LED lights in the shop that are even brighter and makes it more difficult to see the screen. The room has two temperature gages that do not read the same. The room does not have a humidity gage. The room is air conditioned. But in the summer time, they must run a secondary air conditioner to keep the room cool. He said that in the summer time, people come into the room to cool off and that is a distraction plus the heat from their bodies alters the image. He had asked that a light be added at the door to show people when the machine was on.

He could not recall ever seeing an FAA inspector in the shop.

There was not a lot of turn over in the shop. The other TAI inspector had been there longer. He thought it was a good working environment. They work together to get the job done, but they do not socialize on the outside.

When he rejects a blade, the blade goes to MPE. If they accept the blade, it is returned to the shop for processing. But it reenters the system after the TAI step. If it was rejected, he didn’t get any feedback if the indication was a good or bad indication. He has asked the other TAI inspector for a second opinion on an indication. He has never been forced to accept a blade that he thought should be rejected. He said that people have frowned when a blade was rejected, but he was never forced to accept a part. Managers have asked about a blade to get it done. He had felt pressure to get the blades out quicker because they needed to push another set of blades through the system. At the end of the month, the managers want to get their numbers up.

He could not recall of anything in 2015 that could be a life distraction.

On the incident fan blade, he could not recall marking the sheet that it was a paint issue. He had marked off the indications as edges, background, and noise. He thought the noise could be paint. Since they didn’t have any guidance, he would list what he thought the indications were. He felt like he needed to identify what he saw. There are areas on the fan blade where the paint was causing the surface noise. He had been taught that when he gave his evaluations that they had to be attributed to something and he wrote it up as noise due to loose paint. With the indications, white is considered hot and black is cold. When they stepped through the frames, the indication got hotter. He had been taught that true cracks would get hot and then would go cold.

When he inspected a blade and there was an area that had to be repainted, he would give the painters a general location and write reject on it so the painters would repaint that area. He would then get the blade back. He said the inspectors want to run the rejected fan blades on the same machine on which the blades were rejected. The NDIP gives him the option to do the repaint, but as soon as he would touch up the paint, it would lift up. He sends the fan blades back to the painters because they do a better job. There was talk that they would get air brushes to do the touch up painting.

3.2.2 1st shift TAI inspector

The 1st shift TAI inspector was interviewed by members of the Powerplants Group on March 21, 2018.

The 1st shift TAI inspector is an NDT lead man. He holds an FAA repairman's certificate. At the time of the interview, he was certified as a Level 2 inspector in TAI, NDI, and ECI. He was a Level 2 in UTI, but he no longer has that certification. He has been at P&W since 1979. He started working at P&W at Middletown in 1979 and then after about 6 weeks, he transferred to East Hartford where he worked until 1983 at which time he was laid off. He worked at gage standards at Middletown and East Hartford. When he was recalled in 1985, he worked at Southington for about two years and he has worked at East Hartford ever since. He got into NDT as soon as he returned to work. At the time of the interview, he did the TAI, ECI, and local FPI.

He started doing the TAI in 2005. He was trained by people from the NDE lab. The training was OJT that included a certain number of hours running the machine. The machine that they are currently using had been located in manufacturing in C-building. The training to evaluate the indications was also OJT. The blades were engine run blades. In about 2007 or 2008, the inspection was moved from the manufacturing unit to the overhaul unit. He has not received any recurrent training. The company brought in an outside contractor to teach TAI that he attended. It was a 40-hour class, but it was not aviation specific. He received a certificate that he attended the training course. The training material was background and the scientific part of TAI. There was an earlier TAI class that he had not been able to attend because of other work that needed to be done.

When he reviews the images, the software displays the indications on the screen. The screen displays the hot spots as white and the cool spots are a darker image. The indications may be machining chips or peening shot left inside of an internal cavity. He would reject a blade with an indication. If he rejected a blade, they would probably do an x-ray to further evaluate the blade. He cannot decipher if an indication is either a metal chip or peening shot. He just rejects it. If he gets an indication, he has it repainted and may rerun it a second or a third time. There is no limit on how many times that a blade can be rerun. He does not like to touch up the paint because it gets messy. Having an airbrush to do the touch ups would help. If an indication is due to a metal chip or peening shot, the indication would not go away. If he had a repeat indication, he would look to others in the cell for advice. The supervisors that that have had the last couple of years have been new hires on a training rotation. The NDE lab has the only people that have any experience with the TAI. There is an engineer at the NDE lab that knows the inspection, but she is not certified as an inspector. The NDE lab can write an engineering authorization to clear the reject and release the blade back to the shop for further processing. In the last 10 years, he has seen two cracked fan blades. He does get some feedback from the lab who have told him if a blade was cracked. On the TAI inspections that he does, he has the final say and signs it off with his stamp. Then the blade goes on to the next operation.

There are a lot of false reject indications. The number vary from blade to blade. He did not think that it had gotten any better or worse over time.

The 1st shift inspector did work 2nd shift for a while when he worked at Southington. But since he has been doing the TAI, he has always worked on the 1st shift. When he comes into work, no one assigns his work. The blades are on racks lined up outside of the TAI inspection room. Sometimes, they are doing two different sets of blades that are identified by the color of the paper. The supervisor will come down to tell him which of the two is the higher priority that has to be done first. He thought that he could do about five or six blades a day. Sometimes, he might be able to do more, sometimes he might do less depending upon if there is other work that has to be done. Sometimes, he may use both machines if there is a lot of work. He works about an hour of overtime every day, Monday to Friday. He does not work any overtime on the weekend. The overtime that he works is his option, there is no mandatory overtime. He thought the biggest challenge with the TAI was getting a blade that didn't have all of the false positives because the have to spend more time on it. A lot of the false positives are edge indications.

There is not a lot of turnover in the personnel in the shop. No one wants to work in the unit because they don't want to lift the fan blades. They do not have a lifting fixture for the fan blades that will not mar the paint, so they have to lift the blades by hand. He has a good relationship with most of the other workers in the cell.

When he rejects a blade after the reruns, it is given to an inspector who fills out the paperwork to send it to the lab. He gets feedback if the blade has been returned to go onto the next operation. He will see on the paperwork that it has been returned. There were two times that he rejected blades that were cracked. But there were other blades that were rejected because they had peening shot in the blade.

He has had an FAA inspector come into the shop to review his work. There are inspectors assigned to the shop. They were around more frequently in the past than they are more recently. The inspectors would do an audit asking what he would go by, the work instructions, the NDIP, was everything up to date, were things calibrated.

He has never felt coerced to accept a part that he thought should have been rejected.

He has tried to get management to install a heating or cooling unit in the TAI room. If it gets too cold or too hot in the room, the machines do not work. When it gets hot in the summer, they must bring in a portable air conditioning unit. If they didn't have the portable unit, it would get too hot and the machine would fail the self-check. Management has looked into installing a second heating/cooling unit. On 1st shift, he doesn't have a problem with the sun getting into the room. They did have to take out a window to prevent the sun from coming into the TAI room. He thought the darker the room, the better it was for the inspection.

He was doing the TAI before the 2nd shift inspector. He thought the 2nd shift inspector was a good student. Regarding the NDIP, that is what they were given by the lab to do the TAI. He thought the NDIP was good, that it was better than nothing. He thought the process and everything in the room could be better. He thought the TAI could be improved with the software picking the failures so that they didn't have so many false positives. There are indications on the solid edges. The equipment is too sensitive. The combination of everything is what they call noise.

He said that he talks with the NDE engineer quite a bit. If he had a problem with the machine, he would call her for assistance. The NDE engineer calls down to P&W's West Palm Beach facility to see how everything is going. If she cannot answer a question, she will call down to West Palm Beach to get the answer.

He thought that about 25 percent of the blades have to be returned for repainting. When he sees the different shades of paint, the camera will pick that up. He thought that if there was an automated paint machine, the paint finish would be more uniform. The four painters do it differently, some thicker than others. He said that there is not a lot in the NDIP for diagnostic work for false indications. He said that the PowerPoint presentation did show indications and what should be done with the part if those indications exist.

3.2.3 Backup TAI inspector

The backup TAI inspector was interviewed by members of the Powerplants Group on March 22, 2018.

The backup inspector has worked at P&W for almost 40 years and has always worked in NDT in East Hartford. He normally works in the stator department doing FPI, ECI, and laser holography on compressor stators for the PW2000 and sometimes for the PW4000. His records showed that in 2018 up to the time of the interview, he had worked in the TAI shop for 4 days doing 15 fan blades. In 2017, he worked in the TAI shop for 2 days. He works in the TAI shop as needed to clear backlogs or if the other inspectors are not available He currently is working on the 2nd shift, but when he started doing the TAI he was working on 3rd shift. He said that he wears glasses and that he receives and passes an eye test every year.

When he was working on 3rd shift, they were having trouble getting fan blades inspected. When he went to 1st shift, the 1st shift TAI inspector trained him how to run the machine and to do the NDIP. He saw the images and would ask questions. The Level 3 inspector administered the test. The test included a written test and then a practical test on the machine to get the certification for a Level 1 inspector. The Level 1 certification was good for a year. After a year, he was retested to continue his certification. The test was a retest. The 1st shift inspector trained him when he was working on 1st shift and the 2nd shift inspector trained him when he was working on 2nd shift. The 1st shift inspector trained him for the first time in 2011. When he was on 2nd shift, the 2nd shift inspector trained him to get ready to retake the test. The training that the 1st and 2nd shift inspectors gave to him was OJT. He had not been in the department for a while and had to recertified by another Level 3 inspector in 2014. He did attend some classroom training on TAI with a company from Green Bay, Wisconsin. The class was about 3 days long and provided training about the camera, how it worked, used examples of houses to look at a wall showing that the insulation was down. The 1st and 2nd shift TAI inspectors did not attend the training because they were both working a large TAI workload. Of the 20 people that attended the class, he was the only one that actually did the TAI inspection. He said that there was a test given at the end of the class. He would talk to one of the process engineers who had developed the TAI process to ask questions about the TAI.

He said that he did not mind doing the TAI, although he was not comfortable with doing it at the time of the interview. He also thought that it would help if they would hire some more people to do the TAI. He thought the NDIP could be improved with visual pictures or provide a handbook with visual pictures of what they see on the images by providing examples of what is noise and what would acceptable or not acceptable.

He said that if the painter was good, it made the inspection better. He said that there were painters that were better than others. When he was working on 2nd shift and had a question, he would hold it for 1st shift. Or he would have the blade repainted. He does not like to do touch ups with the paint because it gets gloppy. He said it does not go on the same way. If he sees something that is related to the paint, he has the fan blade repainted. If the indication repeated, he would reject the blade to the materials lab that would then decide if it was acceptable. He thought that he had rejected four or five blades, although he never got any feedback on the disposition of those blades.

He said that the sun does go into the TAI room. He would like to have a barrier to block off the sun. He thought the sun might affect the inspection. He was not sure if a lot of light helps the inspection. He said that the TAI room was built with all of the windows at the direction of a former general manager so that the managers look inside to keep an eye on the workers.

3.3 Inspector training and certification

The TAI inspection process went into service in around 2005. From the outset of the TAI inspection process up to the time of the United Airlines incident at HNL, P&W did not have a defined training and certification regimen for TAI inspection process. The 1st shift inspector, who trained the 2nd shift inspector, and the 2nd shift inspector, who was the one who last inspected the United Airlines fan blade that fractured, both stated that the only training they received on the TAI was about 40 hours of OJT. The 1st shift inspector stated the training that he received was from the engineers in Florida and Connecticut who had developed the TAI. In comparison, the certification requirements for the commonly used eddy current and ultrasonic inspections, are 40 hours of classroom training and then 1,200 and 1,600 hours of practical experience, respectively. There is no requirement for recurrent training. During the interview of the manufacturing process engineer who assisted with the development of the TAI process and

NDIP-1065, he stated that there was no specified initial or recurrent training requirement for the TAI because it was classified in 2005 as a new and emerging technology. P&W did provide TAI training that was not specific to fan blades, but the only inspector to receive that training was the backup TAI inspector who is not assigned to the hollow fan blade shop. The two primary TAI inspectors on 1st and 2nd shift were not available to attend the training because they were both working on a backlog of fan blades in the shop.

The engineers who developed the TAI were the ones who trained and approved the inspectors to accomplish TAI. According to NDE national standards, the only person that can certify an inspector is a Level 3 inspector. Although P&W has Level 3 inspectors in various NDE disciplines, P&W does not have a Level 3 TAI inspector. There is an inspector who is working to become certified as a Level 3 TAI inspector. The individual is currently a Level 3 inspector in infrared (IR) testing. He thought that there was not much difference between the TAI and IR inspections and test. The primary difference was how the energy was introduced into the part. But that individual's primary assignment is the inspection of new production GTF fan blades in Michigan.

P&W reported that they will be developing a TAI curriculum for initial and recurrent training.

3.4 Facility

The TAI inspections are accomplished in an enclosed room at one end of the PW4000 hollow fan blade shop. The room has two entrances, a double door in the center of the south wall and a single door that is at the north end of the west wall. There were large clear glass windows in all of the walls and doors. The glass extends from about the center of the wall and doors up almost to the ceiling. The temperature within the room is controlled, however, the general shop area outside of the TAI is not air conditioned. It was reported from several sources that in the summertime that a portable air conditioning unit had to be placed in the TAI room to maintain the temperature to the required level. Within the room, there were two uncalibrated wall thermometers that differed by almost 10°F. There were two TAI machines: one had two computers and the other only had one computer. The operator of the machine with only one computer stated during his interview that he cannot keep the work instructions open while he is inspecting a fan blade.

Based upon comments from members of the Powerplants Group as well as P&W's own review of the TAI room, P&W made many changes and upgrades to the TAI room. Refer to Table 1 for the list of the concerns and issues and the closing action.

Table 1: TAI room concerns and issues

Observations	Corrective action	Status
The room is very bright. The operators have no way to dim the lights.	New LED lights with dimmer switches were installed.	Complete

In the afternoon, the sun shines in through the windows onto the blades undergoing inspection causing false positives.	The glass in three windows and the side door was darkened.	Complete
According to the NDIP, the inspections must be done at 70°F±5°F. The thermometers on the wall read different temperatures, almost 10°F.	New thermometers were installed.	Complete
The TAI machines are very sensitive. It is common for the machines to capture images of the door and door hinges. All of those images must be dispositioned.	Additional screens and shields were installed beyond the camera view to help decrease the number of false positive images.	Complete
In the summer, they need 2 air conditioners to keep the room cool to 70°F. (One a/c is permanent, and the other a/c is portable brought in on the hottest days. People from the shop go into the TAI room to cool off. Nothing prevents them from entering the TAI room when a scan is in progress, which causes the person's image to be captured in the scan. There is not even a light to indicate to the shop that a scan is in progress.	1. A review was completed, and capital expenditure was approved to install an upgraded air conditioning system. 2. A flashing light was installed to show that a TAI scan was in progress.[26] 3. Short term, install an adjustable thermostat.	1. In work 2. Complete 3. Complete
The 1st shift inspector uses the machine on the right and the 2nd shift inspector uses the machine on the left. The 1st shift inspector's machine has two computers and the 2nd shift inspector's machine has only one computer. The 2nd shift inspector, having only one computer with his machine, cannot keep his work instructions open when he is doing an inspection.	An additional computer will be added to the 2nd shift inspector's machine.	Complete

[26] During a subsequent visit to the TAI room, members of the Powerplants Group noted that flashing lights had been installed by the two entrances. The Group also noted that even though the lights were flashing indicating that a scan was in progress, a shop worker not associated with the TAI inspection entered the room.

When the inspectors see an anomaly that they cannot disposition, the blade is sent to the MPE NDE lab for further testing (ultrasonic, x-ray, etc.). A Review Team (MPE engineer, structures engineer, CIPT) make the final determination of whether the blade can be returned to service or must be scrapped. The inspector is not involved in this process and there is no feedback to the inspector to let him know what the Review Team decided.	New procedures specify that the NDT inspector review the Review Team findings and dispositions of the fan blades.	Complete
Both of the TAI inspectors are about 5 years from retirement. The company has not started training anyone younger to take their place.	Establish training for other NDT personnel in the cell within 1 year of announcement of retirement. Employee identified.	Complete. Successor identified.
Most of the training is OJT. There is a lot of institutional knowledge, but not much formal training.	Formal training being created.	Complete
The paint is extremely finicky. Just touching it will cause it to lift off of the fan blade. Even Process Engineering has complained about this.	One possible candidate has been identified. Will require extensive evaluation.	In work. Target date 2/15/2019.
The NDIP needs many improvements.	New NDIP to be issued.	Complete
The TAI scans for NEO blades use a color palette. The PW4000 112-inch fan blade scans are black and white. The inspectors stated that it would be helpful to have colored scans for the PW4000. NDE engineers think a color palette for the PW4000 fan blades could create more confusion.	Not likely. The use of the color palette on this inspection can suppress significant indications and falsely enhance irrelevant features in the images.	Complete. Not being pursued.

When a TAI inspection is complete, the computer generates a "pass" or "fail" for every scan. The fail areas must be dispositioned by the inspector. This usually requires repainting the blade by a 1st shift painter and rescanning. Then the 1st and 2nd scans must be compared. The operators cannot have two scans open at the same time, therefore they have to look at scan No. 1 (try to memorize it, open scan No. 2, and determine if there were any changes. A major improvement would be to have software/hardware that allowed them to compare two scans side by side.	Hardware and software modifications were defined and tested. Installation in both systems to be accomplished.	Complete on one system. Planned to be completed on the other system in October 2018.
The crack on the event fan blade was attributed to paint in 2010 and paint again in 2015. Two different inspectors. It would be nice if the TAI machine had the capability to recall the previous scan and alert the inspector if a spot reoccurred in the same place.	It was determined that the process to retrieve and reprocess the scans in a manner such that the process was uninterrupted for the inspector is complex and did not add enough value to be pursued.	Complete. Not being pursued.
The blade tip, leading edges, and trailing edges cause false indications primarily due to chipped paint. Operators have been instructed to automatically accept those areas. However, all tip, LE, and TE scans must still be dispositioned manually, one by one. Why not change the software so that the tip, LE, and TE are not scanned?	Prerequisite hardware upgrade on both systems in process. Software to be written and validated.	In work. Target date 1/28/2019.
Reference previous item. Whey not change the software to that the tip, LE, and TE are not scanned?	At appropriate time when NDE defines the hardware associated with the software upgrade.	TBD

3.5 FAA oversight

The FAA's Principal Maintenance Inspector (PMI) to the P&W facility was interviewed by members of the Powerplants Group on May 10, 2018.

The PMI to the P&W facility started with the FAA in 1998 and is an aviation safety inspector. He has been a PMI since 1999 when he received his initial training. His office is located at the Flight Standards District Office (FSDO) in Enfield, Connecticut.[27] When he started with the FAA, he was assigned to that FSDO. He has always been in the Connecticut area with the FAA. When he started at the FAA, he provided oversight to between 10 and 20 repair stations. He thought that he had seen about 75 percent of the repair stations in the district. He was assigned to P&W about 10 years ago. At the current time, in addition to being the PMI for P&W, he is the PMI to 5 other Part 145 repair stations, 15 active IA [inspection authorization] holders, and 12 Part 91 operators. He is the FSDO's Level 3 trainer and works on certifying new Part 145 repair stations. He also accomplishes minimum equipment list[28] reviews for the Part 91 operators.

The PMI said that before he worked for the FAA, he worked in military and commercial aviation. Between 1984 and 1987, he was with the U.S. Army working on helicopters. From 1987 to 1989, he worked at Sikorsky Aircraft overhauling and modifying SH3 Sea King, MH53 Super Stallion, and UH60 Black Hawk helicopters. From 1989 to 1998, he was a quality assurance (QA) inspector at Gas Turbine Corporation, a turbine engine overhaul facility, in East Granby, Connecticut. He was hired as a QA inspector, was promoted to a QA lead, and then became a QA manager. He oversaw the test cell operation, field service units, borescoping, modules, and quick engine changes. He had signature authority over about 500 people. He worked there until the facility was bought and closed down by General Electric. He then worked as a QA supervisor at Dow Composite Products that made composite materials for Sikorsky helicopters from May to August 1998. He then accepted employment at the FAA. He holds an FAA mechanics certificate with airframe and powerplants ratings.

The PMI stated that he travels to the P&W facility about once or twice a month. He has almost daily contact with the P&W regulatory compliance manager or the quality manager. When he talks with either of those managers; it could be about an added rating, who is coming in from an airline for an audit, issuing or adding ratings on the certificate, surrendering a certificate, or information on a union action. The discussion could be about anything that involves operations at P&W that they felt they need to disclose because they have disclosure programs. The PMI said that the regulatory compliance manager had called him about the UAL 777 event at HNL to ask him if he had heard about that event and to advise that the two fan blades had been inspected at P&W. The PMI said that he had seen the news of the United event prior to the call from the P&W regulatory compliance manager.

The PMI said that P&W has two certificates. There is one certificate for the shop to repair components and a satellite certificate that allows engines to be tested at Middletown. He

[27] The Enfield, Connecticut FSDO is about 15 miles from the P&W facility in East Hartford, Connecticut.

[28] The minimum equipment list is a categorized list of on-board systems, instruments, and equipment related to the airworthiness of the airplane that may be inoperative and the airplane can still be dispatched for flight.

has encouraged P&W to maintain their capabilities and have the correct ratings for them to be able to legally receive the work. He said that P&W management has worked with him to implement his suggestions. When he was initially assigned to P&W about eight years ago, he had asked why they didn't have a satellite certificate to test engines or do other work, so he did not have to get last minute phone calls and then jump through hoops.

The PMI stated that when he is at P&W, some of his work is to review work orders, audit separate cells for their processes, talk to the individuals in the cells, check rosters (personnel rosters, management, cell leaders, return to service and non-return to service personnel rosters). In accordance with Part 145, the personnel are required to be rostered for their functions within the facility. He said he conducts multiple audits throughout the year. He said that he has done audits in the hollow fan blade shop. He has been to the TAI area several times in the last eight years. When he has audited the shop, he looks at the NDIP and then audits the process to see if they are following the documented process. He said that he had talked to the Level 3 NDI person to talk about master certifications and the calibrated instruments in the shop. He would also talk about the MPI and FPI cells and review their procedures for consistency. He would confirm the procedures were current because they have to be retested every five years.

He has gone into the TAI room to watch the inspection as well as audit the process. The process that he audited was fine. He had noted that there was one screen at one desk and two screens at another desk and questioned why. He said that there was usually only one machine working on the day shift. He had not noticed if there were any environmental issues in the TAI room that were out of the ordinary, although he had seen them drag a screen in front of the windows to block out the sunlight. When he reviewed the TAI process and the NDIP, he noted that it was a pass or fail scenario. When he audited the process, the inspectors showed him examples of anomalies. He said that when a blade was rejected, it had to be stripped, repainted, and all of the zones had to be reinspected. The people knew him, talk to him, and know that he was thorough. He said that he had a good way of talking with people regarding certification activities. When he audited the TAI process, he said that he had spoken to the Level 3 inspector. He reviewed the Level 3's training profiles and reviewed the test scores. He did review the training and certificates for the Level 1 and Level 2 inspectors. He thought the Level 3 inspector was over all of the NDI processes. He was aware of the training requirements for the ECI and UTI as well as those for the TAI. When he was asked if that was a disparity, he thought that was an opinion although he did think the training requirements for the TAI were somewhat low. He thought the TAI process, even though it was proprietary to P&W, should have been reviewed and approved by the FAA's Engine Certification Office in Burlington, Massachusetts. He thought that there might be an IEN [internal engineering notice] or an EA [engineering authorization that is connected to the TAI NDIP and authorized the inspection.

With respect to the dispositions of fan blades that were rejected, his scope of review continues with follow-up visits. There have only been 7 blades scrapped out of about 16,000 that were inspected. He has gone to Engineering to follow up on some of the blade dispositions.

He thought that P&W was very impressive and has brought other inspectors to P&W to show them around. He would show the inspectors from other small shops the technology. He does go out with other inspectors to assist with audits of their shops because of his extensive experience in Part 145 shops and his experience as a QA inspector to increase a shop's capabilities with additional ratings so their parts can be maintained correctly. He has worked heavily with DERs [designated engineering representatives] and most of the high level functions at repair stations.

4.0 Corrective actions

4.1 Overinspections

Because of the United Airlines fan blade separation incident and the finding that the fractured fan blade had a rejectable indication at the previous TAI, P&W initiated an overinspection of all TAI inspection records and a review of all PW4000 112-inch fan blades.

The results of the overinspection were:

Accept	8,819
Unserviceable or returning to P&W	171
Recalled (missing data)[29]	226
Recalled (cause)[30]	2
Retired	93
TAI not required at last shop visit	159
Work in progress	136
Total	9,606

4.2 Fan blades recalled for cause

During the overinspection, there were two fan blades that were in service at Korean Air and United Airlines that had TAI indications that could not be resolved. P&W notified both operators and requested that the blades be removed from service and returned to P&W for evaluation. Both blades were administratively declared as scrap so that they could not be returned to service.

4.2.1 Korean Air fan blade

The FPI of the Korean Air blade revealed a small pit on the concave surface of the airfoil in the mid span area. The TAI inspection of the Korean Air blade did not duplicate the previous

[29] These were fan blades that were recalled because the associated records could not be located or there was information missing from the inspection records.
[30] Refer to Section 4.2

indication. A subsequent x-ray inspection revealed peening shot in the cavity in the area where the previous TAI indication had been reported.

4.2.2 United Airlines fan blade

The FPI of the United Airlines fan blade did not reveal any discrepancies. The TAI inspection of the United Airlines fan blade did not duplicate the previous indication. A subsequent x-ray inspection revealed peening shot in the cavity in the area where the previous TAI indication had been reported.

4.3 Bulletins/directives

The instructions to accomplish the TAI are in P&W "Alert Service Bulletin (ASB) PW4G-112-A72-268, Engine – Blade Assembly, 1st Stage, Low Pressure Compressor (LPC) – Thermal Acoustic Image (TAI) Inspection to Detect Airfoil Cracks." The ASB provides information on when the initial and recurring inspections should be accomplished on the different PN fan blades that are used in the various 112-inch PW4000 engine models from the PW4077 up through the PW4090-3. The ASB summary states that during the manufacture of the [fan blades'] details, improper polishing and machining operations could result in spark impingement and imbedded tungsten carbides in the hollow fan blade that could cause stress concentrations that could lead to the initiation of a crack. The ASB summary also states that micro-texture that is a condition that can occur naturally in titanium materials during the forging process where there is alignment of the grain structure into small colonies. In high stress locations, micro texture can potentially lead to the initiation of a crack depending upon the size and orientation of the colony. The TAI is used to detect for internal crack in the airfoil. ASB PW4G-112-A72-268 is a Category 3 bulletin meaning that P&W recommends that the bulletin be accomplished within the cycles specified in the bulletin.

On October 10, 2018, the FAA ECO issued a Notice of Proposed Rulemaking (NPRM) 2018-NE-27-AD Airworthiness Directives; Pratt & Whitney Division (PW) Turbofan Engines proposing an airworthiness directive (AD) for PW4000 112-inch engines. The proposed AD would require the accomplishment of the TAI in accordance with ASB PW4G-112-A72-268 Revision 7, dated September 7, 2018. The ASB recommends and the proposed AD would require the accomplishment of the TAI for those fan blades with less than 6,500 CSN, at the next time the engine is separated at M-flange, which is the diffuser/combustor rear flange and the HPT case front flange (Figure 2), or prior to the fan blades accumulating 7,000 CSN, whichever occurs first; and for those fan blades that accumulated more than 6,500 CSN, or if the CSN for the fan blade cannot be determined, or if the cycles since the fan blade last had a TAI accomplished, accomplish the TAI within 500 cycles or within 180 days of the effective date of the AD. Thereafter, a repetitive TAI is to be accomplished every time the engine is separated at M-flange and the fan blades have accumulated 1,000 or more cycles since the last TAI not to exceed 6,500 cycles. Any fan blade that fails the TAI must be removed from service and replaced before further flight.

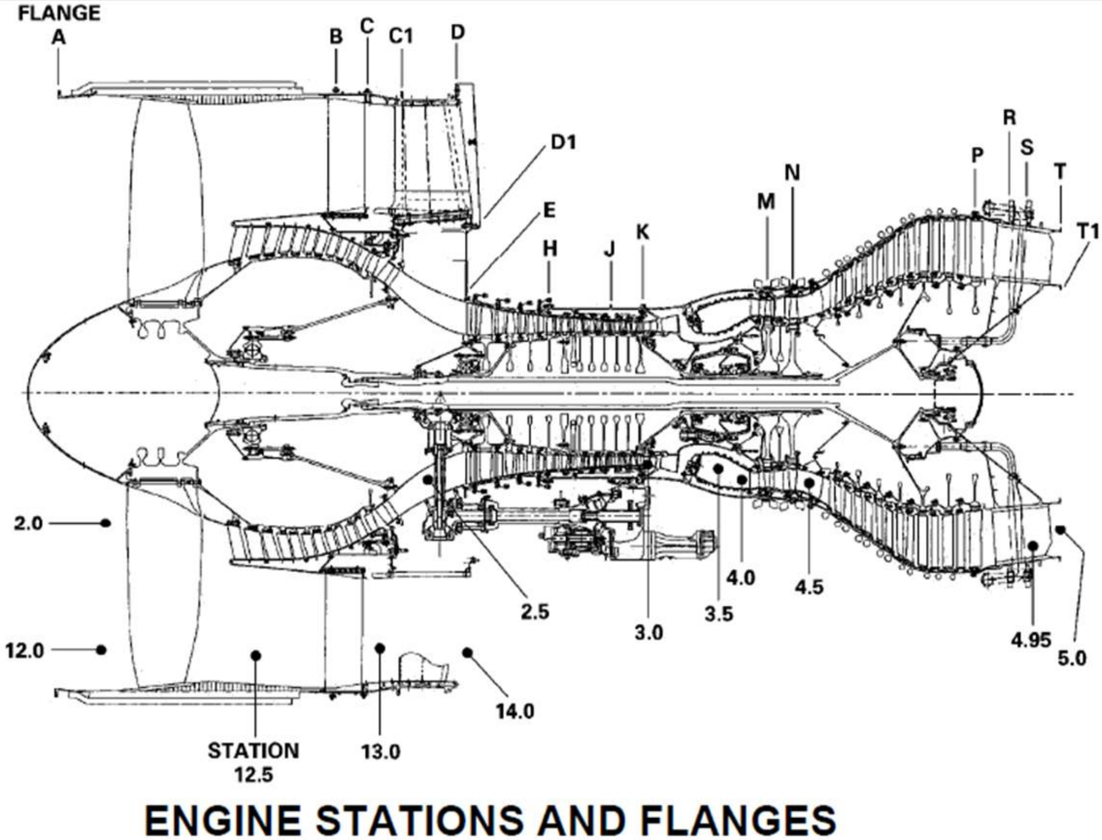

Figure 2: PW4000 112-inch engine stations and flanges. (P&W)

5.0 Crew statements

5.1 Pilots

At the time of the event, there were three United Airlines pilots on the flight deck: the Captain, who was the pilot monitoring, the first officer (FO), who was the pilot flying, and a jump seat rider, who was an off-duty United Airlines 777 FO. All three pilots provided written statements about the event.

The Captain stated that the flight departed SFO on time and that the push back, taxi, takeoff, and climb to FL340 were normal. The Captain further stated that at about the midpoint in the flight, they had to descend to FL 300 and then FL 280 looking for a better ride. Because they were unable to find a better ride at those lower altitudes, they climbed up to FL 360 where they did find smooth flight conditions. All of the pilots stated that they were about 120 miles from HNL at FL 360 when there was what the FO stated was a violent jolt that was also described by the jump seat rider as a very loud bang that both pilots stated was followed by extreme airframe vibrations. The pilots reported that immediately after the jolt and loud bang, the autopilot disconnected, and the airplane began to roll to the right. A positive exchange of control was accomplished with the Captain taking over control of the airplane to become the pilot flying and the FO became the pilot monitoring. The pilots stated that about 15 to 30 seconds after the jolt and loud bang, the EICAS [Engine Indicating and Crew Alerting System][31] showed that there was no EPR [engine pressure ratio],[32] N1,[33] or oil pressure. After accomplishing the Severe Engine Damage checklist, the right engine was shut down and secured. The jump seat rider stated that after the right engine was shutdown, the vibration subsided although the controllability of the airplane was not normal. They declared an emergency with the Honolulu Control Facility and began a drift down descent to FL 230. The Captain directed the jump seat rider to go back into the cabin to assess the condition of the engine. The jump seat rider noted that the engine was oscillating and that the cowling was missing. The jump seat rider stated that he took a video of the engine with his work iPad so that he could show the Captain and the FO what they were dealing with so that they could assess further appropriate action. The pilots reported that concurrently, the purser had come to the flight deck and the Captain briefed her about the emergency and that they would be landing at HNL. The pilots stated that the airplane continued to HNL and they made a visual approach and landed on runway 08R [Right] without further incident. The pilots stated that the airport fire department personnel inspected the airplane and when the airplane was determined to be safe, they taxied the airplane to the gate where the passengers deplaned normally.

For further details, refer to the Captain's, FO's, and jump seat rider's statements, Attachments 4, 5, and 6, respectively.

5.2 Flight attendants

There were eight flight attendants on board the airplane. They described cleaning up the cabin and the galley areas after having completed the arrival meal service. At what they estimated to be between 30 and 45 minutes before their scheduled arrival, all of the flight attendants reported hearing a very loud noise that was followed by what some of the flight attendants described as a violent shaking of the airplane. Several of the flight attendants described the shaking as so bad that it was almost impossible for them to hear anything. Most of the flight attendants returned to their assigned jump seats to sit down although several reported that they were unable to get to their jump seat and that they just sat on the floor where they had been standing and directed nearby passengers to sit down in a seat and buckle the seat belt or sit on the floor with them. One flight attendant reported making a public announcement for the passengers to return to their seats, although the other flight attendants had difficulty hearing what was said because of the noise in the cabin. One of the flight attendants reported trying to call the flight deck, but could not get through because the line was busy. After the flight deck jump seat rider had taken pictures of the right engine with his iPad and showed them to the pilots, the flight attendant stationed at the 1L jump seat heard the Captain direct him to go to the rear of the

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[31] EICAS is an integrated system to provide pilots with information on the airplane's engines including an engine's parameters, configuration, and faults as well as checklists.
[32] Engine pressure ratio (EPR) is a measurement of engine power as a ratio of the total pressure of the gases in the exhaust pipe, station 5, divided by the total pressure of the air entering the engine inlet, station 2. On the PW4000 112-inch engine, EPR is equal to $P_{t4.95}/P_{t2.}$ (Refer to Figure 2)
[33] Nl is the low-pressure rotor speed.

airplane to check for any further damage. The 1L flight attendant then asked the Captain if they should prepare for an evacuation. She said the Captain advised that they had lost an engine, they should prepare for a land evacuation and that they would be landing in about 25 minutes. She said that the Captain had also said that it could be a remain seated incident as well. She said that the Captain said that they would give them the BRACE warning before they landed. The 1L flight attendant then made an ‘all call’ to advise the other flight attendants of the situation and to prepare the cabin for landing and for a possible evacuation. One of the flight attendants reported that the oxygen masks did not deploy, but that many of the overhead bins opened up and some bags did fall out although she didn’t think anyone was hurt with the falling bags. The flight attendants reported that they cleaned up the galleys securing everything in preparation for landing. Several flight attendants reported reviewing their emergency evacuation procedures and reviewing the evacuation procedures with able body assistants to assist with the possible evacuation of the airplane if it became necessary. They also reviewed the brace position with the passengers. The flight attendants reported that the Captain provided the brace signal before the airplane landed and that they began repeating BRACE to the passengers that continued until after the airplane had landed and the Captain advised them to remain in their seats. The flight attendants stated that the Captain advised them to remain in their seats while the fire department examined the airplane. When the fire department determined it was safe, the airplane taxied to the gate and the passengers deplaned normally.

For further details, refer to the flight attendants’ statements, Attachment 7.

6.0 Inlet duct/cowling

The initial examination of the airplane and engine at HNL revealed the inlet duct’s lip, forward bulkhead, and part of the inner and outer barrel were missing. The left and right fan cowls were both missing. (Photo No. 11) The U.S. Coast Guard (USCG) was requested to search the presumed area of the incident. The USCG responded that they did not have any assets in that area. But the USCG did issue a Notice to Mariners for any ships in the presumed area of the incident to be alert for any debris and to report any sightings. However, there were no reports of any debris being sighted.

Photo No. 11: View of the right engine from the right front showing what remained of the inlet duct. White plastic was placed over the broken blades to protect the fracture surfaces. (P&W)

For comparison purposes to show how much of inlet duct and the cowlings were missing, photographs of the No. 2 engine's left and right side and the undamaged left engine's left side are provided. (Photos Nos. 12, 13, and 14.)

Photo No. 12: Left side of engine and cowling.

Photo No. 13: Right side of engine and cowling.

Photo No. 14: Left side of left engine showing exemplar inlet duct and cowling.

The examination of the engine at HNL revealed that of the 44 inlet duct-to-A-flange bolts, almost all were loose except for 1 at about 3 o'clock, a continuous sector of 5 between about 6 and 8 o'clock, and a continuous sector of 4 between about 10 and 11 o'clock that were still tight. There were several bolts that had a gap of about 0.12-inches between the bolt and the rear face of the flange. The piece of the inlet cowl that remained attached to the engine was removed at HNL to facilitate shipment of the engine and inlet cowl back to SFO. At SFO, it was fitted back onto the fan case without fasteners for the investigation. Before the piece of inlet cowl was fitted back onto the engine, the examination of the bulkhead flange, which mates to the engine's A-flange, did not show any indications of deformation or elongation of the bolt holes. However, the paint on the inlet duct rear flange adjacent to the front face of A-flange was scraped up slightly. (Photo No. 15) Only the aft bulkhead and portions of the inner and outer barrel remained attached to the engine.

Photo No. 15: Close up of rear face of inlet duct showing paint scraped up adjacent to the engine's fan case front flange.

Upper aft bulkhead

The inlet assembly, upper half, data plate was affixed to the upper aft bulkhead's web and showed PN 314W3010-30AA, SN 000009. The upper aft bulkhead's outer stiffener was torn and deformed at about 12:30 o'clock above where the fan cowl support beam fittings are attached. (Photo No. 16) The outer barrel to the outer stiffener fasteners were intact and tight, except for those that were removed at HNL. The fasteners were removed at HNL for shipment of the engine and inlet duct to SFO. The inner barrel to the inner stiffener fasteners were intact and tight. The bulkhead's web had three approximately 3-inch long cracks near the stiffener at about 9:45, 10:00, and 10:30 o'clock. The inner stiffener appeared to be undamaged. The upper portions of the fan cowl support beam support fittings were fractured and missing. The aft bulkhead's splice fittings at 3 and 9 o'clock did not have any apparent damage. (Photo No. 17) The P2/T2 sensor was fractured at the B-nut fitting and the bonding strap was separated from its bracket.

Photo No. 16: View of the upper aft bulkhead's outer stiffener was torn and deformed. (Boeing)

Photo No. 17: View of the aft bulkhead splice fitting showing no apparent damage. (Boeing)

Lower aft bulkhead

The inlet assembly, lower half, data plate was affixed to the lower aft bulkhead's web and showed PN 314W3010-30AA, SN 000009. The bulkhead's web was missing except for portions that remained attached to and in the proximity of the splice fittings and an approximately 1.5-inch piece of the web edge band that was still attached to the inner stiffener. (Refer to Photo No. 17) The inner barrel-to-inner stiffener fasteners were intact and tight, except at about 8 o'clock as noted in the fan containment section. (Refer to Section 7.2) The outer stiffener was missing except for the pieces that were still attached to the splice plates near the splices. There was an approximately 5.5-inch long piece of the outer stiffener at about 3 o'clock that remained attached to the splice plate, lower edge that was twisted in a clockwise direction as viewed from below, and bent radially inward. (Refer to Photo No. 17) The outer stiffener had about 7.5-inches remaining attached to the splice plate at about 9 o'clock and was bent in a counterclockwise direction as viewed from below. (Photo No. 18) The inner stiffener was damaged by the anti-ice duct attachment bracket at about 5 o'clock.

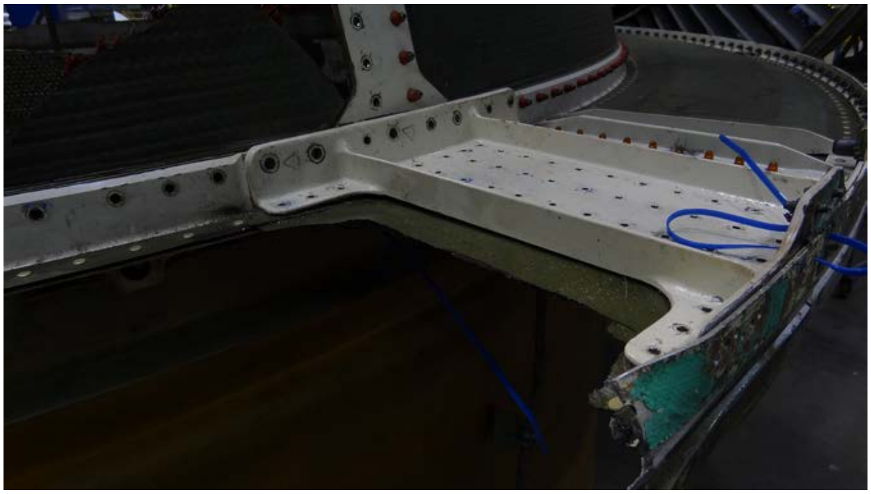

Photo No. 18: View of the outer stiffener remaining attached to the splice plate. (Boeing)

Upper outer barrel

The only portion of the upper outer barrel that remained was about a 1-inch piece of the edge band under the remaining fasteners of the upper outer stiffener between about 9 and 10 and 12 and 3 o’clock. (Refer to Photo No. 17) These remaining pieces were delaminated.

Upper inner barrel

Most of the upper inner barrel composite material remained attached to the aft bulkhead from about 9 to 12 o’clock. (Photo No. 19) The forward edge band of the panel that was attached to the forward bulkhead was missing. The P2T2 probe was still attached in this section. There was a piece of the upper inner barrel, that varied in width between about 1- to 5-inches wide, from about 12 to 3 o’clock that remained attached to the upper aft bulkhead. The perforated face sheet was intact from about 10 to 12 o’clock. Most of the perforated face sheet over the open cell honeycomb was missing from about 9 to 10 o’clock, though the face sheet and honeycomb in the solid core remained. The edges of the inner and outer face sheets showed fractures and delaminations. The edges of the exposed core appeared ragged.

Photo No. 19: View showing that most of the upper inner barrel composite material remained attached to the aft bulkhead from about 9 to 12 o'clock. (Boeing)

Inner barrel splice fittings

The inner barrel splice fittings at 9 o'clock had no apparent damage. (Refer to Photo No. 18) The fasteners were intact and tight except where they were removed at HNL. There were about 3-inches of the inner barrel splice fitting at 3 o'clock that remained attached to the remaining pieces of the inner barrels and aft bulkhead inner stiffeners. (Refer to Photo No. 17)

Lower inner barrel

There was a portion of the lower inner barrel's composite panel that varied in length from about 2- to 7-inches that remained attached to the aft bulkhead inner stiffener. (Photo No. 20) The edges of the face sheets had areas of fractures and fractures with delaminations. Adjacent to the splice fitting at 9 o'clock, there were about 5-inches of the non-perforated face sheet was missing although the core was still attached to the aft bulkhead inner stiffener and the fasteners were intact. (Refer to Photo No. 19)

Photo No. 20: View of a portion of the lower inner barrel's composite panel that varied in length that remained attached to the aft bulkhead inner stiffener. (Boeing)

The left and right fan cowls were missing. The left side actuator, hold-open rods, and the support bracket were missing. The right side hold-open rods were still in place.

The left and right side thrust reversers were in place. The exterior of the left side translating sleeve was coated with oil from the forward edge radiating from the oil tank area aft to the rear edge. The forward face of the bulkhead adjacent to the oil tank was coated with oil. The right side translating sleeve had an approximately 3-inch wide circumferential by 6-inch long axial hole about 6-inches forward of the aft edge at about 4 o'clock and an approximately 4-inch wide circumferential by 6-inch long axial L-shaped split about 9-inches forward of the aft edge at about 4:15 o'clock. There was an approximately 3-inch axial split, 4-inches from the trailing edge located at about 1 o'clock and an approximately 2-inch square hole at the trailing edge located at about 12:30 o'clock. There was an approximately 14-inch long crack on the bypass side of the inner wall extending to the aft edge at about 5:30 o'clock. On the left side of the translating sleeve, there was an axial split measuring approximately 1-inch circumferential by 3-inch axial, 4-inches from the trailing edge at about 7 o'clock. There were numerous tears and punctures to the face sheet of the inner wall and translating sleeve within the bypass duct. The thrust reverser door latches were still latched.

The left and right exhaust cowls were in place and the latches were latched. The two pressure relief doors on the left side were open.[34] The pressure relief doors on the right side were closed and latched. The exhaust cowls did not have any thermal distress or soot stains. The exhaust nozzle and exhaust plug were in place and did not have any damage.

[34] Airport fire department personnel who responded to the airplane and examined it after it had landed and stopped on the runway reported that the pressure relief doors were open when they inspected the engine.

7.0 Rest of engine

The engine was examined by members of the Powerplants Group on scene at the United Airlines hangar at HNL on February 14 to 18, 2018, and also at United Airlines' engine overhaul facility at SFO on March 6 to 9, 2018.

7.1 Exterior

The engine was complete from the fan case front flange to the turbine exhaust case rear flange. The exterior of the engine did not have any indications of an uncontainment, case rupture, or a fire. (Photos Nos. 21 and 22)

Photo No. 21: View of left side of engine showing no indications of an uncontainment, case rupture, or fire. (P&W)

Photo No. 22: View of right side of engine showing no indications of an uncontainment, case rupture, or fire. (P&W)

The fan rotor could be rotated easily by hand. There were no noises or grinding sounds when the fan was rotated. When the fan was rotated, the 9th stage turbine blades rotated concurrently.

7.2 Fan case

The fan case was complete and intact, in place on the fan exit case. (Refer to Photos Nos. 21 and 22) The fan case front and rear flanges, A- and B-flanges, respectively, and their respective bolt holes were intact. (Refer to Figure 2) The A-flange flange bolt holes did not appear to have any evidence of deformation or elongation. However, the paint on the rear face of inlet duct flange adjacent to the fan case lugs was scraped up slightly. (Refer to Photo No. 15) Of the 44 flange bolts, almost all were loose except for 1 at about 3 o'clock, a continuous sector of 5 between about 6 and 8 o'clock, and a continuous sector of 4 between about 10 and 11 o'clock that were still tight. There were several bolts that had a gap of about 0.12-inches between the bolt and the rear face of the flange.

The Kevlar® environmental wrap was in place around the fan case. The Kevlar environmental wrap had an approximately 35-inch long axial tear at about 3 o'clock that was between about 5.5- and 40.4-inches aft of A-flange. (Photo 23) The outermost layer of the Kevlar under the environmental wrap was visible through the tear and there was an area that was approximately 3-inch axial by 2-inch circumferential about 15-inches aft of A-flange that had a frayed appearance and there were tears and separations. The Kevlar environmental wrap had a wrinkled appearance between about 1 and 5 o'clock with outward bulging of the belt between about 2 and 4 o'clock. The maximum deformation of the Kevlar environmental wrap was about 2.5-inches at about 3 o'clock. (Photo No. 24) The location of the maximum deformation of the wrap was coincident with the approximately 34-inch long crack on the inside of the fan case.

Photo No. 23: View of Kevlar wrap showing tear. (P&W)

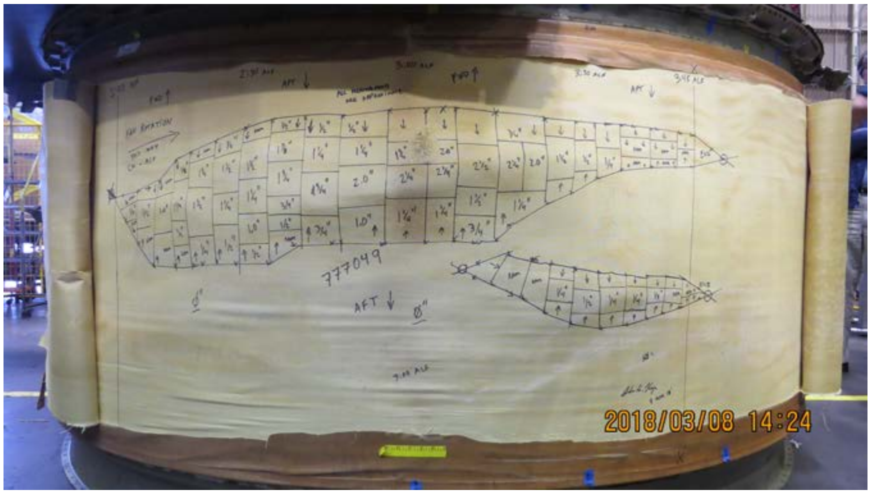

Photo No. 24: View of side of fan containment case showing deformation. (P&W)

On the forward edge of the Kevlar belt, the glue/epoxy and green-colored paint was cracked intermittently around the entire circumference. Between about 1:45 and 4:15 o'clock, there was a continuous sector of chipped and missing glue/epoxy and paint. (Photo No. 25) In the center of the area of continuous chipped and missing glue/epoxy, at about 3 to 3:30 o'clock, the glue/epoxy was separated axially about 0.3-inches consistent with the front part of the belt having moved aft. In the transition radius between the two diameters of the Kevlar belts about 3.25-inches aft of A-flange, there was cracking of the glue/epoxy over much of the circumference. Between about 2:30 and 3:30 o'clock, the cracking was the most extensive with pieces of the glue/epoxy chipped, flaking away, or missing. In this area, the front of the belt appeared to have been displaced outward such that the transition radius area was deformed into a conical shape with the most deformation at about 3 o'clock. (Photo No. 26)

Photo No. 25: View of front of forward edge of Kevlar wrap showing chipped and cracked paint. (P&W)

Photo No. 26: View of front of forward edge of Kevlar wrap
showing chipped paint and aft movement of wrap. (P&W)

On the aft edge of the Kevlar belt, the green paint over the glue/epoxy was cracked around the entire circumference. Between about 12:30 and 6:30 o'clock, the crack was open, and the glue/epoxy was broken. Within this area, the front of the belt was displaced forward with the maximum displacement being about 0.75-inches at about 3 o'clock and tapering to no displacement at the ends of the sector at about 12:30 and 6:30 o'clock. (Photo No. 27)

Photo No. 27: View of aft edge of the Kevlar wrap showing the crack in the epoxy. (P&W)

The blue-colored fan blade rub strip[35] in the plane of the fan was rubbed down to the base metal around the circumference of the case except for some random approximately 1-inch wide patches at the forward-most part of the rub strip. The fan case in the plane of the fan was circumferentially rubbed and scored between about 12.5- and 18.5-inches aft of A-flange. (Photo No. 28) The aft rub strip area, between about 5 and 2:15 o'clock, had patches of crushed honeycomb material amid the glue in the honeycomb cell pattern. Between about 2:15 and 5

[35] The blue-colored fan blade rub strip was located between about 11.6- to 26.6-inches aft of A-flange.

o'clock, only the glue in the honeycomb pattern remained on the aft rub strip area. (Photo No. 29)

Photo No. 28: View of the fan blade rub strip showing the circumferential rub marks and the remains of the blue rub strip. (P&W)

Photo No. 29: View of fan blade rub strip showing only the honeycomb glue remaining. (P&W)

The aft acoustic liners were in place between about 5 and 2:30 o'clock, but had numerous holes, cuts, and punctures. Within this area, at about 6:30 to 7:30 o'clock, there was a triangular-shaped area, about 20-inches long circumferential by 17-inches wide axial, where the acoustic treatment was missing or peeled up. Between about 2:30 and 5 o'clock, the forward half of the acoustic treatment was liberated or loose and the honeycomb on the rear half of the acoustic treatment was generally in place with the face sheet peeled away. The forward side of the honeycomb cells in this area were crushed and compressed circumferentially in the direction of rotor rotation.

There were three areas on the inside of the fan case that appeared to be damaged consistent with impact from a fan blade. The first area was between about 2:15 and 3 o'clock that had an irregular-shaped meandering crack that was at an approximately 40° angle to the axis of the engine. The crack was located between about 27.2-inches aft of A-flange at about 2:15 o'clock and about 13-inches aft of A-flange at about 3 o'clock. The case on the aft side of the crack was deformed outward. The case in this area did not have any circumferential scoring on the forward part of the fan blades' plane of rotation. The Kevlar belt was visible through the crack, but it did not have any visible penetrations. The geometry of the crack corresponded with the geometry on the fractured end of fan blade No. 11 that was recovered from the behind the fan rotor during the on-scene examination of the engine at HNL. (Photo No. 30) The second area of damage consisted of two irregular meandering cracks between about 2:45 and 3:45 o'clock. One of the cracks was about 34-inches long at an angle of about 10° to 15° from the engine's axis and was located about 19.2-inches aft of A-flange at about 2:45 o'clock and about 15.5-inches aft of A-flange at about 3:45 o'clock. The second crack was about 28-inches long at an angle of about 45° to the engine's axis and was located about 14.2-inches aft of A-flange at 2:40 o'clock and about 35-inches aft of A-flange at 3 o'clock. The two cracks in this area intersected at about 3 o'clock. The crack in the first and second areas of damage intersected at about 2:45 o'clock. The fan case aft of the 34-inch long crack was deformed outward. The inner layers of the Kevlar wrap that were visible through the crack were cut. The geometry of the 34-inch long crack corresponded to the geometry of the piece of fan blade No.10 that was recovered from the fan exit guide vanes at HNL. (Photo No. 31) The third area of damage were two holes in the fan case just aft of the fan rotor's plan of rotation at about 3:30 o'clock. The first hole was about 3.5-inches circumferential by 1-inch axial about 29.7-inches aft of A-flange. The second hole was about 2-inches circumferential by 0.5-inches axial about 34.5 inches aft of A-flange. The geometry of the edge of the forward hole corresponded to the geometry of a fragment from fan blade No. 10 while the geometry of the aft hole corresponded to the geometry of a fragment from fan blade No. 11. (Photo No. 32)

Photo No. 30: View of broken tip of fan blade No. 11 matched to hole in fan case. (P&W)

Photo No. 31: View of broken piece of fan blade No. 10 matched to hole in the fan case. (P&W)

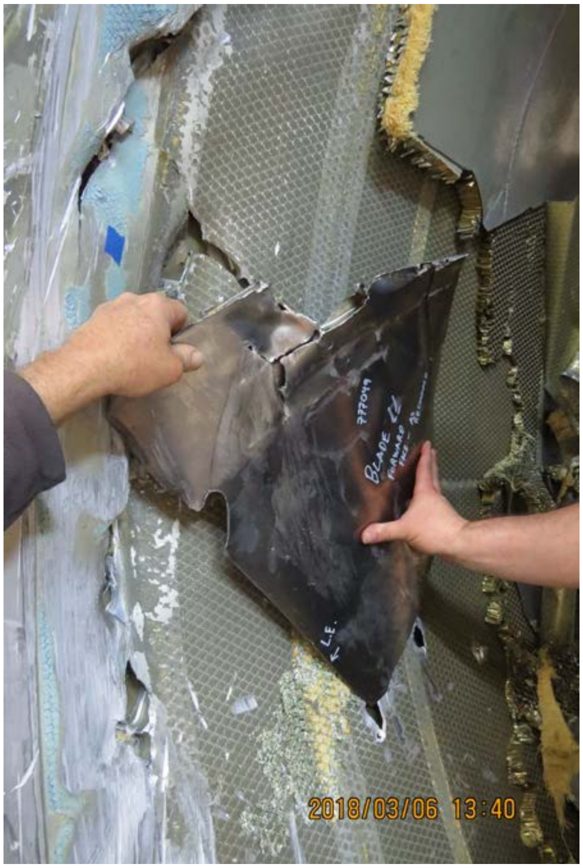

Photo No. 32: View of broken tip of fan blade No. 11 matched to second hole in fan case. (P&W)

The inside of the fan case had an area of circumferential scoring marks that were about 9-inches long between about 3:30 and 4:30 o'clock about 23-inches aft of A-flange. There was an approximately 8.5-inch long circumferential crack between about 10 and 10:30 o'clock about 23-inches aft of A-flange. The fan case had two holes that were slightly forward of the fan blades' plane of rotation. There was a hole at the bottom of an approximately 1-inch long gouge at about 4 o'clock that was about 5-inches aft of A-flange. There was another hole that was about 1-inch in diameter at about 4:15 o'clock about 10 inches aft of A-flange.

The examination of the fan case showed that there were three distinct patterns of tracks along the flow path that appeared to spiral forward from the plane of the fan blades' leading edge across A-flange on to the inlet duct's inner barrel.

The first pattern was about 6-inches wide and originated at about 2:30 o'clock at the plane of the fan blades' leading edge. In the photo, the first pattern was marked with white tape. This pattern was characterized by scuffing and scoring along with small areas that had a darker appearance than the adjacent areas. The forward part of this pattern intersected the circumferential fracture in the inlet duct's inner barrel perforated face sheet at about 5:30 o'clock about 4.2-inches forward of A-flange. The circumferential fracture extended from about 5:30 to 7:45 o'clock. The pattern terminated at a cut in the inlet duct's inner barrel's non-metallic core approximately 3-inches forward of A-flange at about 7:45 o'clock. (Photo 33) The cut transitioned from the inner barrel face sheet to the aft bulkhead inner stiffener flange over an arc of about 8-inches and then along the stiffener flange over an arc of about 16-inches. Along this combined arc length of about 24-inches between about 7:30 to 8 o'clock, 14 Hi-Lok fasteners[36] were severed. (Photo No. 34) The measured angles of the first pattern are listed in Table 2. The pattern appeared to be parallel with A-flange at about 6:30 o'clock. The first pattern appeared to be under the second and third patterns.

Table 2: Fan case first rub pattern angles (white tape)

Axial location	Clock location	Angle (degrees)
6 inches aft of A-flange	4:15	7
At A-flange	5:30	6
4.25 inches fwd of A-flange	6:00	3

[36] A Hi Lok fastener is high strength fastener that consists of an externally threaded pin and an internally threaded collar that has wrenching flats. The pin is inserted into a hole and the collar is threaded onto the pin. As the threaded collar is torqued onto the pin, the portion of the collar with the wrenching flats shears away.

Photo No. 33: View of inside of the fan case showing the three tracks that spiral across the fan case onto the inlet duct. (P&W)

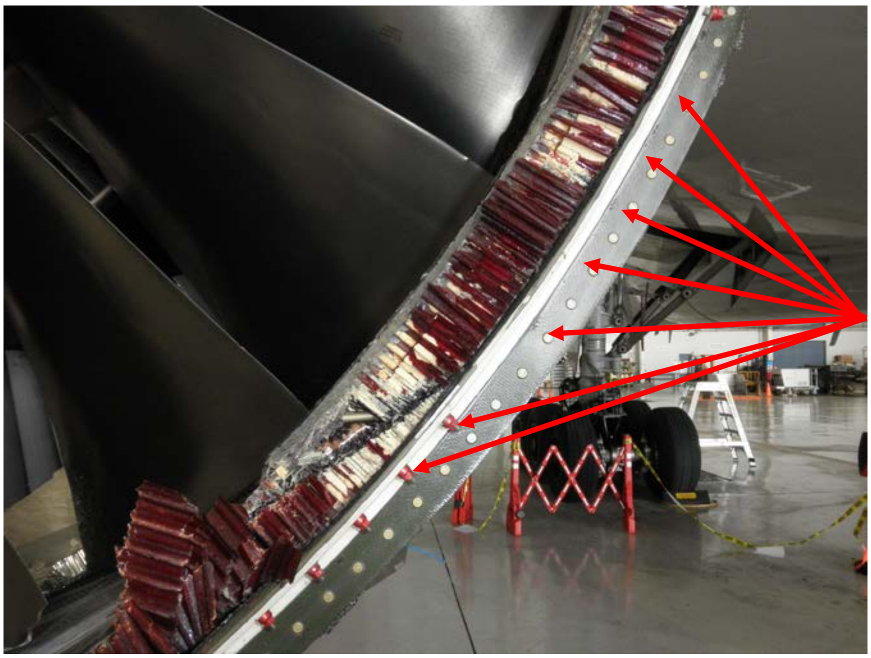

Photo No. 34: Close up view of edge of broken inner barrel showing broken and missing Hi Lok fasteners.

The second pattern was about 2.2- to 2.5-inches wide and appeared to originate at the plane of the fan blades' leading edge at about 2:30 o'clock. In the photo (Refer to Photo No. 33), the second pattern was marked with blue tape. The pattern terminated at about 4 o'clock about 4.5-inches forward of A-flange at the transition between the solid and perforated sheet on the inlet duct's inner barrel. The edge of the inner barrel skin at the area of the termination of the pattern, about 12-inches long, had features that were consistent with having been cut. The measured angles of this second pattern are listed in Table 3.

Table 3**:** Fan case second rub pattern angles (blue tape)

Axial location	Clock location	Angle (degrees)
6 inches aft of A-flange	3:15	22
At A-flange	3:45	19
4.25 inches fwd of A-flange	4:00	16

The third pattern was about 2- to 2.7-inches wide and appeared to originate at the plane of the fan blades' leading edge at about 3 o'clock. In the photo (Refer to Photo No. 33), the third pattern was marked with orange tape. The pattern terminated on the inlet duct inner barrel at about 5:15 o'clock about 7.2-inches forward of A-flange. The edge of the inlet duct at the termination point of this pattern, about 23-inches long, had features that were consistent with the sheet being cut. The measured angles of this second pattern are listed in Table 4.

Table 4: Fan case third rub pattern angles (orange tape)

Axial location	Clock location	Angle (degrees)
6 inches aft of A-flange	3:15	18
At A-flange	4:00	15
4.25 inches fwd of A-flange	4:15	12

7.3 Fan hub

The fan hub was intact. The fan blade retaining ring was in place. There were seven 10-ounce-inch clip-on counterweights on the counterweight flange under blade slots Nos. 10, 11, 12, 13, 14, 15 and 16. There was also a small counterweight riveted to the counterweight flange under blade slot No. 1. (Photo No. 35)

Photo No. 35: View of fan disk showing that it was intact.

7.4 Other fan blades

7.4.1 Maintenance records

The maintenance records showed that the following fan blades were installed in the engine. The examination of the installed fan blade showed that they matched the records. Refer to Table 5.

Table 5: List of installed fan blades

Blade Position	Part Number	Serial Number
1	55A801	CBDUAT7317
2	55A801	CBDUAO2847
3	55A801	CBDUAO0548
4	55A801	CBDUAT6356
5	55A801	CBDUAO0707
6	55A801	CBDUAT6556
7	55A801	CDDUAT6340
8	55A801	CBDUAY4261
9	55A801	CBDUAY2638
10	Fractured blade	CBDUAT7363
11	Fractured blade	CBDUAT7364
12	55A801	CBDUAY2213
13	55A801	CBDUAO1152
14	55A801	CBDUAU2392
15	55A801	CBDUAU2980
16	55A801	CBDUAU2395
17	55A801	CBDUAY1403
18	55A801	CBDUAT6351
19	55A801	CBDUAO0926
20	55A801	CBDUAY4294
21	55A801	CBDUAY2408
22	55A801	CBDUAY2509

7.4.2 Examination of fan blades

At the start of the engine examination at SFO, all of the fan blades were in place in the fan disk with the exception of fan blade Nos. 10 and 11 that had been removed from the engine at Honolulu and shipped to P&W, East Hartford, Connecticut for the metallurgical examination.[37] All of the remaining fan blades were full length. (Photo No. 36)

[37] While it was possible to have removed the other fan blades at HNL, those fan blades were left in the engine to maintain the engine's balance for when it was shipped to SFO.

Photo No. 36: View of other fan blades after that had been removed from the engine. (Boeing)

Fan blade No. 1 PN 55A801 SN CBDUAT7317

There were numerous scuff marks along the full length of the leading edge. The tip of the blade between about 5- and 17.5-inches from the leading edge was curled opposite the direction of rotation and was heat discolored. The leading edge tip corner had an approximately 1.5-inch radial by 2-inch axial section missing and the broken edge was curled opposite the direction of rotation. The trailing edge tip corner had an approximately 1.5-inch radial by 2-inch axial section missing. The convex side of the airfoil between about 4- and 16-inches from the tip had several buckled areas that corresponded to the internal gridwork.

Fan blade No. 2 PN 55A801 SN CBDUAO2847

There was an approximately 1-inch long tear in the tip about 0.5-inches back of the leading edge. There was an approximately 0.25-inch long nick on the leading edge about 5.5-inches inboard from the tip. The tip of the blade was curled opposite the direction of rotation and heat discolored from the trailing edge forward about 6-inches. The leading edge tip corner was curled opposite the direction of rotation.

Fan blade No. 3 PN 55A801 SN CBDUAO0548

There was an approximately 0.03-inch deep nick about 0.6-inches from the tip and an approximately 0.13-inch deep nick about 2-inches inboard from the tip. The tip of the blade was curled opposite the direction of rotation and heat discolored from the trailing edge forward about 6-inches.

Fan blade No. 4 PN 55A801 SN CBDUAT6356

There was an approximately 0.03-inch deep nick about 0.5-inches from the tip and an approximately 0.5- by 0.5-inch tear that was curled opposite the direction of rotation about 3.75-

inches from the tip. There was an approximately 0.75-inch tear on the trailing edge about 14.5-inches below the blade tip. The tip of the blade, between about 3- and 12-inches forward of the trailing edge was bent opposite the direction of rotation and was heat discolored.

Fan blade No. 5 PN 55A801 SN CBDUAO0707

The tip of the blade, between about 11.62-inches and 3-inches from the trailing edge was rubbed. The rub on the tip was about 0.25-inches deep between about 6.5- and 3-inches from the trailing edge and bent opposite the direction of rotation. The blade tip between about 3-inches from the trailing edge and the trailing edge was heat discolored.

Fan blade No. 6 PN 55A801 SN CBDUAT6556

The tip of the blade, between about 6- and 14.25-inches from the leading edge, was rubbed and was bent opposite the direction of rotation. The tip, between about 2.5-inches from the trailing edge and the trailing edge tip corner was heat discolored.

Fan blade No. 7 PN 55A801 SN CDDUAT6340

The tip of the blade between about 6.5- and 3.5-inches from the trailing edge was bent opposite the direction of rotation about 0.13-inches. The convex side of the airfoil was buckled about 3.25-inches down from the tip and about 5.5-inches forward of the trailing edge. The tip of the blade from the leading edge corner to about 2.25-inches aft of the leading edge was heat discolored and the corner was curled slightly in the direction of rotation. The leading edge tip corner was bent slightly in the direction of rotation. There was a scuff mark on the concave airfoil surface from the mid-chord area to about 3.5-inches at the trailing edge. There was an approximately 0.25-inch axial by 0.5-inch radial hole at the bottom of a dent in the mid-chord area in the scuffed area about 1.75-inch below the tip.

Fan blade No. 8 PN 55A801 SN CBDUAY4261

The leading edge tip corner, about 2.5-inches radial by about 2-inches axial was bent opposite the direction of rotation. The blade tip between about 5.5- and 8.5-inches aft from the leading edge was rubbed circumferentially about 0.13-inches deep. The blade tip was also bent opposite the direction of rotation about 0.13-inches between about 8.5- and 6.5-inches from the trailing edge. The convex side of the airfoil had three buckled areas in the center of the airfoil about 7.5-inches from the blade tip. The concave side of the airfoil had an approximately 3.5-inch long axial by 1-inch wide radial, 0.38-inch deep dent with a split along the upper edge about 1-inch below the tip and 6-inches aft of the leading edge. There was a bulge on the convex side of the airfoil that corresponded to the dent on the convex side.

Fan blade No. 9 PN 55A801 SN CBDUAY2638

The leading edge had an approximately 0.38-inch wide radial by 0.5-inch axial piece missing about 0.62-inches from the tip. The blade tip was bent about 0.13-inches opposite the direction of rotation between about 5.25- and 6-inches from the leading edge. The blade tip was rubbed circumferentially between about 8.5- and 17-inches from the leading edge, about 0.25-inches deep. The concave side of the airfoil from about 10-inches above the fairing to the blade tip had numerous scuff marks and dents.

Fan blade No. 10 PN 55A801 SN CBDUAT7363

Refer to Section 2.3

Fan blade No. 11 PN 55A801 SN CBDUAT7364

Refer to Section 2.2

Fan blade No. 12 PN 55A801 SN CBDUAY2213

The leading edge tip corner, about 2-inches axial by about 1.5-inches radial was bent opposite the direction of rotation. The blade tip, from about 7.25-inches forward of the trailing edge to the trailing edge tip corner was rubbed circumferentially and bent slightly opposite the direction of rotation. There was an approximately 0.75-inch wide radial by 0.87-inch long axial piece missing from the leading edge about 4.5-inches inboard from the tip. The convex side of the airfoil had several buckles about 5-inches from the tip and 5-inches from the trailing edge. The concave side of the airfoil had a 1-inch wide radial by 2.5-inch long axial scrape mark at the trailing edge about 3-inches from the tip. The concave side of the airfoil had several bands of axial scuff marks across the full chord of the blade.

Fan blade No. 13 PN 55A801 SN CBDUAO1152

The leading edge tip corner had an L-shaped section missing that was about 5-inches axial by 2.5-inches radial by about 1-inch wide with the fracture surface bent opposite the direction of rotation. At the aft end of the missing section, the internal cavity was exposed. The full length of the remaining part of the blade tip except from the aft approximately 3-inches was bent slightly opposite the direction of rotation and was heat discolored. There were several small nicks, up to about 0.25-inch by 0.25-inch, on the leading edge between about 3- and 4.25-inches from the blade tip. The convex surface of the airfoil had three buckles in the mid-chord area between about 6- and 7-inches from the blade tip. The concave side of the airfoil had axial scuff marks about 9-inches from the blade tip and about 14-inches from the fairing.

Fan blade No. 14 PN 55A801 SN CBDUAU2392

The leading edge tip corner, about 4-inches radial by 4.5-inches axial, was curled back opposite the direction of rotation. There was an approximately 1-inch wide radial by 1.5-inch deep axial piece and an approximately 1.25-inches wide radial by 0.5-inch deep axial piece missing from the leading edge about 1.75- and 3.5-inches from the tip, respectively. The center 10-inches of the blade tip was bent opposite the direction of rotation and was heat discolored. The aft end of the bent area of the blade tip was torn. The mid-chord area of the convex side of the airfoil from the blade tip down to about 14-inches from the blade tip was buckled in multiple places that showed the outline of the internal structure of the airfoil. The concave side of the airfoil, about 7-inches from the tip and 7-inches from the leading edge, had several buckles that showed the internal structure of the airfoil. There were two bands of axial scuff marks on the concave side of the airfoil about 7-inches from the blade tip and about 10-inches from the blade fairing.

Fan blade No. 15 PN 55A801 SN CBDUAU2980

The full length of the blade's tip was rubbed down to the scarf cut[38] fillet radius and was heat discolored. The convex side of the airfoil was buckled in the center of the airfoil about 7-inches below the blade tip that showed the outline of the internal structure. There was an 11-inch long axial crack in the convex side of the airfoil through the center of the buckles. The concave side of the airfoil had axial scuff marks about 10-inches below the blade tip and about 12-inches above the blade fairing.

Fan blade No. 16 PN 55A801 SN CBDUAU2395

The blade tip was rubbed circumferentially. The blade tip between about 5- and 9-inches from the leading edge was broken away adjacent to the tip fillet radius and the edge was heat discolored. The blade tip, between about 9- to 3- inches from the trailing edge was bent opposite the direction of rotation. The leading edge tip corner, about 5.5-inches axial and 4-inches radial, was bent opposite the direction of rotation. The corner of the leading edge tip, about 1.75-inches axial by 1.75-inches radial, was broken away. The center part of the convex side of the airfoil between 3- and 13-inches from the blade tip had multiple buckles that showed the internal structure of the blade. The leading edge had an approximately 0.25- by 0.25-inch heat discolored area about 17-inches above the fairing. On the concave side of the airfoil, there were two holes, about 1.5-inches axial by 0.75-inches radial and 1-inch axial by 0.5-inches radial, that were between about 5- and 7-inches forward of the trailing edge, respectively. There were axial scuff marks on the concave side of the airfoil about 10-inches from the blade tip and about 18-inches from the fairing.

Fan blade No. 17 PN 55A801 SN CBDUAY1403

The blade tip was rubbed circumferentially along the full length and was heat discolored. The tip between about 5- and 11-inches from the leading edge was broken away down to the innermost scarf cut fillet radius. The aft portion of the tip, between about 9- and 3.5-inches from the trailing edge, was bent opposite the direction of rotation. The leading edge had two nicks, about 0.13-inches and 0.25-inches deep, about 4- and 11.75-inches from the tip, respectively. The convex side of the airfoil was buckled in the mid-chord area about 7-inches below the tip. There was an approximately 2.5-inch long crack in the adjacent buckle. The concave side of the airfoil had an approximately 1-inch axial by 0.25-inches radial L-shaped cut about 7.5-inches forward of the trailing edge and a 0.13-inch diameter hole about 4.25-inches forward of the trailing edge.

[38] A scarf cut is a weight saving geometry at the tip of a compressor blade where the airfoil thickness has been locally thinned along the majority, or entire length of, the airfoil's tip chord.

Fan blade No. 18 PN 55A801 SN CBDUAT6351

The blade tip was rubbed circumferentially along the full length and was heat discolored. The tip, between about 5.25- and 11.25-inches from the leading edge, was missing down to the fillet radius. The remainder of the tip was bent opposite the direction of rotation. The leading edge tip corner, about 4.5-inches radial and 5-inches axial, was bent opposite the direction of rotation. There were four nicks up to about 0.25-inches long radial and 0.13-inches deep axial, on the leading edge between about 2- and 9-inches from the blade tip. There was an approximately 1-inch long radial by 0.38-inch deep axial piece missing from the leading edge about 12.5-inches from the blade tip. There were two heat discolored areas, about 0.5-inches long radial by 0.25-inches wide axial about 15- and 21.75-inches from the blade tip. The blade's trailing edge had an approximately 0.5-inch wide about 1.5-inches from the blade tip that was bent opposite the direction of rotation. The convex side of the airfoil had several buckles in the mid-chord area about 7-inches below the blade tip. One of the buckled areas had an approximately 3-inch long crack. There was an approximately 7-inch long transverse cut centered about 6.25-inches from the trailing edge into the concave side and through the airfoil into the convex side. The concave side of the airfoil had axial scuff marks from about 23-inches below the blade tip out to the blade tip.

Fan blade No. 19 PN 55A801 SN CBDUAO0926

The blade tip had almost the full length of the tip missing down to the innermost scarf cut fillet radius. The aft 3-inches of the tip between about 6.5- and 3.5-inches from the trailing edge remained and it was bent opposite the direction of rotation. The full length of the blade tip was heat discolored. The leading edge tip corner, about 6-inches axial by 3.5-inches radial was bent opposite the direction of rotation. There was an approximately 1-inch by 1-inch section of the leading edge tip corner missing and there was an approximately 2-inch long axial by 1-inch wide radial section that was torn and bent opposite the direction of rotation. There was an approximately 0.38-inch deep axial by 0.25-inch wide radial piece missing from the leading edge about 5.5-inches below the blade tip. The leading edge had an approximately 0.75-inch long radial by 0.25-inch wide axial area that was heat discolored that was about 16.25-inches below the blade tip. The convex side of the airfoil was buckled in the mid-chord area about 8-inches below the blade tip. There was an approximately 12-inch long transverse crack through the buckles and an approximately 0.75-inch long axial by 0.5-inch wide radial hole in the center of the crack. The concave side of the airfoil had an approximately 2.5-inch long axial by 1-inch wide radial hole that was centered about 1-inch below the blade tip and 6-inches forward of the trailing edge. The hole went through from the concave side to the convex side of the airfoil. There were axial scuff marks on the concave side of the airfoil between about 11- and 20-inches below the blade tip.

Fan blade No. 20 PN 55A801 SN CBDUAY4294

The blade had only an approximately 4-inch long section of the tip at the trailing edge corner remaining. The remainder of the blade's tip was completely missing exposing the hollow core interior. There was an approximately 4-inch long radial by 2-inch wide axial section of the leading edge tip corner that was bent opposite the direction of rotation. There was an approximately 4-inch by 4-inch section of the trailing edge tip corner that was bent opposite the direction of rotation. The leading edge had an approximately 0.06- by 0.06-inch nick and an approximately 0.25-inch deep axial by 0.13-inch wide radial section missing about 3.25- and 3.5-inches below the blade tip, respectively. The convex side of the airfoil had several buckles between about 3- and 7-inches below the blade tip. There were small cracks in two of the buckled areas. The concave side of the airfoil had several axial scuff marks between about 12- and 18-inches from the blade tip.

Fan blade No. 21 PN 55A801 SN CBDUAY2408

The blade tip was rubbed circumferentially along its full length and was heat discolored. The tip was rubbed down to the innermost scarf cut fillet radius for almost the full length except for approximately 4-inches between about 7.5- and 3.5-inches from the trailing edge. The leading edge tip corner, about 4-inches radial by 5-inches axial, was bent opposite the direction of rotation. The blade tip had an approximately 1.75-inches long radial crack about 6-inches aft of the leading edge. There were parallel axial cracks of 1.75- and 3-inches and 1.5- and 1.5-inches long extending from the radial crack in the forward and aft directions that were about 1- and 2-inches below the blade tip, respectively. The convex side of the airfoil was buckled between about 3- and 13-inches below the blade tip.

Fan blade No. 22 PN 55A801 SN CBDUAY2509

The blade tip was rubbed circumferentially along its full length and was heat discolored. The tip was rubbed down to the innermost scarf cut fillet radius except for the aft approximately 1.5-inches between about 4.25- and 2.75-inches forward of the trailing edge. The leading edge tip corner, about 3.5-inches radial by 4-inches axial was bent opposite the direction of rotation. The forward part of the blade tip between the tip corner and the fillet radius had transferred material on the concave side of the airfoil. The convex side of the airfoil in the mid-chord area had several buckles between about 2- and 9-inches below the blade tip. The trailing edge had an approximately 0.38-inch long radial by 0.06-inch deep axial piece missing about 16-inches from the blade tip. There were axial scuff marks on the concave side of the airfoil about 23-inches from the blade tip.

7.4.3 Fragments

During the disassembly and examination of the fan case, seven fan blade fragments of various sizes were recovered. The largest of these fragments measured approximately 7-inches in length by 1.75-inches in width at its widest point. This fragment was of a size and shape consistent with the missing portion of the tip of fan blade No. 20.

7.4.4 TAI reinspection

As part of the investigation, all of the fan blades with the exception of No. 11 were reinspected with the TAI inspection process. None of the blades had any TAI indications that were rejectable.

7.5 Intermediate case

The fan exit case rear outer diameter had circumferential cracks radiating from the strut mount pads.

The fan exit guide vanes were all in place except for one vane at about 1 o'clock and three consecutive vanes at about 4 o'clock. There was one exit vane adjacent to the three that were missing that was separated at the inner end, but remained attached at the outer end. (Photo No. 37) Between about 3:30 and 5 o'clock, the inner ends of the fan exit guide vanes were displaced rearward. (Photo No. 38)

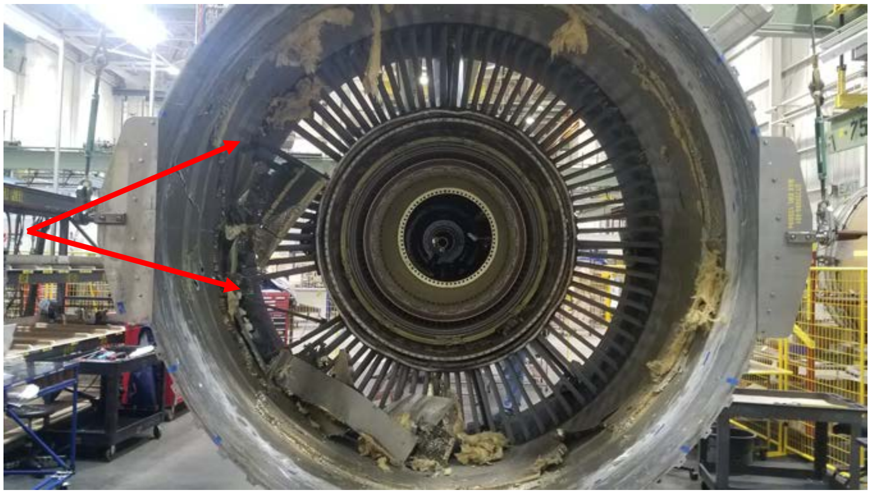

Photo No. 37: View of front of fan exit guide vanes showing locations of missing vanes. (Boeing)

Photo No. 38: Close up view of inboard ends of fan exit guide vanes displaced rearward. (P&W)

7.6 Low pressure compressor

The LPC inlet guide vanes were all in place and undamaged. The splitter fairing was in place and did not have any damage.

The LPC drum was intact. (Photo No. 39)

Photo No. 39: View of LPC drum showing that it is intact.

The LPC was not disassembled. All of the stage 1.1 compressor blades, which were visible from the front of the LPC spool, and all of the 4th stage compressor blades, which were visible from the rear of the LPC spool, were in place in their respective blade slots. The stage 1.1, the visible 3rd stage compressor blades, and the 4th stage compressor blades had nicks, dents, and/or tears on the leading edges. The 3rd stage compressor stator vanes had damage to the airfoils with the trailing edges curled in the direction of rotation. There were several stage 1.1 and 4th stage compressor blades that were bent opposite the direction of rotation. (Photos Nos. 40 and 41) There was an approximately 120° arc of 4th stage compressor blades that had circumferential rub marks on the rear face of the blade roots and on the rear face of the blade retaining lugs. The blade roots and blade retaining lugs in the center of the rubbed area were heat discolored. (Photo No. 42)

Photo No. 40: Close up of 3rd and 4th stage compressor blades and 3rd stage compressor vanes showing damage to the airfoils.

Photo No. 41: Close up of 4th stage LPC blades that were bent opposite the direction of rotation.

Photo No. 42: Close up of rub mark with heat discoloration on rear of LPC drum and 4th stage compressor blade roots.

7.7 High pressure compressor

The HPC was not disassembled. However, a borescope inspection of the HPC at HNL revealed the HPC blades were in place. The blade tips at the forward part of the HPC had tip rub with material displaced opposite the direction of rotation. There were many blades that had cuts, nicks, and dents on the leading edges. The 5th to the 13th stage compressor blades had metal spray material on the convex airfoil surface adjacent to the trailing edge. The damage and amount of metal spray appeared to diminish downstream.

7.8 Diffuser/combustor

The diffuser/combustor was not disassembled.

7.9 High pressure turbine

The HPT was not disassembled. The 2nd stage turbine disk was intact and all of the 2nd stage turbine blades were in place in the disk. The 2nd stage turbine blades had numerous nicks and dents on the airfoils. The blades' airfoils had a dark coating on the leading edge and convex surface.

7.10 Low pressure turbine

The LPT drive shaft was intact. The LPT shaft had several circumferential rub marks. There was an approximately 0.5- by 0.5-inch rub mark that was just aft of the balance section. There was an intermittent rub mark that was approximately 0.75-inches wide and 0.75-, 0.5-, and 1.5-inches long and an approximately 0.6-inch wide by 4-inch long rub mark. (Photo No. 43)

Photo No. 43: View of LPT shaft showing circumferential rub marks. (P&W)

The LPT was not disassembled. The 3rd stage turbine vanes and blades were all in place and were full length. The 3rd stage turbine vanes had metal spatter spots on the airfoils. The 9th stage turbine blades were all in place and were full length. The 9th stage turbine blade airfoils did not have any apparent damage. (Refer to Photo No. 44) The 9th stage turbine vanes were all in place, but some of the turbine vane airfoils had impact marks and metal spatter on the convex surface of the airfoils. There were small metal fragments in the tailpipe.

7.11 Exhaust

The turbine exhaust case was in place on the LPT case. The turbine exhaust case strut at about 11:30 o'clock was buckled at about 6.25-inches from the outer diameter. The trailing edge was cracked at the location of the buckle. The crack did not extend past the trailing edge radius. There was a crack on the strut's leading edge about 8-inches from the outer diameter that was about 1.75-inches long on the convex side and about 3.5-inches on the concave side. (Photos Nos. 44 and 45)

Photo No. 44: View of buckled turbine exhaust case strut. Also shown are the 9th stage turbine blades showing that they are all intact.(P&W)

Photo No. 45: Close up of buckled turbine exhaust case strut showing leading and trailing edge cracks. (P&W)

7.12 Gearbox

The gearbox was in place. The engine gearbox attachment flange located at the top dead center of the gearbox was damaged with all seven mating bolts fractured. (Photo No. 46) The bracket located at 6 o'clock on the HPC case to which the front gearbox linkages attach to was fractured. The forward side of the gearbox had a crack at the layshaft drive pad. (Photo No. 47)

Photo No. 46: View of the engine gearbox attachment flange showing all seven mating bolts fractured. (P&W)

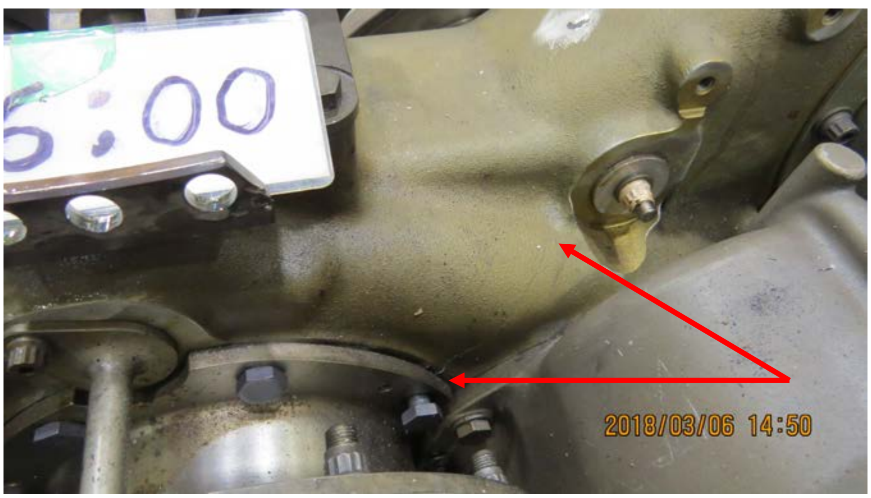

Photo No. 47: Close up showing crack on front of gearbox from lay shaft drive pad. (P&W)

7.13 Bearings and oil system

The Nos. 1, 1 1/2, and 2 bearing compartment was wet with oil, but was a black color. The bearing compartment did not have an acrid odor. (Photo No. 48)

Photo No. 48: Interior of Nos. 1, 1 1/2, and 2 bearing compartment showing black color.

The Nos. 1 and 1 1/2 bearings were intact, wet with oil, and did not have any apparent rotational damage on the rolling elements. (Photos Nos. 49 and 50) The respective bearing supports did not have any apparent damage.

Photo No. 49: Close up of No. 1 bearing balls showing they are wet with oil and have no visible rotational distress.

Photo No. 50: View of No. 1 1/2 bearing showing that it is wet with oil and did not have any rotational distress. (P&W)

The engine was not disassembled sufficiently to expose the other bearings.

The magnetic chip detectors in the oil tank, the main and accessory gearboxes, and the lube and scavenge pump were removed for inspection. (Photo No. 51)

Main oil tank	A few small metal chips
Main gearbox	A few small metal chips
No. 3 bearing	Very fine metal chips
No. 4 bearing	Clean
Accessory gearbox	Clean
No. 1 bearing	1 metal sliver and a few small metal chips

Photo No. 51: View of magnetic chip detectors. (P&W)

7.14 Engine mounts

The engine mounts and mount bolts did not have any apparent damage. (Photos Nos. 52, 53, and 54) The engine mounts and mount bolts were removed from the airplane and engine and underwent an FPI. It was reported that there were no cracks or defects noted during the inspection.

Photo No. 52: View of forward engine mount. (P&W)

Photo No. 53: View of aft engine mount. (P&W)


Photo No. 54: View of aft engine mount bolts. (Boeing)

8.0 Airplane

8.1 Airplane description

The Boeing 777 is a long-range, wide-body, twin-engine airplane.[39] The Boeing 777-200 series is about 209 feet long with a wing span of about 200 feet. (Figure 3) It has a maximum takeoff weight of 545,000 pounds. According to the FAA's Type Certificate Data Sheet No. T00001SE, the Boeing 777-200 series can be powered by the General Electric GE90-76B, GE90-85B, GE90-90B, and GE90-94B[40] turbofan engines; P&W PW4074, PW4074D, PW4077,

[39] The Boeing 777F is a freighter version of the airplane
[40] According to the FAA Type Certificate Data Sheet No. E00049EN, those model GE90 engines have a takeoff thrust rating ranging between 81,070 and 97,300 pounds of thrust.

PW4077D, PW4090, PW4084D, and PW4090-3[41] turbofan engines; and Rolls-Royce RB211-Trent 875-17, RB211-Trent 877-17, RB211-884-17, RB211-Trent 892-17, and RB211-Trent 895-17[42] turbofan engines. Other models of the Boeing 777 such as the -200ER, -200LR, -300, and the -300ER, can be over 242 feet long, have a wingspan of over 217 feet, and have a maximum takeoff weight of up to 775,000 pounds.

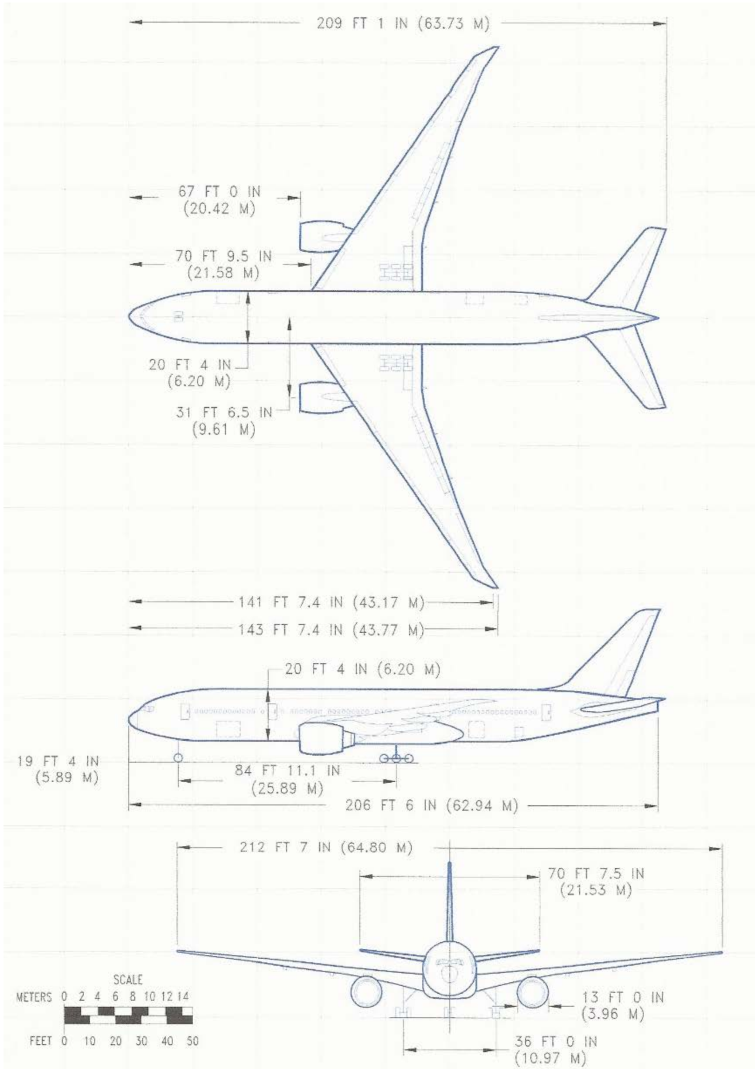

Figure 3: Boeing 777-200 airplane general dimensions. (Boeing)

[41] According to the FAA's Type Certificate Data Sheet No. E46NE, those model PW4000 112-inch engines have a takeoff thrust rating ranging between 77,740 to 91,740 pounds of thrust.
[42] According to the FAA's Type Certificate Data Sheet No. 00075EN, those model RB211-Trent engines have a takeoff thrust rating ranging between 77,750 and 94,320 pounds of thrust.

8.2 Airplane history

The airplane, manufacturer's SN 26929 and line number 4, flew for the first time on October 28, 1994. The airplane was delivered to United on January 31, 1996.[43] According to United Airlines' records, at the time of the incident, the airplane, had accumulated 89,723 hours and 16,339 cycles since new.

8.3 Cockpit

The examination of the cockpit revealed the No. 2 engine's fire handle was pulled. (Photo No. 55)

Photo No. 55: View of center console showing right engine's fire handle pulled up.

8.4 Fuselage

8.4.1 Damage to fuselage

There was an approximate 2-inch by 3-inch by 0.15-inch deep dent that had an approximate 0.25-inch long crack that was located at about BSTA [body station] 730 and between stringers Nos. 33R and 34R. (Photo No. 56) This damaged piece of skin was cut out of

[43] Between October 28, 1994, the date of the airplane's first flight and January 31, 1996, when the airplane was delivered to United Airlines, the airplane was used extensively in the flight test program for interior noise testing and the 1,000 cycle ETOPS (Extended-range Operational Performance Standard) certification test with both Boeing and United flight crews at the controls.

the fuselage and sent to the NTSB Materials Laboratory for examination. (Refer to Section 8.4.2)

Photo No. 56: View of dent and crack in fuselage skin at BSTA 730. (P&W)

There was approximate 2.5-inch by 3-inch dent with an approximately 0.25-inch diameter puncture that was located at BSTA 913 and the stringer No. 24R lap joint. (Photo No. 57) The cabin's interior sidewall panels were removed from the area of seat rows 20 and 21, BSTA 908 to 928, to document the inner surfaces of the dent and to determine if the skin was punctured. The skin was dented inwards at a skin lap joint under an extruded zee stringer. The zee stringer was cracked about 17-inches longitudinally, and there was a small puncture that was visible in the underlying skin. (Photos Nos. 58 and 59) This damaged piece of skin was also cut out of the fuselage and sent to the NTSB Materials Laboratory for examination. (Refer to Section 8.4.2)

Photo No. 57: View of gouge in fuselage skin at BSTA 913. (P&W)

Photo No. 58: View of top of bent and cracked zee stringer at BSTA 913. (P&W)

Photo No. 59: View of underside of bent and cracked zee stringer at BSTA 913. (P&W)

There was an approximately 1-inch by 3-inch by 0.15-inch deep dent that was located at about BSTA 928 and stringer 25R.

The right main landing gear door had two gouge marks that were about 1-inch by 2-inches long, located in the middle of the door. The gouges penetrated the outer skin, but did not penetrate the inner skin.

8.4.2 Metallurgy

The two pieces of the skin from BSTA 730 between stringers Nos. 33R and 34R and BSTA 913 and stringer No. 24R that were excised from the fuselage were returned to the NTSB's Materials Laboratory for metallurgical examination. The pieces were examined with a field emission (FE) scanning electron microscope (SEM) that had the capability of energy dispersive x-ray spectroscopy (EDS). Both pieces had multiple gouges and embedded particles in their surfaces. The appearance of the embedded particles was different from the fuselage skin when viewed using the backscattered electron imaging. The EDS of the embedded particles produced a spectrum that was rich in titanium and vanadium and to a lesser extent aluminum.

For further details, refer to Materials Laboratory Factual Report No. 18-031, dated April 11, 2018.

8.5 Wing

The first slat outboard of the right engine had an approximately 6-inch by 6-inch by 0.25-inch dent on the leading edge. The dent was located about 18-inches from the inboard end of the slat. (Photo No. 60)

Photo No. 60: Dent in leading edge slat outboard of right engine. (P&W)

The inboard flap's outboard flap track canoe fairing had an approximately 12-inch long gouge on the fixed leading edge nose. (Photo No. 61)

Photo No. 61: Gouge in the inboard flap's outboard flap track canoe fairing. (Boeing)

The right hand flaperon lower skin outboard trailing edge had an approximately 12-inch long shallow dent with multiple cracks.

There were small scratches and scrapes on the right wing's lower skin. There were a few of the scrapes that went through the paint down to the bare metal.

The right wing's landing light fairing had an approximately 1-inch by 3-inch by 0.20-inch dent near the outboard edge. Just outboard of the landing light, the lower fixed leading edge panel, which was identified as 611AB, had an approximately 1-inch by 5-inch puncture in the outer fiberglass honeycomb skin. The inner skin was not punctured.

8.6 Empennage

The right-hand horizontal stabilizer had a shallow dent that was approximately 3-inch by 4-inch by 0.1-inch deep on the fixed leading about 6-inches outboard of the third production splice.

8.7 Cabin

In row 46, there was an overhead panel that contained the oxygen cannisters that was open. In row 47, there was a passenger service unit door open with six oxygen masks that had dropped down.

9.0 Airline information

9.1 Air Carrier Certificates

United Airlines, Inc., is headquartered at 233 South Wacker Drive, Chicago, Illinois 60606. United Airlines operating certificate, Certificate No. CALA014A, was issued on July 11, 1938. It was last amended by the FAA, Great Lakes Region on March 31, 2013.

United Airlines' Repair Station Certificate, Certificate No. UALR011A was issued on July 1, 1953 to United Airlines, San Francisco International Airport, San Francisco, California 94128 with the following ratings: Airframe, Radio Instrument Accessory, Powerplant, and Limited Non-Destructive Inspection/Testing.

9.2 Operations Specifications

United Airlines has a Part 121 certificate. Parts D and E of the certificate that included the standards, terms, conditions, and limitations contained in the FAA-approved Operations Specifications[44] (OpSpecs) were reviewed.

(a) The air carrier was authorized as a 14 CFR Part 121 operator.

(b) Per section D072 of the OpSpecs, the Continuous Airworthiness Maintenance Program (CAMP) authorized United Airlines to use the manufacturer/United Airlines maintenance and engine maintenance programs to maintain the airplanes.

(c) Per section D074 of the OpSpecs, United Airlines was authorized to use the provisions of a maintenance reliability program on their fleet.

(d) Per section D083 of the OpSpecs, United Airlines was authorized to use short-term escalations of maintenance intervals on their fleet.

(e) Per section D085 of the OpSpecs, United Airlines had the following airplanes in its fleet: Airbus A319 – 67, Airbus A320 – 99, Boeing 737 – 329, Boeing 747 – 13; Boeing 757 – 77, Boeing 767 – 51, Boeing 777 – 88, and Boeing 787 – 36.

(f) Per section D086 of the OpSpecs, United Airlines has a Maintenance Program Authorization for Two-Engine airplanes used in Extended-Range Operation.

(g) Per section D090 of the OpSpecs, United Airlines was authorized to use CASE[45] as a means of qualifying a vendor for services, parts, and materials to satisfy the requirements of 14 CFR Section 121.373.[46]

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[44] Operations Specifications contain the authorizations, limitations, and certain procedures under which each kind of operation, if applicable, is to be conducted by the certificate holder.

(h) Per section D091 of the OpSpecs, United Airlines was authorized to make arrangements with other organizations to perform substantial maintenance.

(i) Per section D095 of the OpSpecs, United Airlines was authorized to use an approved Minimum Equipment List (MEL).

(j) Per section D097 of the OpSpecs, United Airlines had an Aging Aircraft Program.

(k) Per section D096 of the OpSpecs, United Airlines was authorized for a Weight and Balance Program.

United Airlines has a Part 145 Certificate that included the standards, terms, conditions, and limitations contained in the FAA-approved Operations Specifications for the Repair Station.

(a) Per section D100 of the OpSpecs, United Airlines was authorized to perform work at a place other than the repair station's fixed locations.

(b) Per section D107 of the OpSpecs, United Airlines was authorized for Line Maintenance Authorization.

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[45] The Air Carrier section of the non-profit Coordinating Agency for Supplier Evaluations (CASE) was organized as a means of sharing non-prejudicial supplier quality approval data among the member airlines. This increases the surveillance coverage of suppliers and thereby upgrades their quality programs. It also has an economic impact on each CASE member by decreasing the cost of supplier surveillance and making their surveillance programs more effective.

[46] 14 CFR Section 121.373(a) states: Each certificate holder shall establish and maintain a system for the continuing analysis and surveillance of the performance and effectiveness of its inspection program and the program covering other maintenance, preventative maintenance, and alterations and for the correction of any deficiency in those programs, regardless of whether those programs are carried out by the certificate holder, or by another person.

ATTACHMENTS

1. P&W Materials & Process Engineering Metallurgical Investigation Final Report Metallurgical Investigation of Fan Blades No. 11 and No. 10 from PW4077 Engine 777049, dated October 9, 2018

2. FAA Form 8130-3, Airworthiness Approval Tag, April 2010

3. FAA Form 8130-3, Airworthiness Approval Tag, August 2015

4. UAL flight 1175's Captain's written statement

5. UAL flight 1175's first officer's written statement

6. UAL flight 1175's jump seat rider's written statement

7. UAL flight 1175's flight attendants' written statements