Aviation Investigation Final Report

Location:	Broomfield, Colorado	**Incident Number:**	DCA21FA085
Date & Time:	February 20, 2021, 13:09 Local	**Registration:**	N772UA
Aircraft:	Boeing 777-222	**Aircraft Damage:**	Minor
Defining Event:	Powerplant sys/comp malf/fail	**Injuries:**	239 None
Flight Conducted Under:	Part 121: Air carrier - Scheduled		

Analysis

United Airlines flight 328 was climbing through 12,500 ft mean sea level about 5 minutes after departure from Denver International Airport (DEN), Denver, Colorado, when the right engine, a Pratt & Whitney PW4077, sustained a full-length fan blade separation, or fan blade out (FBO) event. This resulted in the subsequent separation of the engine inlet lip skin, fan cowl support beam, and components of the inlet, fan cowls, and thrust reversers (TRs), as well as an engine fire. The flight crew declared an emergency and landed the airplane without incident at the departure airport about 24 minutes after takeoff. There were no injuries to the passengers or crew, and no ground injuries due to debris; however, a vehicle and a residence sustained damage when impacted by the inlet lip skin and fan cowl support beam, respectively.

Fan Blade Impact Damage

Examination of the engine revealed that the separated fan blade and other fan debris impacted the fan case, which successfully contained the fan blade fragments. Damage to the nacelle inner and outer barrels was observed, and a postaccident evaluation indicated that the displacement wave of the impact resulted in a deflection of the fan case and contact with the nacelle doors and hinges, which subsequently resulted in the failure of the inlet aft bulkhead and the fan cowl support beam. The failure of the bulkhead, along with the damage to the inner and outer barrels, allowed these structures, as well as the inlet lip skin, to separate from the engine.

Following the separation of the inlet, air loads resulted in the separation of the fan cowls and the fan cowl support beam. Simulation studies indicated that the carbon fiber reinforced plastic (CFRP) honeycomb structure of the event engine inlet and inlet aft bulkhead was unable to dissipate and redistribute the energy of the loads imposed by the FBO event in the same manner as the aluminum structure inlet that was used during certification tests.

Separation of the inlet and fan cowls due to an FBO event is not allowed under certification standards, and following this event, Boeing developed modifications to the inlet to ensure that inlets and fan cowls remain in place during an FBO event that may damage the aft bulkhead, inner barrel, or outer barrel and modifications to add strength and ductility to the inlet by incorporating additional metallic structure. Boeing also developed procedures for inspection and repair for moisture ingression damage to the fan cowls, which can degrade the strength of the cowls. These modifications were subsequently mandated by Federal Aviation Administration (FAA) Airworthiness Directives (AD) 2022-06-10 and 2022-06-11, effective April 15, 2022. Additional modifications are expected to the fan cowl.

This event was the fourth in-service FBO event due to fatigue cracking recorded for PW4000-powered 777 airplanes and resulted in the most nacelle damage of the four events. In the first event in 2010, approximately 50 percent of the blade airfoil was released. Full-span separations occurred in 2018, 2021, and during this event.

Engine Fire Propagation

Seconds after the FBO event, the flight crew received a right engine fire warning. The crew completed the engine fire checklist, which included activating the fire switch and discharging both engine fire extinguishing bottles; however, the fire was not arrested and continued to propagate through the engine for the remainder of the flight due to damage the engine sustained during the fan blade out event. Although the cockpit fire warning light extinguished shortly before landing, this was likely the result of thermal damage to the engine fire detection system.

The engine fire propagated as the result of several cascading failures following the FBO event. The engine core was subjected to high dynamic loads due to the energy of the initial blade release; the fan blade rubbing against the case, which created rotating torsion loads through the engine core structure; and the continued fan shaft imbalance during the engine run-down, which created rotating bending loads through the core structure. The loading associated with the high dynamic activity of the attached main gearbox (MGB) ultimately resulted in the failure of the “K” flange bolts that attached the MGB to the engine. The remaining “K” flange bolts then fractured, resulting in the total separation of the “K” flange, which allowed hot, compressed gases to escape the engine core and provided an ignition source in the engine nacelle.

As the “K” flange was part of the MGB support structure, the failure of the flange also allowed the MGB to rotate and the MGB-mounted servo fuel heater to contact the engine core-mounted fuel oil cooler. As a result of this contact, a high-pressure fuel cavity within the servo fuel heater was fractured open, releasing high-pressure fuel into the nacelle, where it was ignited by the hot, compressed gases that escaped through the “K” flange separation.

Pratt & Whitney is evaluating actions to improve the strength of the “K” flange and expects hardware to be available in 2025.

The fire spread to the TR lower bifurcation area, burned away the support structure for the nacelle drain access door, and exited the lower aft TR area. The undercowl fire melted the aluminum latch beams at the lower end of each TR and through the TR inner wall and translating sleeves. One of the last components to separate from the airplane was a section of the outboard TR translating sleeve, which was located about 30 miles southeast of the debris associated with the initial FBO event. The burn-through of the TR lower bifurcation area likely occurred within about six to nine minutes of the initial FBO event, though certification standards required that materials in this area withstand fire for a minimum of 15 minutes.

Examination of the engine's fire suppression system revealed that the engine driven hydraulic pump supply shutoff valve failed to close as designed upon the crew's activation of the engine fire handle due to silicone lubricant contamination of electrical contact components in the valve's DC motor. The failure of the valve to close allowed a limited amount of hydraulic fluid to leak into the engine compartment and feed the undercowl fire.

FAA AD 2022-06-10 and 2022-06-11 required installation of debris shields on the TR inner wall lower bifurcation area, as well as repeated functional checks of the engine driven hydraulic pump supply shutoff valves to ensure proper operation in response to fire switch activation.

Fan Blade Fatigue Failure and Inspection Process

The separated fan blade was fractured transversely across the chord of the airfoil near the fan hub fairing as the result of a fatigue crack, which originated at the surface of an internal radius in a hollow cavity within the blade. The event blade had accumulated 2,979 cycles since overhaul; at the time of the event, overhaul inspection was required every 6,500 cycles. As part of the overhaul, blades were inspected for both external and internal cracks using a proprietary thermal acoustic imaging (TAI) process.

The most recent TAI inspection of the event fan blade occurred about five years before the event, in 2016. Inspection imagery revealed multiple low-level indications, two of which were in the fatigue crack origin area, that were reviewed further and interpreted as being generated by camera sensor noise or loose contamination within the cavity. Given the observed indications and the inspection criteria in place at the time, the blade should have received a second TAI inspection, or the images should have undergone a team review; however, there was no record that either of these occurred, and the blade was approved for continued service.

Following an FBO event in 2018 involving another PW4077 engine, the data from the 2016 inspection of the blade involved in this event were reviewed again; once more, the indications were not identified as anomalous and the blade continued in service. Two of the low-level indications identified during the 2016 TAI inspection were likely associated with the fatigue crack that grew to result in the blade failure.

The accident blade had accumulated 15,262 cycles since new, which was less than one quarter of the expected life for a nominal blade, and only 2,979 cycles since its last overhaul, less than half the prescribed inspection interval at the time. Metallurgical examination identified two conditions which contributed to the reduced fatigue life of the accident blade: a surface carbon contamination; and a geometric discontinuity that occurred during manufacturing. In assessing fatigue life of this blade relative to the nominal expectation, the reduced fatigue capability from the surface carbon contamination accounted for approximately 2/3 of the difference, and the increased stress from the geometric discontinuity accounted for approximately 1/3 of the difference.

Following this event, Pratt & Whitney performed an immediate TAI inspection of the entire fleet before the next flight and issued a service bulletin introducing ultrasonic testing (UT) blade inspections to occur both immediately and at regular intervals. Additionally, the frequency of required TAI inspections was increased from every 6,500 cycles to every 1,000 cycles. The increased inspection interval and the immediate TAI inspection were made mandatory on April 15, 2022, when the FAA issued AD 2022-06-09. Additionally, the new UT inspection that was developed by Pratt & Whitney for the flowpath and midspan areas has shown a capability to detect small cracks that are below the threshold of detectability for the TAI inspection. The blades are now inspected by UT every 275 cycles.

Examination of the crack in this event and previous fan blades failure events have shown the growth rates of the fatigue crack, from detectable size to full-wall penetration, are relatively stable and predictable in each case, since the sources for premature fatigue initiation are surface related and do not have a significant impact on growth through the thickness of the blade. The increased TAI inspection interval and the new UT inspections should provide multiple opportunities to detect cracks in the high-stress areas.

Probable Cause and Findings

The National Transportation Safety Board determines the probable cause(s) of this incident to be:

The fatigue failure of the right engine fan blade. Contributing to the fan blade failure was the inadequate inspection of the blades, which failed to identify low-level indications of cracking, and the insufficient frequency of the manufacturer’s inspection intervals, which permitted the low-level crack indications to propagate undetected and ultimately resulted in the fatigue failure. Contributing to the severity of the engine damage following the fan blade failure was the design and testing of the engine inlet, which failed to ensure that the inlet could adequately dissipate the energy of, and therefore limit further damage from, an in-flight fan blade out event. Contributing to the severity of the engine fire was the failure of the “K” flange following the fan blade out, which allowed hot ignition gases to enter the nacelle and imparted damage to several components that fed flammable fluids to the nacelle, which allowed the fire to propagate past the undercowl area and into the thrust reversers, where it could not be extinguished.

Findings

Aircraft	Compressor section - Fatigue/wear/corrosion
Aircraft	Compressor section - Failure
Aircraft	Scheduled maint checks - Inadequate inspection
Organizational issues	Equipment design - Manufacturer

Factual Information

History of Flight

Initial climb	Powerplant sys/comp malf/fail (Defining event)

On February 20, 2021, about 1309 mountain standard time, a Boeing 777-222, N772UA, operated by United Airlines (UAL) as flight 328, experienced a right engine fan blade separation and subsequent engine fire shortly after takeoff from Denver International Airport (DEN), Denver, Colorado. The two pilots, eight crew members, and 229 passengers onboard were not injured. The airplane was operated as a Title 14 *Code of Federal Regulations* Part 121 scheduled passenger flight.

The airplane departed DEN about 1304 enroute to Daniel K. Inouye International Airport (HNL), Honolulu, Hawaii. The captain was the pilot flying, and the first officer was the pilot monitoring. The pilots reported that preflight weather forecasts indicated moderate turbulence from about 13,000 ft mean sea level (msl) to 23,000 ft msl, and as the airplane climbed through about 12,500 ft msl at an airspeed about 280 knots (kts), they increased engine power in order to minimize the time spent climbing through the altitudes where turbulence was forecast. About 5 to 7 seconds after advancing the throttles, the cockpit voice recorder (CVR) captured a loud “bang,” and the flight data recorder (FDR) showed an uncommanded shutdown of the No. 2 (right) engine. Shortly thereafter, an engine fire warning activated on the engine indicating and crew alerting system (EICAS).

The flight crew declared an emergency with air traffic control (ATC) and completed multiple checklists, including the engine fire checklist. As part of the engine fire checklist, the crew discharged both right engine fire extinguishing bottles; however, the engine fire warning continued to display on the EICAS until shortly before landing. The crew landed the airplane on runway 26 at DEN at 1328 and the airplane was met by aircraft rescue and firefighting (ARFF), which applied water and foaming agent to the right engine for about 40 minutes. The airplane was then towed off the runway, where the passengers disembarked via air stairs and were bussed to the terminal. Figure 1 below, a still image captured from in-flight video recorded by a passenger, shows the damage to the engine nacelle as well as the under-cowl fire about 11 minutes after the fan blade separation.

Figure 1. Still image from passenger in-flight video showing engine nacelle damage and under-cowl fire about 11 minutes after fan blade separation (Courtesy Boeing via YouTube).

At the time of the event, the airplane was over Broomfield, Colorado; multiple pieces of the engine inlet, fan cowls, and thrust reversers separated from the airplane and were found scattered over an area of about 40 acres, including a public park and residential areas. There were no ground injuries reported.

Pilot Information

Certificate:	Airline transport; Commercial; Flight engineer; Flight instructor	**Age:**	60,Male
Airplane Rating(s):	Single-engine land; Multi-engine land	**Seat Occupied:**	Left
Other Aircraft Rating(s):	None	**Restraint Used:**	5-point
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	Airplane multi-engine; Airplane single-engine; Instrument airplane	**Toxicology Performed:**	
Medical Certification:	Class 1 Without waivers/limitations	**Last FAA Medical Exam:**	February 23, 2021
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	February 5, 2021
Flight Time:	28062 hours (Total, all aircraft), 538 hours (Total, this make and model), 24278 hours (Pilot In Command, all aircraft), 155 hours (Last 90 days, all aircraft), 113 hours (Last 30 days, all aircraft)		

Co-pilot Information

Certificate:	Airline transport; Commercial; Flight instructor	**Age:**	53,Male
Airplane Rating(s):	Single-engine land; Multi-engine land	**Seat Occupied:**	Right
Other Aircraft Rating(s):	None	**Restraint Used:**	5-point
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	Airplane multi-engine; Airplane single-engine	**Toxicology Performed:**	
Medical Certification:	Class 1 With waivers/limitations	**Last FAA Medical Exam:**	June 4, 2020
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	November 28, 2020
Flight Time:	18612 hours (Total, all aircraft), 4190 hours (Total, this make and model), 2400 hours (Pilot In Command, all aircraft), 166 hours (Last 90 days, all aircraft), 21 hours (Last 30 days, all aircraft), 2 hours (Last 24 hours, all aircraft)		

Captain

The captain, age 60, held an airline transport pilot certificate with a rating for airplane multiengine land and multiple type ratings, including the B-777. His most recent first-class Federal Aviation Administration (FAA) medical certificate was issued on February 23, 2021. Operator records indicated that the captain had 28,062 total hours of flight experience, including 414 hours on the B-777 in the previous 12 months. His most recent proficiency check was completed on February 5, 2021.

First Officer

The first officer, age 54, held an airline transport pilot certificate with a rating for airplane multiengine land and multiple type ratings, including the B-777. Operator records indicated that the first officer had 18,612 total hours of flight experience, including 355 hours on the B-777 in the previous 12 months. His most recent proficiency check was completed on November 27, 2020.

Aircraft and Owner/Operator Information

Aircraft Make:	Boeing	**Registration:**	N772UA
Model/Series:	777-222	**Aircraft Category:**	Airplane
Year of Manufacture:	1995	**Amateur Built:**	
Airworthiness Certificate:	Transport	**Serial Number:**	26930
Landing Gear Type:	Retractable - Tricycle	**Seats:**	400
Date/Type of Last Inspection:	January 16, 2021 Continuous airworthiness	**Certified Max Gross Wt.:**	545000 lbs
Time Since Last Inspection:		**Engines:**	2 Turbo fan
Airframe Total Time:	96814.41 Hrs as of last inspection	**Engine Manufacturer:**	P&W
ELT:	C126 installed, not activated	**Engine Model/Series:**	PW4077 SER
Registered Owner:	United Airlines	**Rated Power:**	77000 Lbs thrust
Operator:	United Airlines	**Operating Certificate(s) Held:**	Flag carrier (121)

Overview

The Boeing 777-222 is a long range, twin-engine, transport category airplane. The primary wing and fuselage structure is of all metal construction, primarily aluminum alloys. The control surfaces and engine cowlings are of composite construction, which comprises graphite epoxy carbon fiber reinforced plastic (CFRP), fiberglass, or honeycomb sandwich. The incident airplane was manufactured in September 1995.

Engines

The airplane was powered by two Pratt & Whitney (P&W) PW4077 turbofan engines. The right engine was manufactured in 1995 and installed on the accident airplane in August 2016. At the time of the event, the engine had accumulated 12,384 hours and 2,979 cycles since overhaul and 81,768 hours and 15,262 cycles since new.

The PW4077 is a dual-spool, axial flow, high-bypass turbofan engine that features a single-stage, 112-inch diameter fan (low pressure compressor [LPC] 1st stage), a 6-stage LPC, 11-stage high pressure compressor (HPC), annular combustor, a 2-stage high pressure turbine (HPT) that drives the HPC, and a 7-stage low pressure turbine (LPT) that drives the fan and LPC. Each engine is attached to a pylon on its respective wing. The engine inlet is attached to the forward end of the engine, the fan cowls are attached around the center portion of the engine, and the thrust reversers are attached around the aft portion of the engine. (see figure 2.) Engine flanges are identified alphabetically from the front of the engine aft, with the A-flange located where the inlet attaches to the fan case and the T-flange at the aft end of the exhaust case. (see figure 3.)

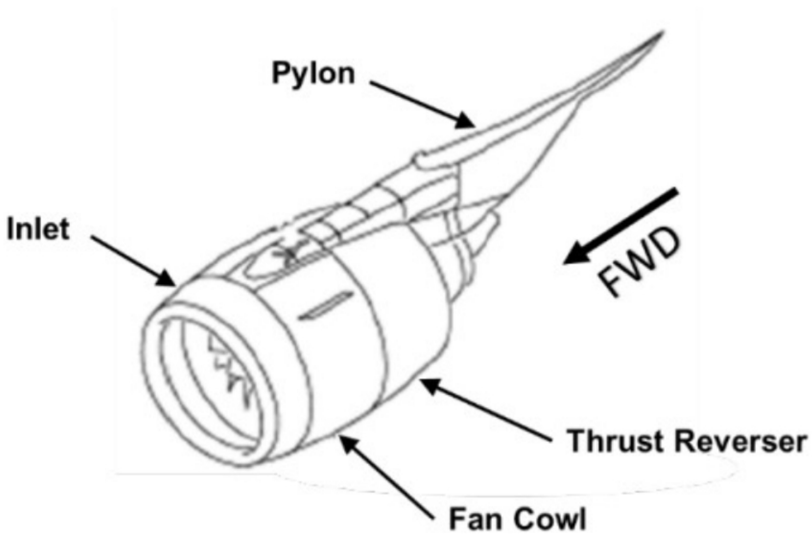

Figure 2. Engine installation drawing for 777-200 (Source: Boeing).

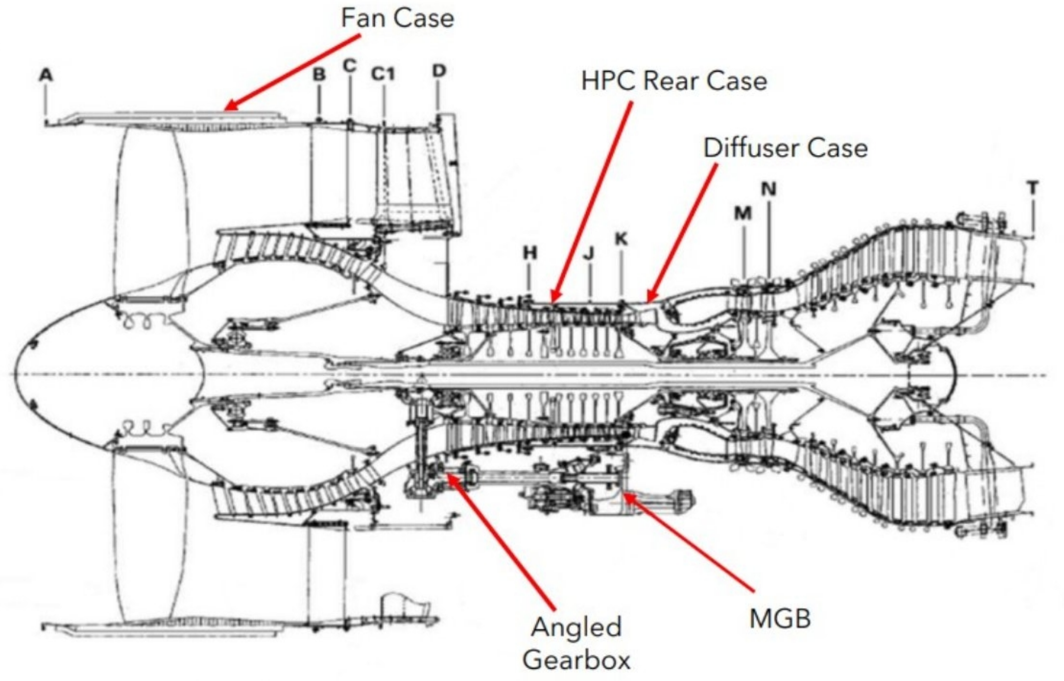

Figure 3. PW4000 112-inch significant engine flanges (Source: Pratt & Whitney)

Inlet

The engine inlet is a cantilevered structure attached to the forward flange of the engine fan case through the inlet attach ring with 52 bolts. The inlet consists of two concentric cylindrical structures joined together by forward and aft bulkheads (see figure 4). The hollow aluminum lip skin is attached to the forward bulkhead and provides an aerodynamic surface for the leading edge of the inlet and a passage for engine anti-ice air. The inlet aft bulkhead consists of the aluminum inlet attach ring and aluminum outer ring chord with a CFRP honeycomb sandwich composite web. The inlet forward bulkhead consists of the aluminum inner and outer ring chords with a stiffened aluminum web.

The inlet outer barrel comprises three CFRP honeycomb sandwich panels. A section of the outer barrel in the lower right quadrant is comprised of a titanium skin, where the anti-ice exhaust duct is located. The inlet inner barrel is comprised of two CFRP honeycomb sandwich panels. The inner face sheet of the inner barrel is perforated for noise suppression and the outer face sheet is solid.

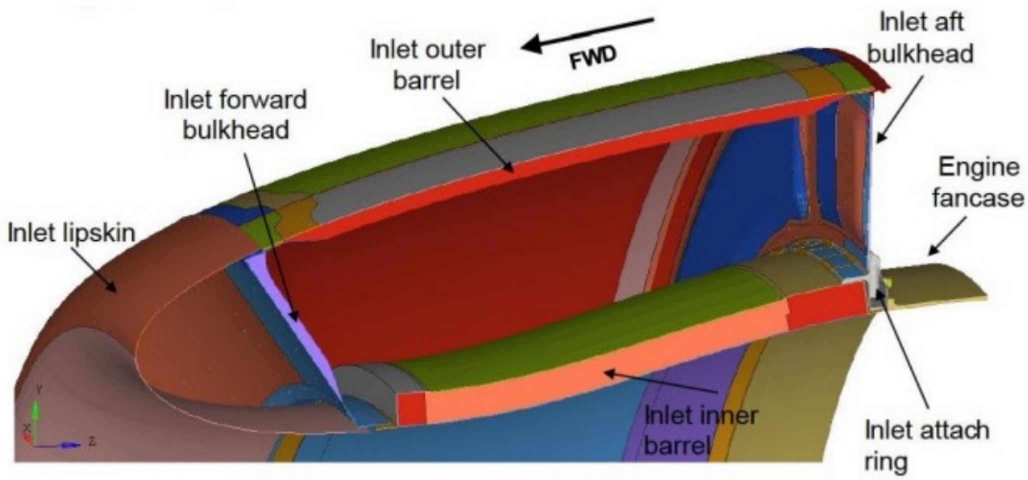

Figure 4. Inlet cross-section drawing for 777-200 (Source: Boeing).

Fan Cowl

The fan cowl provides an aerodynamic closure around the engine fan cases and the doors open to allow maintenance access to the engine. The CFRP honeycomb sandwich construction cowls are semi-cylindrical doors fastened to four hinges at the upper ends; two on the cowl support beam, one floating hinge, and one hinge on the engine. The fan cowl support beam is a CFRP honeycomb sandwich panel attached at the forward end to the inlet attach ring and to the fan case at the aft end through aluminum fittings. The fan cowls interface with the inlet at the forward edge through a v-blade on the fan cowls that seats in a v-groove on the inlet aft bulkhead. The fan cowls interface with the thrust reversers at the aft edge through a sliding contact seal.

Thrust Reversers

The thrust reversers (TRs) provide an aerodynamic enclosure around the core of the engine, direct the fan exhaust, and actuate to provide reverse thrust during landing. The two semi-cylindrical TR halves comprise three main components; the translating sleeve, the fan duct cowl, and the aft cowl. The CFRP honeycomb sandwich inner wall of the fan duct cowl and the titanium aft cowl enclose the engine core and comprise the fire zone in the TR. The TRs are hinged at the upper end to the pylon and open to provide maintenance access.

The main structural skeleton of the TR consists of the aluminum hinge beam at the upper end, the aluminum torque box at the forward end, the aluminum latch beam at the lower end, and the aluminum aft support ring and titanium aft cowl at the aft end. The CFRP honeycomb sandwich inner wall is connected to the TR at the upper and lower bifurcations. The CFRP honeycomb sandwich translating sleeve forms the outer surface of the TR and the outer wall of the fan duct cowl in the closed position. The translating sleeve slides aft along a mechanism attached to the torque box when actuated for reverse thrust.

Rubber fire seals are installed in each TR half to help contain an undercowl fire within the interior of the fan duct inner wall and aft cowl. The fabric-reinforced silicone rubber seals are installed along the upper and lower bifurcation walls and down the upper aft edge of the aft cowl. Kapton-faced thermal insulation blankets are installed on the upper and lower bifurcations and on the inside of the inner wall in the fire zone to protect the composite structure from radiant engine heat and fire.

Engine Fire Protection and Extinguishing Systems

The B-777 engine fire protection comprised two systems: an engine fire and overheat detection system, and an engine fire extinguishing system.

The engine fire and overheat detection system comprised two detector loops in each engine nacelle. Normally, both loops must detect a fire or overheat condition to cause an engine fire warning or overheat caution message to display on the EICAS. If a fault was detected in one loop, the system automatically switched to single-loop operation. If there were faults in both detector loops, no fire or overheat detection would be provided. The EICAS advisory message DET FIRE ENG (L or R) would be displayed if the engine fire detection system failed.

An engine fire warning would be accompanied by several indications, including an aural fire bell, the illumination of master WARNING lights, an EICAS warning message (FIRE ENG [L or R]), the illumination of the affected engine fire switch, unlocking of the engine fire switch, and the illumination of the engine FUEL CONTROL (L or R) switch fire warning light.

Each engine was equipped with two fire extinguisher bottles, which were located inside the engine nacelle and cowling and activated by engine fire switches in the flight deck. When the switch is pulled out and rotated in either direction, a single extinguisher bottle is discharged into the associated nacelle cavity. When the switch is rotated in the other direction, the remaining extinguisher bottle is discharged into the same engine.

Activation of the fire switch is also designed to isolate the engine by closing the fuel spar valve, de-energizing the engine fuel metering unit cutoff solenoid, closing and depressurizing the engine driven hydraulic pump supply shutoff valve, closing the pressure regulator and shutoff valve, removing power from the thrust reverser isolation valve, and tripping the generator and backup generator fields.

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual (VMC)	**Condition of Light:**	Day
Observation Facility, Elevation:	KDEN,5404 ft msl	**Distance from Accident Site:**	15 Nautical Miles
Observation Time:	12:53 Local	**Direction from Accident Site:**	109°
Lowest Cloud Condition:	Few / 8500 ft AGL	**Visibility**	10 miles
Lowest Ceiling:		**Visibility (RVR):**	
Wind Speed/Gusts:	5 knots /	**Turbulence Type Forecast/Actual:**	/
Wind Direction:	180°	**Turbulence Severity Forecast/Actual:**	/
Altimeter Setting:	29.7 inches Hg	**Temperature/Dew Point:**	13°C / -9°C
Precipitation and Obscuration:	No Obscuration; No Precipitation		
Departure Point:	Denver, CO (DEN)	**Type of Flight Plan Filed:**	IFR
Destination:	Honolulu , HI (HNL)	**Type of Clearance:**	IFR
Departure Time:	13:04 Local	**Type of Airspace:**	Class E

Wreckage and Impact Information

Crew Injuries:	10 None	**Aircraft Damage:**	Minor
Passenger Injuries:	229 None	**Aircraft Fire:**	None
Ground Injuries:		**Aircraft Explosion:**	None
Total Injuries:	239 None	**Latitude, Longitude:**	39.929179,-104.96439

Examination of the airplane revealed that the right engine inlet and fan cowls had separated from the engine and the right engine thrust reversers were thermally damaged.

Fan Blades

Examination of the right engine revealed that one fan blade, identified as No. 19, was fractured transversely across the chord of the airfoil at the plane of the fan hub fairing, known as a full-span blade separation, or fan blade out (FBO). A piece of fan blade, which measured about 13 inches long by 6 inches wide, was recovered with the debris that had fallen from the airplane during flight and was identified with the last five digits of the fractured blade serial number.

The adjacent fan blade (No. 18) was fractured across the airfoil about 25 inches above the fairing and displayed evidence of overload failure. All of the other fan blades were intact, but displayed varying degrees of impact damage to the airfoils, with the tips bent and curled opposite the direction of rotation. (see figure 5.)

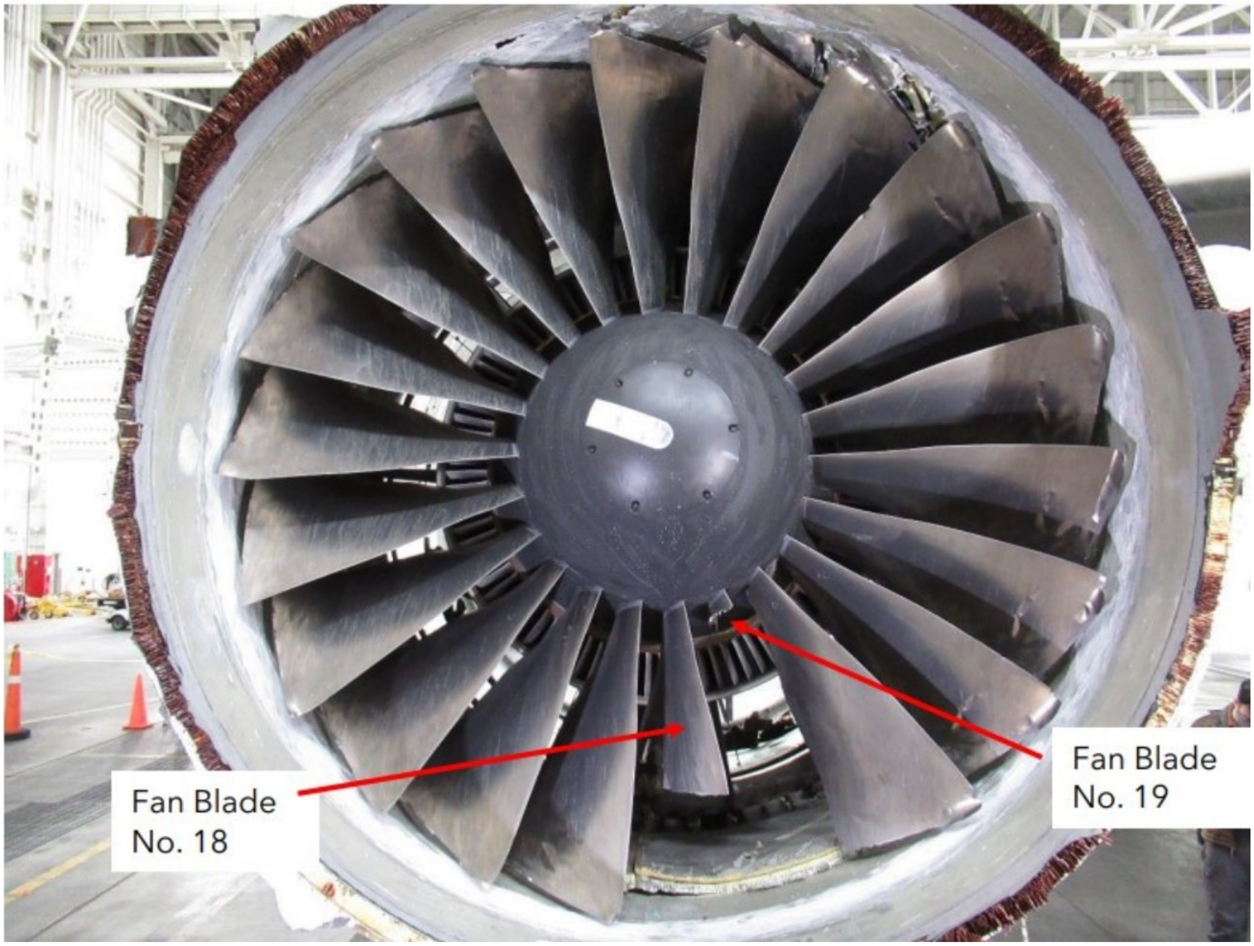

Figure 5. Fan blades as viewed from front, showing the two fractured blades and damage to the remaining intact blades.

Main Gearbox and “K” Flange

The main gearbox (MGB), normally supported by the “J” and “K” flanges via three brackets, was separated from the two flanges and fractured. The left MGB mount bracket, upper clevis, mount link, and MGB clevis were intact and still connected to the MGB; however, the left MGB link bracket was detached from the “J” and “K” flanges due to the fractures of all of the flanges’ bolts. The MGB housing was deformed in the area of the left clevis, consistent with multiple impacts against the upper clevis in an orientation where the MGB had rotated counterclockwise as viewed from the top. The MGB sustained significant thermal damage, and most of its housing was melted away. The servo fuel heater, which is mounted on the MGB, was found fractured at a high-pressure fuel cavity location. The fracture texture was sharp and jagged, consistent with contact against the fuel oil cooler, and the lack of thermal distress on the impact marks suggested that this may have been the initiating fracture of the fire event.

The “K” flange joins the HPC rear case with the diffuser case, which contains the internal hot gases of the operating engine (refer to Figure 3 for location of the “K” flange). Examination revealed that the “K” flange was separated, and all the fastening bolts had failed. Most of the bolt holes were empty; in the locations where bolt remnants were found, the bolts were sheared in the plane of the aft face of the forward flange. Some of the fractured bolts or nut ends were retained by case features. At the location of the “K” flange near the HPC discharge plane, the compressed air temperature exceeds 1,000°F. In the event of a “K” flange separation, the leaking high temperature HPC discharge gas could provide an ignition source of any fuel present in the nacelle.

Fan Case

The front fan case comprises a cylindrical aluminum isogrid structure wrapped externally with multiple layers of continuously wound Kevlar fabric strip, then covered with an epoxy resin environmental wrap, the purpose of which is to prevent penetration of the engine case in the event of a fan blade failure or separation. A honeycomb acoustic structure is bonded to the entire inner surface, upon which a fan blade rub strip is bonded in the plane of the fan. The clock positions referenced in the following paragraph are as viewed from aft of the engine looking forward. The 12:00 position is the upper center line of the engine as installed on the wing.

The outer two layers of the Kevlar containment belt, inclusive of the environmental wrap, were torn with split and frayed fibers along the edges. The tear near the 11:30 position extended aft about 34 inches axially starting about 1 inch aft of the forward edge. There was a hole in the third layer of Kevlar from the outside that measured about 5 inches axially and 3.5 inches circumferentially. All of the remaining Kevlar layers were penetrated by an embedded piece of fan blade that was centered about 15 inches aft of the A-flange near the 11:30 position. The hole through the layers measured 1 inch axially and 1.5 inches circumferentially. The Kevlar containment belt layers were displaced outward about 3 inches from their nominal position with the blade fragment still in place.

The forward edge of the containment belt was displaced aft between 11:15 and 12:00 with a maximum displacement of about 0.5 inch centered near 11:30 that cracked the sealant. The sealant bead on the aft edge of the containment belt was cracked and displaced forward from 9:00 to 1:30. The maximum displacement was about 1.75 inches between 11:15 and 11:45. The inner three layers of the containment belt remained in place, while the rest were displaced forward. There was red sealant on the aft edge between 1:45 and 7:00 and between 8:00 and 9:45.

The fan blade rub strip and its honeycomb substrate material were completely missing; the underlying fan case material was circumferentially scored and gouged around the full circumference. The interior surface of the fan case displayed significant damage, including an area of heavy scoring and gouging of the case aluminum isogrid material around nearly the entire circumference in the fan blade plane of rotation. A rectangular puncture of the aluminum isogrid was located near the 11:00 position.

A section of fan blade about 18 inches by 16 inches was lodged in the aluminum isogrid between 11:15 and 12:05. Multiple witness marks corresponding to fan blade fragment trajectories were identified on the inner surface of the fan case; the witness marks were consistent with blade fragments moving forward, aft, and circumferentially.

Six distinct witness marks consistent with fan blade fragment paths were identified during reconstruction of the inlet inner barrel; four of these paths aligned with those identified on the fan case inner surface.

Most of the composite outer barrel was recovered and identified. A two-dimensional reconstruction revealed several axial fractures and an arc-shaped mechanical cut. Two pieces of metallic debris were found embedded in the outer barrel panel near 6:00. One piece had coloration and composition consistent with the aluminum fan case isogrid, and the other was consistent with the titanium alloy used in construction of the fan blades. Additionally, two areas of the outer barrel exhibited evidence of fluid ingression into the honeycomb.

Engine Driven Pump (EDP) Supply Shutoff Valve

Examination of the right engine fire suppression system revealed that the EDP supply shutoff valve, which stops hydraulic supply from the reservoir to the EDP when the fire switch is pulled, was in the OPEN position. Fire switch and wire continuity was confirmed with no shorts or anomalies found, and the circuit breaker associated with the valve was found closed. Additionally, a maintenance message stating, “Supply shutoff valve (EDP R) is not in the commanded position” was active in the central maintenance computer existing faults.

The unit was removed for further examination and testing. Disassembly and examination of the unit’s DC motor revealed silicone contamination of the brushes and commutators consistent with the silicone-based lubricant used in the unit’s motor bearings, as well as fretting debris from the commutators, which increased the electrical contact resistance between these components.

Tests and Research

Fan Blade Description

The PW4000 112-inch engine fan blade is a hollow core airfoil made of a titanium alloy. The blades are manufactured with a waffle-style core structure; the interior of the blade comprises a pattern of cavities separated by spanwise and chordwise ribs.

The blades are manufactured from two titanium alloy plates from which the internal and external features of the blade are machined. The two halves are then diffusion bonded, inspected, and machined before being formed into the final airfoil shape. During the hot final forming process, pressurized argon is introduced into most of the blade cavities to prevent skin deformation.

Fan Blade Failure Analysis

Metallurgical examination of the fractured blade was performed at the P&W Materials Laboratory under NTSB supervision. The examination revealed a fatigue crack that initiated internally about 6.6 inches above the root on the surface of an internal radius in a cavity of the hollow core fan blade. (see figure 6.) The fracture surface showed evidence of an estimated 3,150 cycles of stable low-cycle fatigue growth between 0.063 inch to 0.199 inch from the fatigue origin.

In addition to the primary fracture, multiple fatigue cracks were identified in the flowpath and midspan of the fractured blade. These secondary fatigue cracks had origins at the internal cavity surfaces, and many of the cracks exhibited multiple origins, consistent with the primary fracture. The largest of the secondary cracks had a maximum crack depth of 0.065 inch.

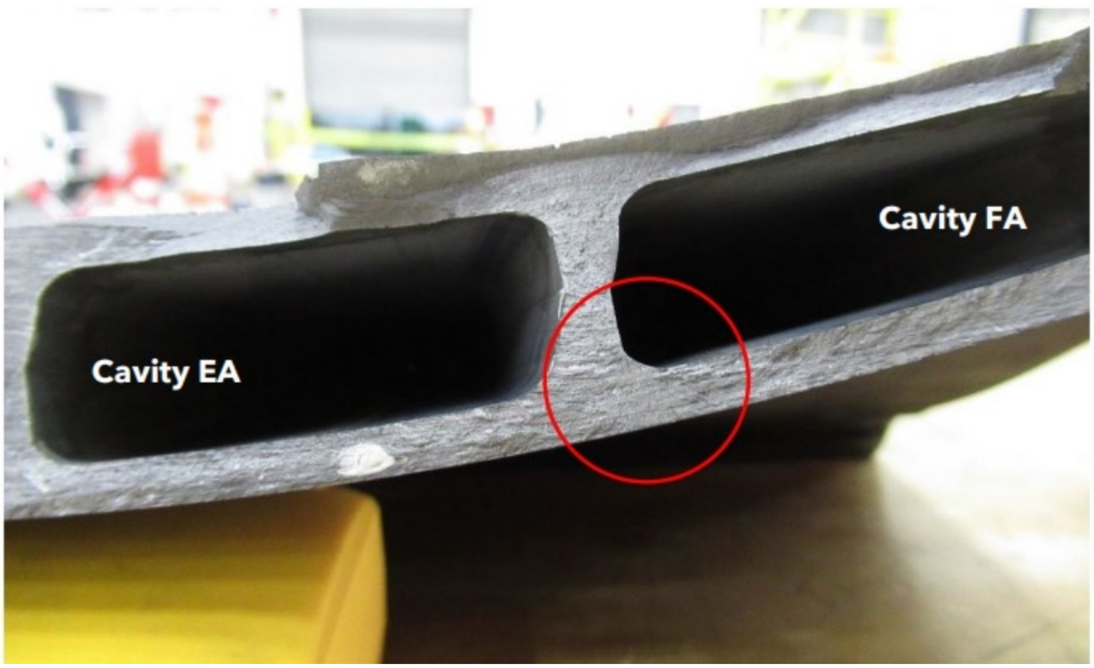

Figure 6. Closeup of fan blade No. 19 fracture surface and fatigue evidence.

Examination of the crack that led to the failure of the blade revealed a discontinuity in a local tight radius in the internal blade geometry that had been introduced during the machining and manufacturing process. A P&W technical review of the discontinuity estimated a local steady stress increase of 30% at the location, reducing the fatigue life by 50%.

Metallurgical and chemical characterization revealed that the surfaces of the internal cavities were contaminated with carbon that had diffused into the parent material. According to P&W engineers, carbon contamination of titanium can cause decreased fatigue resistance capability. It was observed that the carbon surface contamination was not present in the cavities of the blade that are sealed off during the diffusion bonding process, indicating that the contamination was introduced after the diffusion bonding process.

Review of the manufacturing process revealed that the most likely source of the carbon contamination was the shop argon system used during the hot final forming process. Before 1997, P&W's high-pressure argon was supplied through the regular shop lines, which are not cleaned and can contain various contaminants. In 1997, P&W began using a clean dedicated argon system. The hot final forming of the event blade occurred in 1994.

Additional Information

Maintenance History and Inspection Process

The UAL maintenance program for the fan blades was governed by UAL's Federal Aviation Administration (FAA) approved engine maintenance program, based on P&W's PW4000 112-inch maintenance planning document. The installed set of fan blades, including the fractured blade, had undergone two overhauls at the manufacturer's overhaul facility; once in 2014 and again in 2016. The overhaul included removal of the outer protective coating and a fluorescent penetrant inspection (FPI) to detect surface cracks, a visual inspection, and a thermal acoustic imaging (TAI) inspection. At the time of the accident, overhaul inspection of the blades was required every 6,500 cycles. Blades were permitted to continue in service as long as they passed the required inspections.

During the TAI process, the fan blade's airfoil is coated with heat conductive and radiating paint, after which sonic transducers that vibrate the entire blade structure are attached to the blade root. The vibrational excitation causes a high-frequency movement between faying sides of any contacting discontinuity (or crack), causing frictional heating of the crack, which can then be detected on the surface of the fan blade with a thermal camera. These thermal camera images are then processed via computer, which amplifies and interprets the temperature signatures and displays them for evaluation by an inspector.

The inspectors occasionally encounter extraneous or questionable indications in the TAI results, which must be evaluated to determine if the indication is a true crack or caused by other benign conditions, such as a loss of thermal paint adhesion on the outer surface or grit particles that have accumulated in the internal cavities of the airfoil, neither of which are reasons for removing the blade from service. If the inspector is not able to clearly evaluate an indication, they are instructed to forward the images and the blade itself to a process engineer, who can use other non-destructive inspection methods.

In response to a similar in-flight fan blade failure event on February 13, 2018, involving a UAL PW4077-powered Boeing 777-222 airplane while over the Pacific Ocean (NTSB report ID DCA18IA092), Non-Destructive Inspection Procedure (NDIP) 1065 Revisions B, C, and D were issued to introduce process improvements and additional controls, as well as more detailed examples of acceptable and rejectable TAI inspection indications. Following the 2018 event, the digital data of the thermal images captured in April 2016 of the incident fan blades were reviewed; the reviewers accepted the previous interpretations and the blade continued in service.

In 2021, the data from the April 2016 TAI inspection of the incident fan blades were again retrieved and reviewed by P&W. Although the software identified two low-level indications on the convex side of the blade near the center of the airfoil chord in the flow path region, the inspector categorized the findings as “extraneous” and concluded that they were likely generated by either camera sensor noise or loose grit in the cavity. A review of the NDIP procedure that was in effect at the time of the 2016 inspection indicated that, given the low-level indications observed, the blade should have been either stripped and re-painted for a second TAI inspection, or the ambiguous indications should have been elevated to a team review for further inspections; however, there is no evidence to suggest that either of these additional reviews occurred. The anomalous indications were located very close to the origin of the fatigue crack that led to the fracture of blade No. 19 and were likely associated with the initiating fatigue fracture in this event.

Boeing Failure Analysis

Following the February 2018 FBO event, Boeing produced a dynamic simulation model to examine failure scenarios of the inlet and fan cowl structures using data collected during certification FBO tests along with physical evidence collected during previous FBO events, which included the February 2018 event as well as an incident in 2010. During an FBO event, the released fan blade has a significant amount of centrifugal and circumferential energy. The fan case and Kevlar containment belt were designed to absorb the energy and prevent fan blade fragments from exiting radially through the fan case. Although the fan case and Kevlar containment belt will deflect outward as they absorb this energy, significant A-flange deflections were not anticipated.

Certification test simulation studies of an FBO event with an aluminum aft bulkhead predicted a bulkhead displacement of 0.47 inch with localized yielding, but without a failure of the inlet structure or the inlet-to-fan-case interface. Analysis of the 2018 event predicted a displacement of 0.55 inch and delamination of the installed CFRP bulkhead face sheets, which exceeded the face sheet laminate rupture strain in compression, leading to the failure of the inlet aft bulkhead. Analysis of the 2010 event predicted a displacement of 0.46 inch and compression buckling of the CFRP aft bulkhead, but no failure. The aluminum structure in the certification inlet had the ability to yield and absorb the same amount of energy and redistribute the FBO loads between the fan case and the inlet without causing failure of the inlet aft bulkhead.

Boeing records also indicated that evidence of moisture ingression had been found on multiple other 777 fan cowls, and although varied in extent and location, was reported in the area of the latches on the lower fan cowl panels and the area of the hinge attachments on the upper fan cowl panels. Such moisture ingression would degrade the strength of the cowls.

Safety Actions

Following this event, the FAA issued Emergency AD 2021-05-51, effectively grounding all PW4000 112"-powered 777-200 and -300 airplanes so that a one-time TAI inspection of the 1st stage LPC blades could be completed. On October 21, 2021, P&W issued Alert Service Bulletin (SB) PW4G-112-A72-361, Engine – Blade Assembly, 1st Stage, Low Pressure Compressor (LPC) – Ultrasonic Testing (UT) Inspection and Thermal Acoustic Image (TAI) Inspection of 1st Stage LPC Blade Assemblies to Find Airfoil Cracks. The SB included both immediate and repetitive UT inspections for three specific high-risk areas on the PW4000 112-inch hollow fan blades. It also added a required TAI inspection every 1,000 cycles for all 1st stage LPC blades. The inspections included in this SB were subsequently made mandatory on April 15, 2022, when the FAA issued Airworthiness Directive (AD) 2022-06-09.

As of January 31, 2023, seventeen confirmed cracked fan blades have been found, the first of which was identified in December 2004. These do not include the three fan blades that sustained full-blade separation in service. Prior to release of the UT inspection, seven cracked fan blades were identified via TAI and one visually. Nine cracked blades were identified following the introduction of the new UT inspection process.

UT indications have been identified in 102 fan blades, of which fifteen have been destructively examined, with nine being confirmed cracks. The selection of blades for destructive evaluation is based on Pratt & Whitney's evaluation of the UT inspection results and prioritizing those whose indication characteristics are more likely to be cracks. All confirmed cracks greater than 0.016-inch deep exhibited evidence of low-cycle fatigue progression, with contributing crack accelerating factors that included discontinuities and molten metal deposits introduced during machining processes, surface damage, microtexture regions, and surface contamination.

Also in response to this event, Boeing developed an interim design solution incorporating engine nacelle modifications, and Boeing subsequently issued multiple alert SBs for fan cowl inspections; modifications to the inlet cowls and thrust reversers on 777-200 and -300 airplanes equipped with PW4000 series engines; and inspection/repair of fan cowls for moisture ingression. These SBs were subsequently mandated via FAA ADs 2022-06-10 and 2022-06-11.

Administrative Information

Investigator In Charge (IIC):	Bower, Daniel
Additional Participating Persons:	Dave Gerlach; FAA Eric East; Boeing Ryan Hurling; United Airlines Mitch Hunt; IBT Doug Zabawa; Pratt and Whitney Steve Demko; ALPA
Original Publish Date:	September 7, 2023
Last Revision Date:	
Investigation Class:	[Class 3](#)
Note:	
Investigation Docket:	https://data.ntsb.gov/Docket?ProjectID=102652