BOEING

Submission to the

National Transportation Safety Board

for the

United Airlines 777-200 N772UA Engine Failure and Inlet-Fan Cowl Departure
Denver, CO
20 February 2021

The Boeing Company
12 June 2023

INTRODUCTION

On February 20, 2021, at about 1309 Mountain standard time (MST), United Airlines flight 328, a Boeing 777-200, registration number N772UA, powered by two Pratt & Whitney (P&W) PW40777 turbofan engines experienced a right engine failure and loss of portions of the engine inlet and fan cowl during climb at an altitude of about 12,500 feet (mean sea level) MSL shortly after takeoff from Denver International Airport (DEN). Fragments from the engine nacelle structure contacted the wing, horizontal stabilizer, and fuselage wing to body fairing. The flight crew reported an engine fire, declared an emergency, and returned to DEN. Of the 239 passengers and crewmembers onboard, no injuries were reported. The airplane sustained minor damage. This regularly scheduled domestic passenger flight was operating under 14 Code of Federal Regulations Part 121 from DEN to Daniel K. Inouye International Airport (HNL), Honolulu, Hawaii. After the incident, the FAA issued Emergency Airworthiness Directive (AD) 2021-05-51 effectively grounding all PW4000-112" powered 777-200 and 777-300 airplanes.

Submission Abstract

- The Boeing Company, as the airplane's manufacturer, is an invited party to the investigation and provides technical and operational assistance to the National Transportation Safety Board (NTSB) in their investigation.
- The conclusions presented in this submission are based on factual information received from the NTSB, Boeing expertise, the use of analytical tools, and a methodical investigation process.
- During climb shortly after takeoff from DEN, the right engine experienced an engine failure involving the loss of a single fan blade and failure of the engine 'K' Flange. This caused portions of the engine inlet and fan cowls to depart the airplane and initiated an under-cowl engine fire that affected the thrust reversers.
- The airplane and all airplane systems were functioning as expected prior to the engine failure. After the engine failure, the airplane systems and remaining structures functioned to maintain continued safe flight and landing.
- The engine fire detection, engine control, and fuel cutoff systems functioned as designed enabling shut down of the right engine when commanded by the flight crew.
- The hydraulic fluid supply shutoff valve for the right engine driven hydraulic pump did not close when commanded by the flight crew.
- The fan blade failure and failure of the engine 'K' flange resulted in the structural failures of the engine nacelle during the engine failure and the subsequent engine fire that spread to the thrust reverser translating sleeves.
- The FAA granted a time limited exemption to Boeing in March 2022 that included structural modifications to engine inlets and thrust reversers, inspections of fan cowls, and functional testing of hydraulic pump shutoff valves enabling the affected PW4000-112" fleet to return to service.

BOEING ASSISTANCE WITH THIS INVESTIGATION

The National Transportation Safety Board (NTSB) is conducting the investigation into this United Airlines 777-200 incident. Assisting the NTSB in their investigation are the Federal Aviation Administration (FAA); Pratt & Whitney; Boeing; and other designated parties.

As the manufacturer of the 777-200 airplane, Boeing's specific role in this investigation has been to provide technical information regarding the airplane design, manufacture, and operation to assist the NTSB.

The NTSB requested that all parties submit proposed findings to be drawn from the factual information established during the course of the investigation. Boeing has responded to the NTSB request with this document, which:

- Provides an assessment of the factual information and other pertinent data;
- Identifies knowledge gained from the investigation; and
- Identifies conclusions supported by the knowledge gained from the investigation.

BOEING ASSESSMENT

The Boeing assessment of the incident is based upon the facts as documented in the NTSB's factual reports and other published final reports, Boeing expertise, the use of analytical tools, and a methodical investigation process. These reports contain observations of the airplane and incident site, post-incident examination of airplane systems and components, flight data recorder (FDR) data, the cockpit voice recorder (CVR) transcript, airline maintenance records, materials and systems laboratory data, and crew interview data.

WEATHER

The engine failure occurred near latitude 39.9353° N, longitude 105.0511° W, at a pressure altitude of about 12,570 feet over Broomfield, Colorado. The DEN weather observation prior to the incident at 1253 MST reported winds from 180º at 5 knots, 10 miles visibility or greater, few clouds at 8,500 feet above ground level (AGL), scattered clouds at 13,000 and 20,000 feet AGL, and a temperature of 13º C.[1] The flight returned to DEN, conducted a one engine inoperative ILS approach to runway 26, and landed at 1328 MST. The DEN weather observation at 1353 MST reported winds from 360° at 19 knots, 10 miles visibility or greater, broken ceiling at 10,000 feet AGL, broken skies at 20,000 feet AGL, and a temperature of 11° C.[2] Weather conditions were not considered to be factors in this incident.

THE INCIDENT AIRCRAFT

The Boeing Company delivered the airplane (registration N772UA, serial number 26930) on September 29, 1995. The airplane had about 96,975 total hours with 17,784 total cycles at the time of the incident.[3] The airplane was equipped with two Pratt & Whitney PW4077 engines.

---

[1] DCA21FA085 NTSB Operational Factors Factual Report, dated 24 October 2022, page 14

[2] DCA21FA085 NTSB Operational Factors Factual Report, dated 24 October 2022, page 14

[3] DCA21FA085 NTSB Maintenance Records Factual Report, dated 02 February 2022, page 6

FLIGHT AND CABIN CREW

The crew consisted of the Captain (CA) and First Officer (FO) and 8 flight attendants. The captain was the pilot flying (PF) and the FO was the pilot monitoring (PM) when the engine failure occurred.

SEQUENCE OF EVENTS

Below is a chronological overview of the events that occurred based on the FDR data, ADS-B data, witness and passenger photograph reviews, CVR transcript, structural analysis, and crew interviews. The events below are referenced to an estimated elapsed time (+/- *minutes:seconds*) from when the engine failure occurred. References to explicit times represent local time during the event which was Mountain Standard Time (MST). All times should be considered approximate.

Estimated Elapsed Time	Event Description
t = 00:00	Right engine failure occurs at 13:08 MST (estimated based upon FDR data, including recorded acceleration, pitch, roll, and engine data).
t = +00:05	R ENG FIRE WARN is recorded on the FDR indicating that the engine fire detection system detected a fire condition on the right engine.
t = +02:58	R Engine Fuel Cutoff was recorded by the FDR indicating that the right engine fuel control switch was moved from the RUN to the CUTOFF position by the flight crew.
t = +03:00	Witness photographs from the ground show the right engine inlet and both fan cowls are missing and a fire is present that appears to initially emanate from lower thrust reverser pressure relief doors. Consecutive photos show that the fire transitions to the nacelle drain access panel area of the thrust reversers with no visible fire from the pressure relief doors (estimated by photo metadata, ADS-B/FDR recorded flight path; available metadata from photographs is to the nearest minute; photographer latitude longitude was provided).
t = +03:14	ENG BTL 2 DISCH is recorded on the FDR indicating that the engine fire bottle #2 was discharged by rotating the right engine fire handle to the right.
t = +03:47	Passenger photo from the cabin shows areas of discoloration expanding upward along the right engine inboard thrust reverser translating sleeve (estimated by photo metadata, ADS-B/FDR recorded flight path, and ground features visible from passenger window).

Estimated Elapsed Time	Event Description
t = +04:03	ENG BTL 1 DISCH is recorded on the FDR indicating that the engine fire bottle #1 was discharged by rotating the right engine fire handle to the left.
t = +04:23	Passenger photo from the cabin shows areas of discoloration continuing to expand upward along the right engine inboard thrust reverser translating sleeve. (estimated by photo metadata, ADS-B/FDR recorded flight path, and ground features visible from passenger window)
t = +08:07	Passenger photo from the cabin shows that the majority of the visible right engine inboard thrust reverser translating sleeve is discolored with sooting appearing along the leading edge. Smoke is visible near the top and outboard portion of the right engine fan case. (estimated by photo metadata, ADS-B/FDR recorded flight path, and ground features visible from passenger window)
t = +10:49	Passenger video from the cabin shows that a portion of the right engine inboard thrust reverser translating sleeve is missing, an area of the inboard thrust reverser cascades are exposed, and a fire is visible in this area. (estimated by ADS-B/FDR recorded flight path and ground features visible from passenger window)
t = +12:43	R ENG FIRE WARN is no longer active as recorded on the FDR.
t = +19:37	Airplane touches down on runway 26 at KDEN.

Table 1 – Sequence of Events

POWERPLANT

The incident airplane was powered by two P&W PW4077 turbofan engines. The right engine installed on the incident airplane (registration number N772UA) was engine serial number (ESN) 777047. This engine was installed on N772UA on August 15, 2016.

Examination of the right engine following the event revealed that fan blade no. 19 was fractured transversely across the airfoil above the fairing at the leading edge and slightly below the fairing at the trailing edge. This is known as a full-span blade separation or fan-blade-out (FBO). Fan blade no. 19 entered service when it was first installed in an engine in 1995 (not the event engine). At that time, it was installed with the 21 other fan blades, 3 of which were removed and replaced in 2000. This set of 22 fan blades remained together from that time up to the event. At the time of the incident, the failed fan blade had accumulated a total of 77,827 hours and 15,379 cycles.[4] The PW4000 112-inch fan blade is not a life-limited part. It is an on-condition part which can remain in-service until the blade no longer passes on-wing or overhaul inspection criteria.

It was also observed that the right engine sustained a failure of all the ‘K’ flange fastening bolts. The ‘K’ flange joins the high-pressure compressor (HPC) rear case with the diffuser case which contain the internal hot gases of the operating engine. The compressed air temperature at this location is above 1000° F, which is well above the approximately 350° F auto ignition temperature of jet fuel.[5] The main gearbox (MGB), normally supported by the ‘J’ and ‘K’ flanges via three brackets, was separated from the two flanges and fractured. The servo fuel heater, which is mounted on the MGB was found fractured at a high-pressure fuel cavity location. Contact marks between the servo fuel heater and the engine mounted fuel oil cooler (FOC) were observed.

Fan Blade Overhaul and Inspection

The fan blades were last overhauled in May 2016 before they were installed on the incident engine in August 2016. At that time, the blade overhaul process included masking certain areas of the fan blade, and removal of the outer protective coating from the blade root. The fan blade was cleaned after which it underwent a fluorescent penetrant inspection (FPI), which was intended to detect external surface cracks. After a visual inspection the blade then underwent a thermal acoustic imaging (TAI) inspection.

TAI is a non-destructive inspection (NDI) process that was developed by P&W and introduced in 2004. TAI is intended to detect internal or subsurface cracks and other anomalies in the PW4000 112-inch hollow core fan blades. In the TAI process utilized during the last blade overhaul, the fan blade’s airfoil is first coated with a special paint to improve the radiant heat transfer into and out of the blade, after which special sonic transducers that vibrate the entire fan blade’s structure are clamped 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. The heat generated at any discontinuity conducts through the fan blade material and is detected on the surface of the fan blade by a thermal camera. The computer controlled thermal camera takes a pattern of electronic images of the convex and concave surfaces, which are processed by computer software that interprets the temperature signatures on the specially painted blade surfaces and displays them on a monitor for an inspector to evaluate. The images can also be manipulated and enhanced by the software to assist the inspector in interpreting and evaluating the indications. When the process is complete, the special paint is removed from the airfoil. Extraneous or questionable indications in the graphic TAI results are evaluated by qualified inspectors (level 1) to determine if the indication is a true crack that may require removal from service. Other benign conditions, including loss of thermal paint adhesion on the outer surface, other paint imperfections such as remnant dried paint on the part (sometimes referred to as grit), or foreign material in the internal cavities, can produce an indication, but are not reasons for removing the blade from service.

The last two TAI inspections of the event fan blade occurred in July 2014 and in April 2016. An indication very close to the initiating fatigue fracture[6] that later resulted in the subject 2021

---

[4] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 16

[5] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 49

[6] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 22

FBO event was identified in the 2016 TAI as ‘grit/noise’ and was dispositioned as ‘accepted’. Following a February 13, 2018, FBO event involving a Boeing 777-200 with P&W PW4077 engines (NTSB reference DCA18IA092), the TAI digital data of the thermal images captured during the 2016 TAI inspection were reviewed by P&W in 2018. The reviewers again accepted the 2016 interpretations and decisions and recommended the event fan blade for continued service.

Fan Blade Laboratory Examination and Testing

As discussed more thoroughly below, the portions of fan blade no. 19 that remained attached to the fan hub were examined as part of the investigation. The fracture surfaces on those remnants revealed features consistent with fatigue cracking.

The metallurgical examination of the fractured blade no. 19 was performed at the P&W Materials Laboratory under direction of the NTSB. The examination confirmed that the fan blade fractured due to a fatigue crack, which initiated internally about 6.6 inches above the root bottom at the surface of an internal radius in the FA cavity[7] of the hollow core fan blade shown in Figure 1.

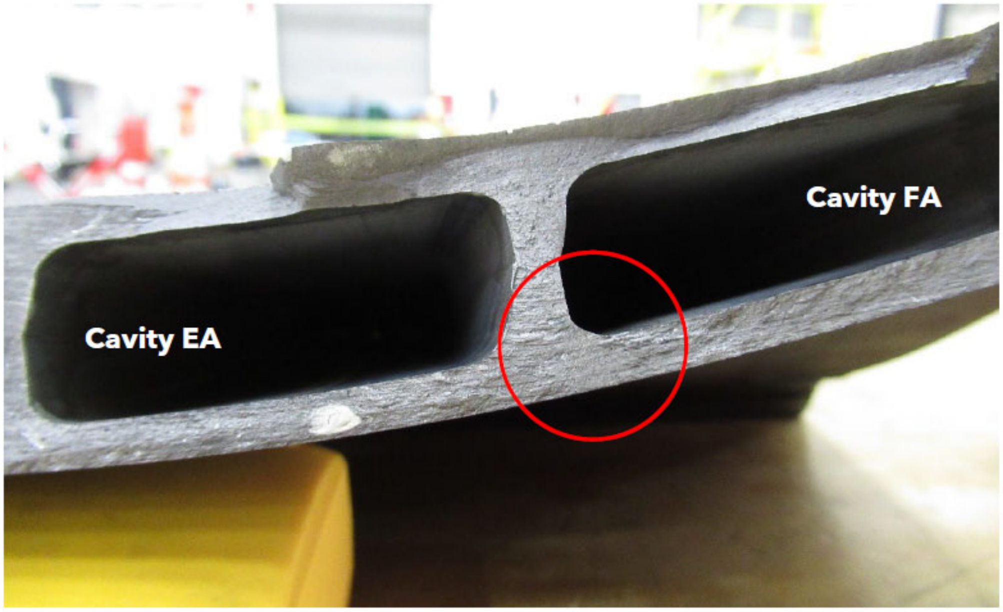

Figure 1 - Fan Blade No. 19 Fracture Surface and Fatigue Evidence

The team concluded that the two most significant contributing factors that decreased the life of the blade material were (1) a local geometric discontinuity and (2) carbon contamination of the internal cavity surface that had likely formed from contact with contaminated argon gas that was used during the blade manufacturing process.[8]

The analysis of the internal blade geometry discovered a local tight radius in the flowpath cavity caused by machining and exacerbated by forming operations. A P&W technical review of the geometric discontinuity estimated a local steady stress increase at the location that

---

[7] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 13, photo 5

[8] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 22

reduced the fatigue life resistance. P&W performed an analysis of the diffusion bonding and forming process that showed that the bonding / forming process exacerbates the discontinuity at any tight radius that was caused by machining.

Advanced metallurgical and chemical characterization performed by the P&W laboratory revealed the internal surface of the blade cavities had carbon contamination. Carbon contamination of titanium can cause decreased fatigue resistance capability. A review of the blade manufacturing process revealed that the most likely source of carbon contamination was the shop argon system. After the diffusion bonding process was completed during initial manufacture, the blades were subjected to the hot final form process at which time high-pressure argon was introduced into the part to prevent buckling of the unsupported outer skin. The event fan blade was manufactured during a time when the high-pressure argon was supplied through the regular shop lines that were not cleaned and could have contained various contaminants.

Engine Main Gear Box and Flange Evaluations

The engine, without its fan blades, was removed from the airplane and shipped to the UAL engine overhaul facility at the San Francisco International Airport where it was stored in a secure location. The powerplants group convened on April 12-16, 2021, to examine the engine core structure, MGB and accessories to determine the source of the engine core firezone fire.

The FOC, which is mounted to the engine core structure, was found to be fractured and thermally distressed at the upper aft outboard section, exposing the internal heat exchanger core. There was impact damage on one mount flange of the FOC consistent with contact against the servo fuel heater.

The servo fuel heater, which is mounted to the MGB, was heavily sooted but intact; however, a forward inboard corner was fractured at the axial cross-drilled pressure fuel channel. This damage is consistent with contact against the FOC housing. The lack of thermal distress on the impact marks suggests this could have been the initiating fracture of the fire event.[9]

Figure 2 below depicts a cross section of the engine and MGB and the relative locations of the FOC and the servo fuel heater.[10] The FOC is mounted with brackets to the engine frame while the servo fuel heater is mounted to the MGB. If the MGB mount brackets became separated from the ‘K’ flange the MGB was free to move relative to the engine core allowing possible contact between the FOC and the servo fuel heater. The contact and contact locations observed between the FOC and servo fuel heater were confirmed[11] by the NTSB powerplants group during the examinations described above.

---

[9] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 59

[10] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 61, Figure 11

[11] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 61

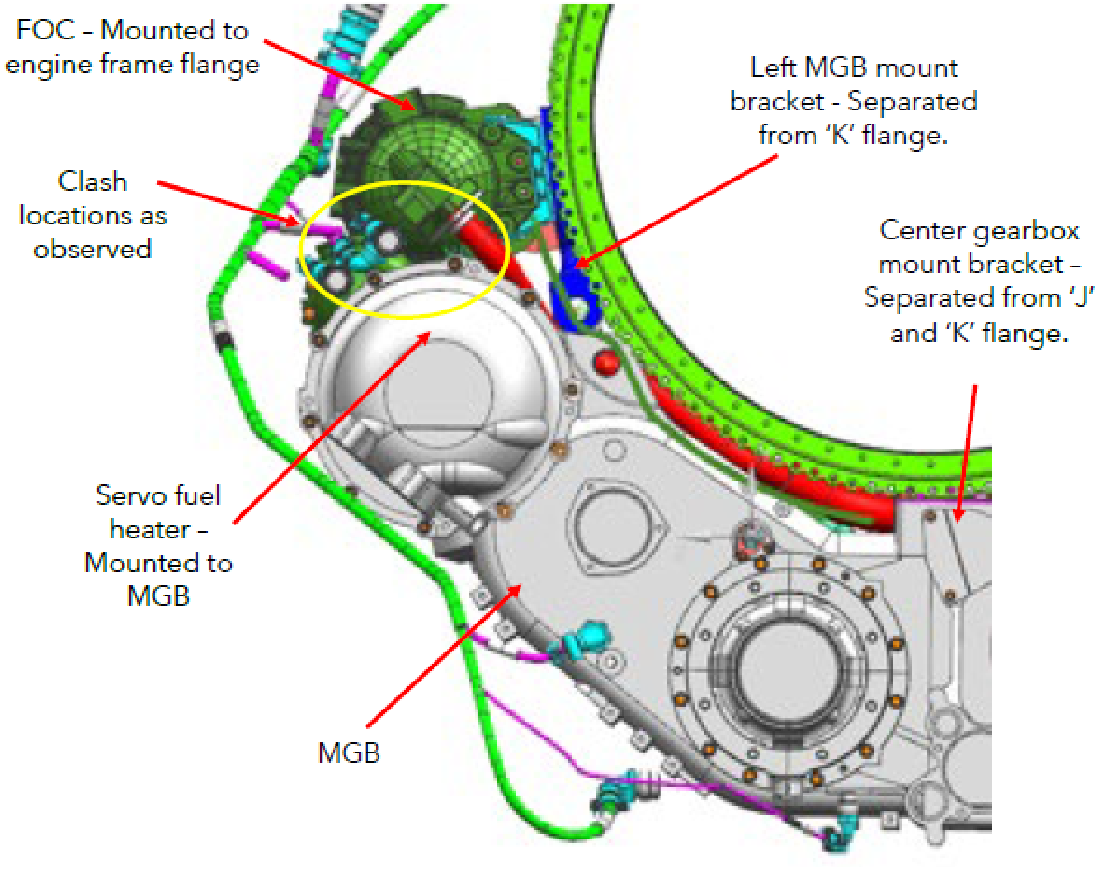

Figure 2 – Relative Locations of servo fuel heater and FOC (Aft Looking Forward)

P&W performed a hardware engineering analysis, a fault tree analysis, as well as a structural engine modelling which is capable of computing spool down, engine loads, part strength and damage simultaneously. According to that analysis the probable sequence of events that led to the 'K' flange bolts failure was:

- Fan blade release
- Engine case bending due to fan imbalance
- Fan blade rub against fan case creating a torsion through engine case
- Lateral motion of the engine case accelerates the MGB
- MGB center mount is loaded due to gearbox inertia
- MGB inertia load combines with case bending load
- MGB center bracket bolts fail due to the combined inertial and bending loads
- Remaining K-flange bolts progressively overload
- 'K' flange separates

Engine Manufacturer Actions and associated Regulatory Agency Releases

Following earlier FBO events, P&W developed enhancements to existing fan blade inspection processes and introduced new fan blade inspection methods that took place after the subject event.

On February 13, 2018, a Boeing 777-200 airplane, N773UA, operated by United Airlines as flight 1175, experienced a FBO event on a PW4077 engine, during cruise flight while enroute to

Honolulu, Hawaii. The aircraft landed safely in Honolulu (HNL). The NTSB initiated an investigation into that event.[12]

On December 4, 2020, a Boeing 777-200 airplane, JA8978, operated by Japan Airlines as flight 904, experienced a FBO event on a PW4077 engine, after takeoff from Naha Airport in Okinawa prefecture, Japan. The aircraft returned to Naha and landed safely. The Japan Transport Safety Board (JTSB) initiated an investigation into that event.[13]

During the investigation of the 2018 Honolulu FBO event, P&W issued Revision B, C, and D to TAI inspections contained in the P&W Non-Destructive Inspection Procedure (NDIP). These revisions added more detailed examples of acceptable and rejectable indications, introduced and updated a flowchart of the evaluation process, and incorporated improved evaluation sections and an improved feedback process involving process engineers. Improvements in training and equipment for the TAI process were also made, including introducing room temperature controls and the procedures to reduce stray heat sources that could affect the thermal camera. Revision E of the NDIP, issued in October 2018, introduced clarifications of accept / reject references and introduced a requirement for daily calibration of the TAI equipment as well as references to x-ray and UT procedures. P&W also reviewed the TAI digital data of the thermal images captured during fan blade inspections prior to 2018.

In response to the 2018 Honolulu FBO event, on February 15, 2019, the FAA issued Airworthiness Directive (AD) 2019-03-01, which required initial and repetitive (not to exceed 6,500 flight cycles) TAI inspection for cracks in the PW4077 112-inch fan blades in accordance with P&W Alert Service Bulletin (ASB) PW4G-112-A72-268, Revision No. 7, dated September 6, 2018.

In response to the subject event, on February 22, 2021, P&W issued Special Instruction (SI) 29F-21 which reduced the Alert SB A72-268 inspection intervals from 6,500 to 1,000 cycles for the first stage LPC blades on the affected engines.

In response to both the subject event and the 2020 Naha FBO event the FAA issued emergency AD 2021-05-51 on February 23, 2021, which instructed owners and operators of P&W PW4077 engines to perform an immediate TAI inspection of the blades for cracks before further flight, and to remove from service blades which failed the inspection.

In response to the subject event and to address the unsafe condition as defined by the FAA in prior ADs, on October 21, 2021 P&W released Alert SB PW4G-112-A72-361 entitled "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", superseding SI 29F-21. The inspections described in this Alert SB were made mandatory by AD 2022-06-09 that was released by the FAA on April 15, 2022, and superseded the two existing ADs: 2019-03-01 and Emergency AD 2021-05-51. The UT inspection targets three critical locations on fan blades and is required in addition to the prior TAI inspection requirements for the entire blade. Additionally, AD 2022-06-09 increased the frequency of inspections by requiring:

- all fan blades in service to be UT inspected before further flight, and TAI inspection before further flight if they are over 1,000 cycles since last TAI,

---

[12] NTSB reference number DCA18IA092

[13] NTSB reference number ENG21WA007

- the new UT repetitive inspection every 275-cycles for the convex flow path location and every 550-cycle for the convex and concave mid span locations.
- the existing TAI repetitive inspection interval to be shortened from 6,500 cycles to 1,000 cycles.

P&W developed a specialized portable automated UT scanning device consisting of 3 scanning systems that could scan the convex flow path, concave midspan, and convex midspan locations of the fan blade for internal cracks. With the kit, operators could perform the UT scan of the fan blades at their facility; however, the TAI inspection still required the fan blades to be returned to the P&W facilities in East Hartford. Seventeen confirmed cracked fan blades have been found as of January 31, 2023, nine of which were identified through the new UT inspection process.

The following table summarizes the various SBs and ADs:

Action	SB	Date of SB release	AD	Date of AD Release
- Require TAI inspection of 1st stage LPC blades that have accumulated fewer than 6,500 cycles since new (CSN) the next time the engine is separated at the M-flange, or prior to the 1st stage LPC blade accumulating 7,000 CSN, whichever occurs first. - For 1st stage LPC blades that have accumulated 6,500 or more CSN, or if the cycles since the blade was new cannot be determined, or if the cycles since the blade was last TAI inspected cannot be determined, perform a TAI inspection within 500 flight cycles or 180 days from the effective date of the AD, whichever occurs first. - Thereafter, perform a TAI inspection of 1st stage LPC blades every time the engine is separated at the M-flange and the blades have accumulated 1,000 or more flight cycles since the last TAI inspection, not to exceed 6,500 flight cycles since the last TAI inspection.	PW4G-112-A72-268, Revision No. 7	9/6/2018	2019-03-01	2/15/2019

Action	SB	Date of SB release	AD	Date of AD Release
Revised the Alert SB A72-268 TAI inspection intervals from 6,500 to 1,000 cycles for the first stage LPC blades on the affected engines	Special Instruction (SI) 29F-21	2/22/2021	2021-05-51	2/23/2021
Introduced UT inspection requirement for three critical locations on fan blades in addition to the prior TAI inspection requirements for the entire blade. • All fan blades in service to be UT inspected before further flight, and TAI inspection before further flight if they are over 1,000 cycles since last TAI, • UT repetitive inspection every 275-cycles for the convex flow path location and every 550-cycle for the convex and concave mid span locations. • TAI repetitive inspection interval to be shortened from 6,500 cycles to 1,000 cycles.	PW4G-112-A72-361	10/21/2021	2022-06-09	4/15/2022

Table 2 - Engine AD and SB Summary

AIRPLANE SYSTEMS AND STRUCTURES

The airplane and all airplane systems were functioning as expected prior to the engine event.

The right engine FBO event caused damage to the engine and nacelle structure. It also resulted in portions of the inlet and fan cowls separating from the nacelle and damage to the thrust reversers. Some of the fragments that departed contacted the right wing lower surface, right horizontal stabilizer, and fuselage wing to body fairing resulting in minor damage. Significant heat and fire damage to both thrust reversers halves occurred.

The adjacent airplane structures and systems in the engine strut and wing sustained the loads generated during the FBO event and maintained their integrity and function. After the FBO event the airplane systems and structures functioned to maintain continued safe flight and landing.

Engine Control and Fuel System

Each engine fuel feed line on the 777-200 is equipped with a rear spar-mounted shutoff valve, also called the spar valve, to terminate fuel flow to an engine when it is shut down. The flight crew moved the right engine fuel control switch to CUTOFF and the right engine fire switch was pulled to the up position during the event flight in response to the R ENG FIRE WARN warning that occurred after the FBO event. Either of these actions closes the right engine fuel shutoff spar valve which was confirmed to be in the CLOSED position on the incident aircraft as expected. This prevented further fuel flow to the damaged engine.

Engine Driven Hydraulic Pump Supply Shutoff Valve

The engine driven pump (EDP) supply shutoff valve closes to stop hydraulic supply from the reservoir to the EDP when the engine fire switch is in the up position. However, the EDP supply shutoff valve for the incident engine was found in the OPEN position after the event.

The right hydraulic system continued to operate throughout the event flight. A reservoir quantity of about 90-95% was recorded at the time of the engine failure and a quantity of about 65% was recorded at the time of the landing.

The NTSB formed a sub-group to investigate the operation and condition of this valve. This sub-group conducted examinations and disassembly of the valve and actuator at the manufacturer and at Boeing. The event valve did not initially operate with the existing actuator installed when tested at the manufacturer but did operate when tested with an exemplar actuator. High resistance measurements were recorded across several event actuator commutator bars. A chemical analysis was conducted on material that was present on the actuator motor commutator bar and brush surfaces removed from the event EDP supply shutoff valve. A silicone substance that contained copper metal and copper oxide fretting debris was found on these surfaces.

Although it was acknowledged that while the failure of the EDP supply shutoff to close during the event did not significantly contribute to the fire[14], the FAA issued an airworthiness directive requiring a periodic check of valve function. AD 2022-06-10 was published on 11 March 2022 requiring repetitive functional checks of affected 777-200 and 777-300 EDP supply shutoff valves to ensure they close in response to the fire handle input.

Engine Mounts and Fuel Tank Integrity

The engine mount structures of the 777-200 are designed to maintain their integrity and function during an FBO event. Examination after the event showed there was no evidence of damage to the aft engine mount and the associated links and attach hardware. At the front engine mount location, contact between the monoball housing and the front mount beam at the upper left and lower right locations was observed. Deformation of the bolts that attach the monoball to the engine were also observed. There were no penetrations observed common to the wing fuel tank structure and there was no evidence of any fuel leaks from the wing fuel tanks.

The Nacelle

The nacelle is the structure that surrounds the engine. At the front of the nacelle is the inlet. The inlet is an aerodynamic assembly that directs smooth, uninterrupted airflow into the engine, and around the external surface of the nacelle. Figure 3 below shows the inlet and other nacelle components:

---

[14] DCA21FA085 NTSB Powerplants Factual Report, dated 16 February 2023, page 34

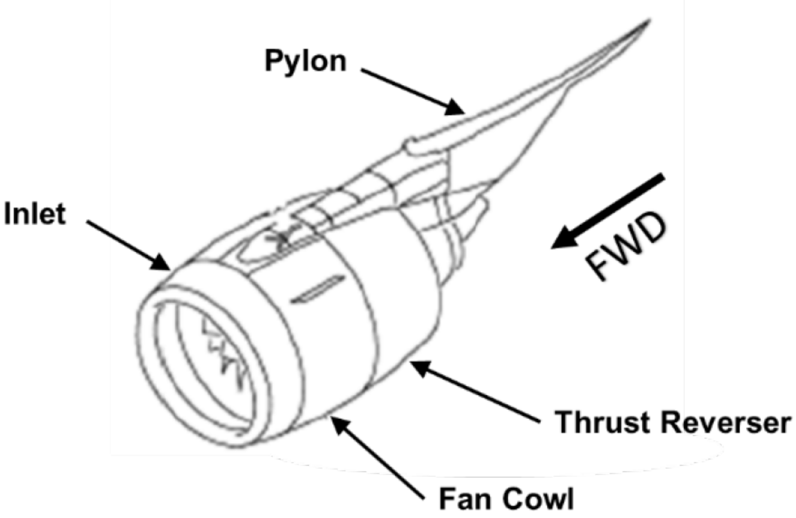

Figure 3- 777-200 PW4000 Engine Nacelle Components

The inlet is a cantilevered structure attached to the forward flange of the engine fan case (A-flange) through the inlet attach ring with 52 bolts. The inlet consists of two concentric cylindrical structures joined together by forward and aft bulkheads (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 the engine anti-ice air. The inlet aft bulkhead consists of the aluminum inlet attach ring and aluminum outer ring chord with a carbon fiber reinforced plastic (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 is comprised of 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.

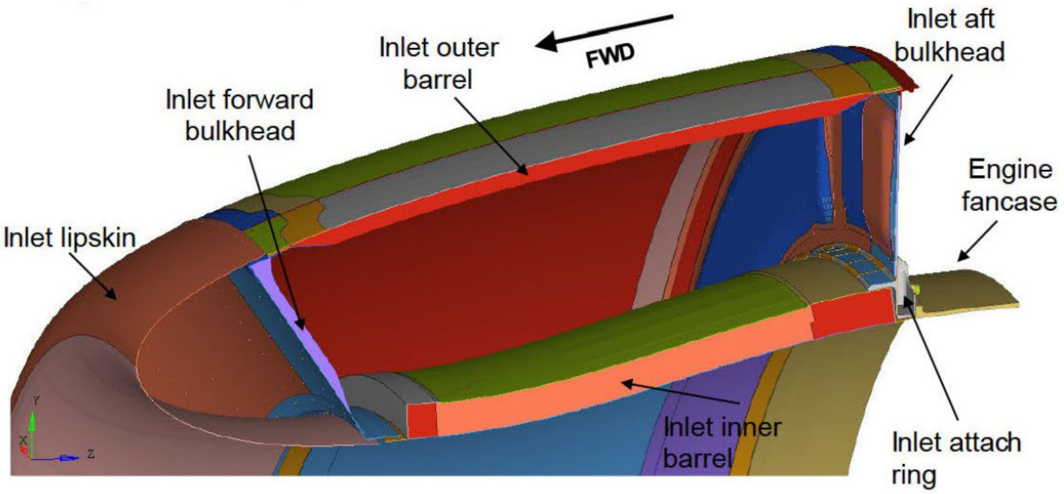

Figure 4- Inlet Cross Section for PW4000 powered 777-200

Aft of the inlet on the nacelle is the fan cowl. The fan cowl provides an aerodynamic enclosure around the engine fan cases and the doors open to allow maintenance access to the engine. The two fan cowls are semi-cylindrical doors that are each fastened to 4 hinges at the upper ends; 2 hinges on the fan cowl support beam, 1 floating hinge, and 1 hinge on the engine. The fan cowls are held together at the lower centerline through 4 latches (Figure 5). The fan cowls are CFRP honeycomb sandwich construction. The fan cowl support beam is a CFRP honeycomb sandwich panel and aluminum assembly 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.

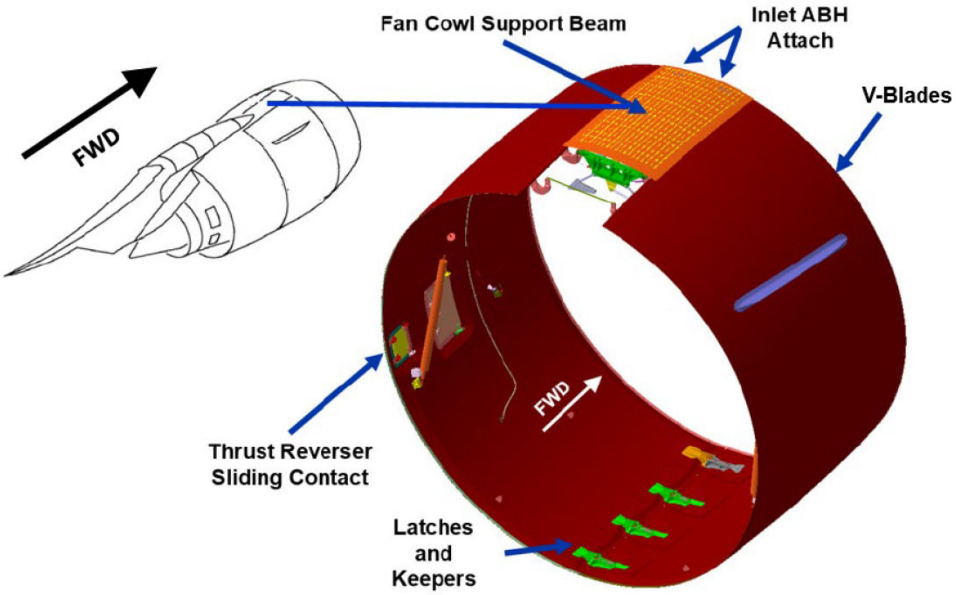

Figure 5 - Fan Cowl for PW4000 powered 777-200

Aft of the fan cowl are the thrust reversers (TRs). The TRs enclose the engine core to provide an aerodynamic enclosure around the engine, direct the fan exhaust, and actuate to provide reverse thrust during landing. The two semi-cylindrical TR halves are comprised of 3 main components, the translating sleeve, the fan duct cowl, and the aft cowl (Figure 6). 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 structure 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. The mechanism also deploys the blocker doors to direct the fan exhaust. Once the translating sleeve moves aft, the fan exhaust is directed through the CFRP cascades installed between the torque box and aft support ring to direct the air forward for reverse thrust. The CFRP honeycomb sandwich fan duct cowl outer wall engages the fan case through the outer v-blade seal and the fan duct cowl inner wall engages the engine core through the inner v-blade seal when the TR is closed. The TR halves are held in the closed position with 2 load share latches, 2 hoop tie latches, and 2 split line latches on the aft cowl and 6 latch beam latches on the fan duct cowl. There are three latch beam access doors on the inboard TR to allow access to the latch beam and drain lines at the lower centerline of the TR.

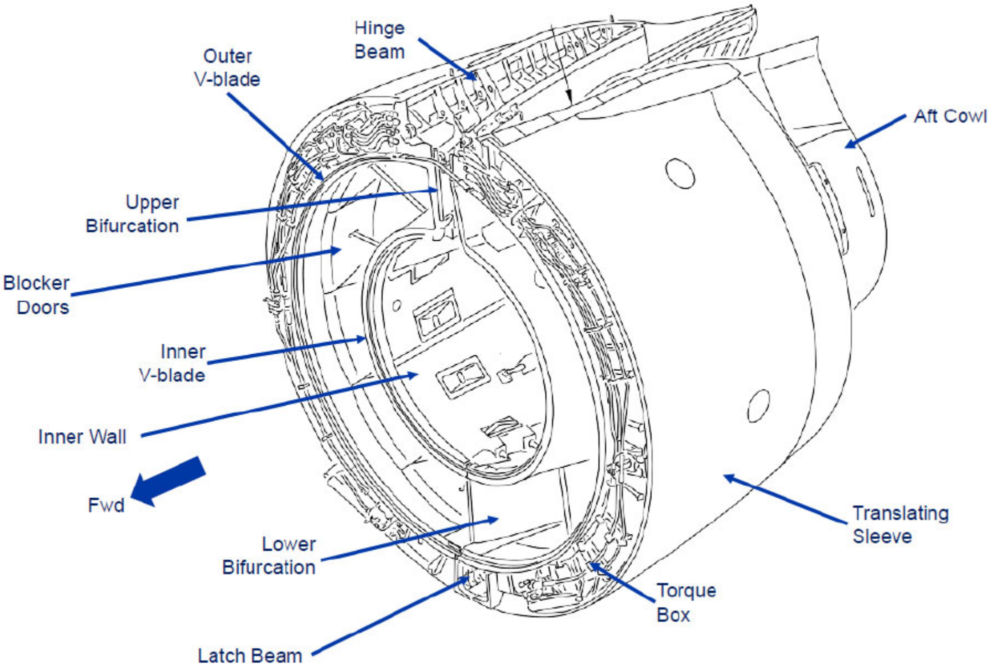

Figure 6 – Thrust Reversers for PW4000 powered 777-200

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 surface of the inner wall in the fire zone to protect the composite structure from radiant engine heat and fire.

Damage to the Nacelle During the Incident

Following the separation of fan blade no. 19 and failure of the engine ‘K’ flange, portions of the right engine’s inlet, fan cowl support beam, and fan cowls departed the airplane and the thrust reversers were damaged by an under-cowl engine fire.

The inlet separated from the right engine and was recovered on the ground in multiple pieces. The inlet attach ring remained attached to the engine A-flange after the event. The aluminum attach ring was mostly intact around the perimeter and all the fasteners were installed. The vertical leg of the attach ring was fractured where it attached to the fan cowl support beam. Most of the composite aft bulkhead web fractured from the attach ring at the outer edge of the vertical flange leaving small portions of the composite web attached.

A majority of the inboard and outboard fan cowl doors were recovered but had fractured into many pieces. The fan cowl support beam separated from the engine during the event. The forward attach point was fractured from the inlet attach ring and the three aft attach brackets installed on the fan case hinge beam were fractured. A portion of the inlet aft bulkhead and the fractured portion of the attach ring remained attached to the fan cowl support beam. Small portions of the right and left fan cowl doors remained attached to the forward two hinges on the left and right sides. The aft two fan cowl door hinges on the left and right sides remained on the airplane with small portions of the doors attached.

The left (inboard) and right (outboard) TRs remained installed after the event with the latches closed and latched. There was significant heat and fire damage to both TRs. A portion of the outboard TR translating sleeve outer skin about 52-inches wide circumferentially and 64-inches long axially was recovered separately on the ground. The Nacelle Drain Access Door normally installed on the inboard TR separated during the event was recovered separately on the ground and had moderate fire damage. The aft half of the lower bifurcation of the inboard TR inner wall was charred and sooted and there was an area of burn through damage in the drain mast area that measured 6-inches radially and 24-inches axially.

Following the incident, investigators attempted to recover as many of the pieces of the nacelle that had separated as possible. The NTSB led reconstruction of the inlet inner barrel, inlet outer barrel, and fan cowls at Boeing. As discussed more thoroughly in the airworthiness factual report[15], those recovered structures as well as the thrust reversers were examined as part of the investigation. Detailed observations and photos can be found in the Boeing EQA Report.[16]

The Effect of Fan Blade Out Events on an Aircraft's Structure

The incident aircraft experienced an FBO event, which means that a fan blade in one of its engines broke off while in flight. Figure 7 below shows the fan blades inside the fan case when they are intact:

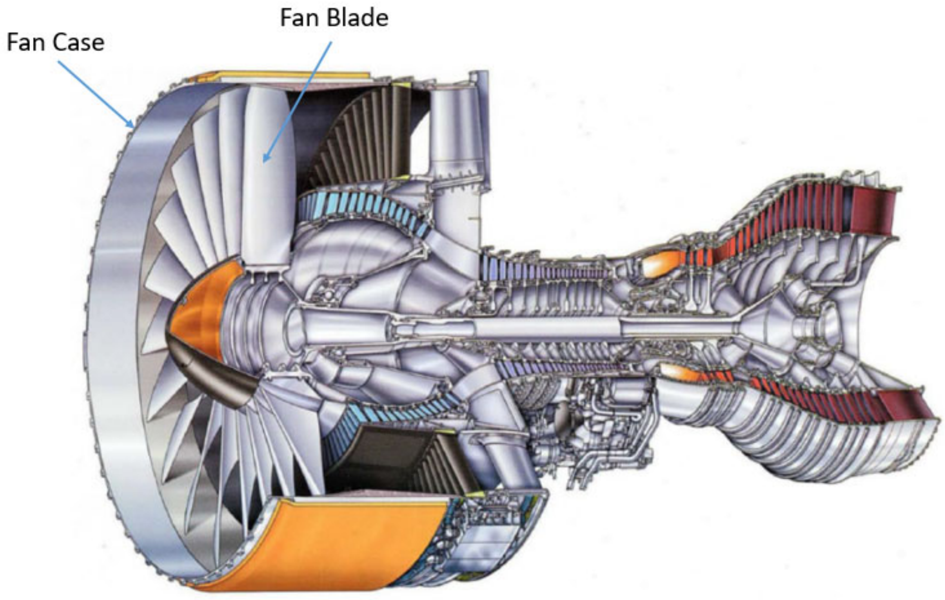

Figure 7 - Section view of Pratt & Whitney PW4077 Turbofan Engine

---

[15] DCA21FA085 NTSB Airworthiness Factual Report, dated 14 March 2022, pages 15 - 25

[16] DCA21FA085 NTSB Airworthiness Factual Report, Appendix A – Boeing EQA Report AS13328

In considering the effects of the FBO event on an aircraft's engine and the surrounding structure, it is helpful to break the event down into four phases based on our current understanding which has evolved since 777-200 certification due to advancements in analytical tools and their capabilities:

- **Impact phase (0.0 to 0.02 seconds)**: When the aircraft engine is running, the fan blades are rotating at high speeds. When part of a fan blade breaks off, the forces from the rotation cause it to travel away from the center of the fan disk, striking the fan case that surrounds the engine. That impact imparts forces into the fan case that cause it to deform outwards. That outward deformation can be viewed as a displacement wave that then travels both around the circumference of the fan case and forward and aft of the impact point until it depletes its energy. That deformation can cause damage to the surrounding structure. The impact also typically causes the portion of the fan blade that strikes the fan case to break into fragments of different sizes that can travel forward into the inlet or aft into the rest of the engine. When traveling forward into the inlet, the fragments are often rotating around the circumference of the fan case and inlet in a helical pattern, scraping across the fan case and then inlet. As they travel forward in the helical pattern, those fan blade fragments can cause damage to the inlet. Below is a diagram illustrating the helix angle at which fan blade fragments can travel:

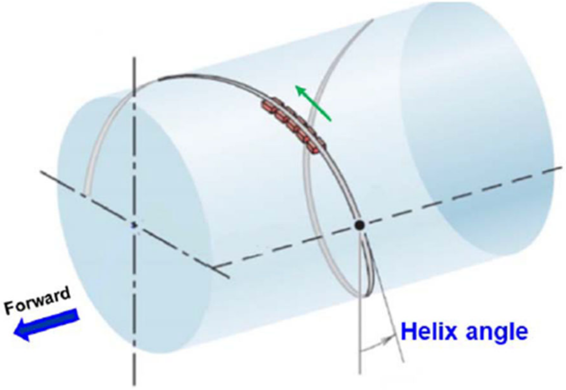

Figure 8 - Diagram showing helical pattern of forward-moving fan blade fragments.

- **FBO surge phase (0.02 to 0.2 seconds)**: With one fan blade missing, the fan rotor becomes unbalanced, which causes the remaining fan blades to rub against the fan case (normally there is clearance between the fan blades and the fan case). That contact in turn rapidly slows the fan rotor and related components, changing the pressure within the engine, which is normally carefully balanced. At the same time, the absence of one fan blade disrupts the normal air flow through the engine, causing additional pressure changes. The result of all this is a surge of high-pressure air flow through the engine, exiting the front and back of the engine. That surge can cause additional damage to the inlet.

- **FBO rundown phase (0.02 to 2.0 seconds)**: Following an FBO event, the fan rotor decelerates as the engine shuts down. This deceleration or "run down" typically takes approximately 2 seconds. During this time the surrounding structure experiences significant vibratory loading from the fan rotor deceleration, fan blade rubbing forces, and the imbalanced engine.

- **Windmilling phase (2.0 seconds to landing)**: Even after the engine decelerates, the fan continues to rotate due to airflow through the engine, albeit at a slower speed than when the engine is powering rotation. The continued imbalance caused by the damage to the fan blades imparts vibratory imbalance loads on the connecting structure.

FBO Certification History

In 1994 Pratt & Whitney performed a FBO test for certification of the PW4000 engine. The certification test was designed to demonstrate containment and safe shutdown of an engine after the intentional fracture of a fan blade at redline speed. The main focus of the test was on meeting applicable 14 CFR Part 33 engine certification requirements, including the response of the engine during an FBO event. Data from the test was also used in meeting 14 CFR Part 25 airplane certification requirements, including the response of engine mounts and TRs during an FBO event. Typically, an inlet and TRs are installed for the test, but fan cowls are not installed so that containment case behavior can be observed. The inlet installed for the test does not need to be a production part, but it must be representative of a production part. The engine mounts must be equivalent to production mounts. For the certification test, the inlet installed was of a different design than the production inlet and included an aluminum aft bulkhead, instead of the CFRP aft bulkhead, and a fiberglass and aluminum outer barrel, instead of the CFRP outer barrel installed on production units. During the test, the intended blade was released near the blade root and a portion of the following blade also fractured and separated. The containment case successfully retained the blade fragments. Within about two revolutions after blade release, fan blade segments traveled forward of the fan case, sliced through and separated about half of the inlet inner barrel, and one blade fragment exited the inlet inner and outer barrels. After design changes and analysis to show the observed failure effects relevant to 14 CFR Part 33 compliance were addressed to the satisfaction of the FAA Engine Certification Office, the engine was approved without repeating the fan blade out test.

Fan Blade Fragment Trajectories During the Incident Event

The investigation examined the fan case from the right engine of the incident aircraft along with the portions of the inlet that were recovered. Based on evidence obtained during that investigation, the NTSB and parties worked together to assess the fragment-induced fan case and inlet damage that is discussed in more detail within the airworthiness factual report.[17] A summary of the observations are noted below.

A section of fan blade about 18 inches spanwise by 16 inches chordwise was lodged in the aluminum isogrid of the fan case between 11:15 and 12:05. The group identified multiple witness marks corresponding to fan blade fragment trajectories on the inner surface of the fan case. The group mapped the more significant witness marks that included 4 forward moving fragments, 1 circumferential moving fragment, and 2 aft moving fragments.

The group identified 6 distinct witness marks corresponding to fan blade fragment paths on the inlet cowl inner barrel structure using the scuffing of the inner barrel skin, damage to the face sheet and core, transfer marks on the perforated face sheet, and damage to the lip skin and forward bulkhead inner and outer chords. Four of these fragment paths aligned with paths identified on the fan case inner surface.

---

[17] DCA21FA085 NTSB Airworthiness Factual Report, dated 14 March 2022, pages 15 - 19

Analysis of the Damage to the Nacelle During the Incident

Boeing used data collected during the investigation, including data from observations and laboratory examinations of recovered components. Using that data, Boeing employed current state-of-the-art structural analysis methods, which were not available at the time of certification, to conduct a progressive failure analysis. Boeing validated this analysis by comparing the results to the actual hardware recovered following the subject event and other FBO event incidents. This analysis is built upon the techniques described below and was used to inform the nacelle structural design changes that were implemented as part of the FAA approved time limited exemption mandated via ADs 2022-06-11 and 2022-06-10.

Following the 2018 Honolulu FBO event, Boeing began work on a dynamic simulation model to examine the failure scenarios of the inlet and fan cowl structures in comparison to the data collected during the certification FBO tests. The analysis utilized finite element modeling and progressive failure analysis with the physical evidence collected from the 2018 Honolulu FBO event and other subsequent FBO events. The analysis expanded the damage simulation beyond the typical 20-30 milliseconds following a FBO to capture the progressive failure effects up to 2 seconds following the FBO event. The loading conditions and simulations were broken down into the above noted four phases of an FBO event: (1) the impact phase (2) the surge phase (3) the rundown phase and (4) the windmilling phase.

Based on the data generated in the initial dynamic simulation that included findings from the 2018 Honolulu FBO event, Boeing began to develop inlet and fan cowl modifications intended to prevent the loss of both during an FBO event. After the 2020 Naha FBO event and the subject event in 2021, the documented damage from these two most recent events were used to inform the dynamic simulation used in the development of the interim solution nacelle modification design as discussed below. Simulation efforts at Boeing and P&W are ongoing to support longer term actions for the nacelle structure and engine designs.

Interim Nacelle Design Solution

After the subject event the FAA issued Emergency Airworthiness Directive (AD) 2021-05-51 effectively grounding all PW4000-112” powered 777-200 and 777-300 airplanes. In order to show full compliance with the regulations for the FBO failure condition, several design enhancements to the engine nacelle and engine for the PW4000 powered 777 models were required. In August 2021 Boeing applied for a time limited, partial exemption from the FAA to allow for expedited incorporation of safety improvements in the form of airplane design enhancements to the engine nacelle structure independent of engine design enhancements. The FAA approved Exemption No. 19032 in March 2022 and Boeing updated Section 9 Airworthiness Limitations (AWL) of the 777 Maintenance Planning Document (MPD) with this exemption. This time limited exemption enabled the affected 777 fleet to return to service with AD mandated engine nacelle modifications and enhanced fan blade inspections. This resulted in incorporation of an interim design solution that enabled earlier incorporation of modifications designed to reduce risks related to FBO.

Boeing developed the interim design solution and issued multiple Alert Service Bulletins to enable return to service of the affected 777 PW4000-112” powered fleet. The service bulletins include fan cowl inspections and modification to the inlet cowls and thrust reversers on 777-200 and 777-300 airplanes equipped with Pratt & Whitney PW4000 series engines. The FAA has mandated these Boeing Service Bulletins (SB) via ADs 2022-06-11 and 2022-06-10.

An inspection and repair of the fan cowls for moisture ingression was implemented in Alert SB 777-71A0092 associated with AD 2022-06-10.

Engine inlet cowl modifications were implemented in Alert SB 777-71A0085 associated with FAA AD 2022-06-11. This modification includes the replacement of fasteners used to attach the inlet to the engine at the A-flange with increased strength fasteners. The fasteners used to attach the aft edge of the outer barrel panels to the aft bulkhead were changed from countersunk head fasteners to pan head fasteners. Additional fasteners were installed on the panels at the upper quadrant of the inlet, to prevent pull through failures along the interface. Metallic doublers were added to the aft side of the aft bulkhead web to add strength and prevent the aft bulkhead failure from the FBO displacement wave. Metallic ballistic shielding panels were added between the inner barrel and outer barrel to prevent fan blade fragments from penetrating both barrels of the inlet. In conjunction with the modification, an inspection and repair of the outer barrel panels for moisture ingression was implemented.

Thrust reverser modifications were implemented in Alert SB 777-78A0103 associated with FAA AD 2022-06-10. Modification instructions for the TRs on affected airplanes were provided to install metallic debris shields on the inner surface of the fan duct inner wall behind the thermal blankets in the lower bifurcation area on both the inboard and outboard TR halves.

KNOWLEDGE GAINED DURING THE INVESTIGATION (Findings)

The following knowledge gained is pertinent to drawing conclusions:

- Weather conditions were not a factor in this incident.
- During climb shortly after takeoff from DEN, the right engine experienced an engine failure involving the loss of a single fan blade and failure of the engine ‘K’ Flange. This caused portions of the engine inlet and fan cowls to depart the airplane and initiated an under-cowl engine fire that affected the thrust reversers.
- The airplane and all airplane systems were functioning as expected prior to the engine failure. After the engine failure, the airplane systems and remaining structures functioned to maintain continued safe flight and landing.
- The engine fire detection, engine control, and fuel cutoff systems functioned as designed enabling shut down of the right engine when commanded by the flight crew.
- The hydraulic fluid supply shutoff valve for the right engine driven hydraulic pump did not close when commanded by the flight crew.
- An under-cowl engine fire initiated near the engine fuel oil cooler and servo fuel heater, both of which suffered impact damage during the engine failure. The under-cowl fire was unable to be extinguished by the engine fire bottles.
- The under-cowl fire spread to the thrust reverser translating sleeves due to the failure of the inboard thrust reverser firewall in the lower bifurcation area.
- The fan blade failure and failure of the engine ‘K’ flange resulted in the structural failures of the engine nacelle during the engine failure and the subsequent engine fire that spread to the thrust reverser translating sleeves.

CONCLUSIONS

Boeing believes that the evidence supports the following conclusions for the incident:

> This incident occurred due to failure of the right engine and the subsequent engine nacelle damage due to the resulting fan blade-out loads generated during the event. The engine failure was due to a fracture in a single fan blade caused by fatigue crack growth at a local geometric discontinuity and carbon contamination at an internal cavity surface that occurred during the manufacturing process. Failure of the engine 'K' flange occurred due to insufficient 'K' flange bolt strength in the presence of fan-blade out loads. Portions of the inlet cowl and fan cowls departed the airplane due to damage and stresses experienced in excess of those observed during certification. The under-cowl fire resulted from auto ignition of flammable fluid leakage likely from the engine fuel oil cooler and servo fuel heater that impacted each other due to main gearbox separation from the engine 'J' and 'K' flanges. The under-cowl fire spread to the thrust reverser translating sleeves due to the failure of the inboard thrust reverser firewall in the lower bifurcation area.

BOEING ACTIONS

As a result of this investigation, Boeing has taken the following actions:

- Boeing released a multi-operator message (MOM-MOM-21-0398) to affected PW4000 series operators in September 2021 requesting operators perform a functional test of both EDP shutoff valves per Airplane Maintenance Manual (AMM) procedures prior to return to service. The FAA mandated that these checks be performed every 10 days with the release of FAA AD 2022-06-10.
- Boeing released revised and new Fleet Team Digest (FTD) articles 777-FTD 71-18003, 777-FTD-71-20001, 777-FTD-71-22001, and 777-FTD-71-22002 informing 777 operators of the ongoing NTSB investigation into the subject event and the issuance of Alert Service Bulletins for interim solutions.
- Boeing updated Section 9 of the 777 Maintenance Planning Document in March 2022 to include a Systems Airworthiness Limitation referring to approval of FAA Exemption No. 19032 regarding fan blade out conditions.
- Boeing released Alert Service Bulletin 777-71A0092 issued on January 13, 2022 to implement Fan Cowl Fluid Ingression Inspections. This SB is associated with FAA AD 2022-06-10.
- Boeing released Alert Service Bulletin 777-71A0085 issued on May 16, 2022 to implement Engine Inlet Cowl Modifications. This SB is associated with FAA AD 2022-06-11.
- Boeing released Alert Service Bulletin 777-78A0103 issued on May 16, 2022 to implement Left and Right Thrust Reverser Halves, Lower Bifurcation Wall Reinforcement Plate installation. This SB is associated with FAA AD 2022-06-10.
- Boeing continues to work with the FAA, engine manufacturers, and the industry as part of the FAR 21.3 continued airworthiness corrective action process.