Aviation Investigation Final Report

Location:	Atlanta, Georgia	**Incident Number:**	ENG18IA036
Date & Time:	September 5, 2018, 23:32 Local	**Registration:**	N668DN
Aircraft:	Boeing 757	**Aircraft Damage:**	Minor
Defining Event:	Uncontained engine failure	**Injuries:**	N/A
Flight Conducted Under:	Part 121: Air carrier - Scheduled		

Analysis

The high-pressure turbine (HPT) uncontainment was caused by the failure of a rotating seal located between the HPT 1st-stage (S1) disk and 2nd-stage (S2) hub (the lenticular seal). The lenticular seal outer structure separated from an inner brace piece and unwound, destroying the turbine. Seal fragments breached the turbine cases. A fragment traveled forward, destroying the HPT S1 blades and penetrating the S1 turbine nozzle assembly and combustor, damaging a fuel nozzle stem, and releasing fuel.

The crack initiation site was destroyed by secondary damage. Although the failure mode was not determined, PW2000 engine lenticular seal cracks are a known failure associated with knife edge tip fatigue cracks that originate at the first or second knife edge tip and propagate down the knife edge pedestal to the barrel. Past root cause investigations determined that normal knife edge rub can cause local increases in knife edge tip temperature when the knife edge coating is worn and has begun to spall. Continued rub with degraded knife edge coating creates a heat affected zone at the knife edge tip that can lead to thermo-mechanical fatigue (TMF) and tip crack initiation. TMF is more likely to develop with second run seals matched with new honeycomb material.

Review of the engine service records found that the failed lenticular seal was installed new during a 2008 overhaul when the engine had accumulated 61,385 time since new (TSN) and 25,462 cycles since new (CSN). The seal was visually inspected and reinstalled during a 2013 overhaul at 74,042 TSN and 31,701 CSN. During the 2013 shop visit, 40% of the

lenticular seal land honeycomb surface was replaced. The lenticular seal chromium carbide knife edge coating was not renewed, so that the second-run lenticular seal knife edges with chromium carbide coating ran against new honeycomb material. The lenticular seal failed 6,460 cycles after the 2013 shop visit.

An improved-design lenticular seal with the chromium carbide knife edge coating replaced with a more durable, temperature-resistant aluminum oxide coating was released by PW2000 SB 72-754 in 2011. The new-design seal was introduced as a part replacement on an attrition basis (use down-change part until exhausted).

Probable Cause and Findings

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

A right engine turbine uncontainment resulting from failure of the high pressure turbine (HPT) lenticular seal due to a fatigue crack originating from an overheated region at a knife edge tip.

Contributing to the failure was Pratt & Whitney's decision to introduce the temperature-resistant knife-edge coating as a new-part number lenticular seal on an attrition basis without the option to recoat existing lenticular seals, which delayed implementation of the more durable seal material into the fleet.

Findings

Aircraft	Turbine section - Design

Factual Information

History of Flight

Initial climb	Uncontained engine failure (Defining event)
Initial climb	Loss of engine power (partial)
Initial climb	Engine shutdown

HISTORY OF FLIGHT

On September 5, 2018, about 2332 EDT, a Delta Air Lines (DAL) Boeing B757-232, N668DN, experienced a right engine failure during climb after departing Hartsfield-Jackson International Airport, Atlanta, Georgia (ATL). The flight crew reported hearing a loud bang and noting airplane vibration and engine failure indications. The right engine was shut down and the flight returned to ATL where an uneventful single-engine landing was performed. The airplane was being operated as a Title 14 *Code of Federal Regulations* Part 121 scheduled flight from ATL to Orlando International Airport (MCO). The airplane damage was minor. No injuries were reported.

DAMAGE TO THE AIRPLANE

Post-incident airplane inspection found a hole in the inboard side of the right nacelle and minor impact damage to the airplane's right wing, fuselage, and horizontal stabilizer. A piece of debris identified as high pressure turbine (HPT) lenticular seal material was observed protruding from the engine case.

RECORDERS

Review of DFDR data found no abnormal engine operation or indications prior to the failure.

TEST AND RESEARCH

Lenticular seal

The lenticular seal is a labyrinth-type rotating seal located between the HPT S1 disk and S2 hub. An outer seal structure with five knife edges and forward and aft snap surfaces fits to an inner brace. Both pieces are IN-100 alloy steel and become an inseparable assembly during manufacture. The five knife edges run against honeycomb-surfaced seal lands attached to the HPT S2 vane assemblies. See Figure 1.

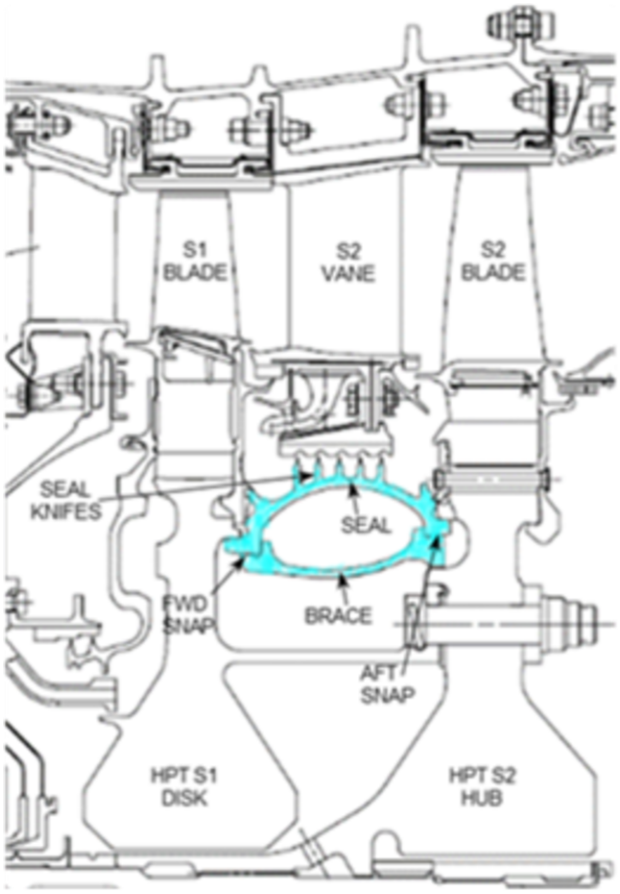

Figure 1. Cross section drawing of the HPT showing lenticular seal

Engine maintenance

The lenticular seal was installed new during a 2008 engine overhaul when the engine had accumulated 61,385 time since new (TSN) and 25,462 cycles since new (CSN). The seal was visually inspected and reinstalled during a 2013 overhaul at 74,042 TSN and 31,701 CSN. During the 2013 shop visit, 40% of the seal land honeycomb surface was replaced. The

lenticular seal knife edge coating was not renewed. The lenticular seal failed 6,460 cycles after the 2013 shop visit.

Engine disassembly examination

There was a 14-inch circumferential by 3-inch axial hole in the engine HPT case along the plane of the HPT S2 vanes at 7 o'clock. A 6-inch-long debris fragment identified as lenticular seal material was protruding from this breach. There was a 7-inch circumferential by 2 1/2-inch axial hole in the low pressure turbine (LPT) case in plane with the outer transition duct at 8 o'clock. There was a 6-inch circumferential by 1 1/2-inch axial hole in the HPT case along the plane of the HPT S1 blades at 5 o'clock. All HPT S1 blades were fractured to an inch or less above their platforms. The HPT S1 blade outer air seal (BOAS) supports were intact. The HPT S1 BOAS were liberated between 5 and 1 o'clock; the other BOAS were intact. A 30° arc of the tangential on-board injector seal knife edges was slightly damaged. A piece of lenticular seal was found spiraled over the S1 blade stubs at 10 o'clock, extending forward about 12 inches into the diffuser/combustor case. The HPT S1 vanes between 9 and 12 o'clock were fractured or liberated and the combustion outer liner dome was inwardly deformed and displayed a 5-inch circumferential by 2½-inch axial hole at 10 to 11 o'clock upstream of the penetration. A fuel nozzle in line with this damage was punctured through the stem and heat shield; the fuel nozzle leaked when shop air was applied.

The HPT S2 vanes between 3 and 11 o'clock were liberated. One HPT S2 blade was fractured below the platform. The remaining HPT blades were fractured one inch or less above their platforms. Secondary damage obscured the fracture surfaces of the above-platform fractures; the below-platform fracture surface was clean and uniformly granular.

The LPT gas path components from the LPT S3 vanes to the S5 vane leading edges were thermally consumed or had the appearance of re-hardened slag over a 30° arc centered on 9 o'clock.

Disassembly of the HPT rotor found the inner brace structure of the lenticular seal in place and intact between the S1 disk and S2 hub. The downstream face of the S1 disk and the upstream face of the S2 hub exhibited heavy circumferentially oriented damage. A rough reconstruction of the lenticular seal fragments confirmed the 64-inch circumference of an intact seal. All S2 vane honeycomb material was consumed. See Figure 2.

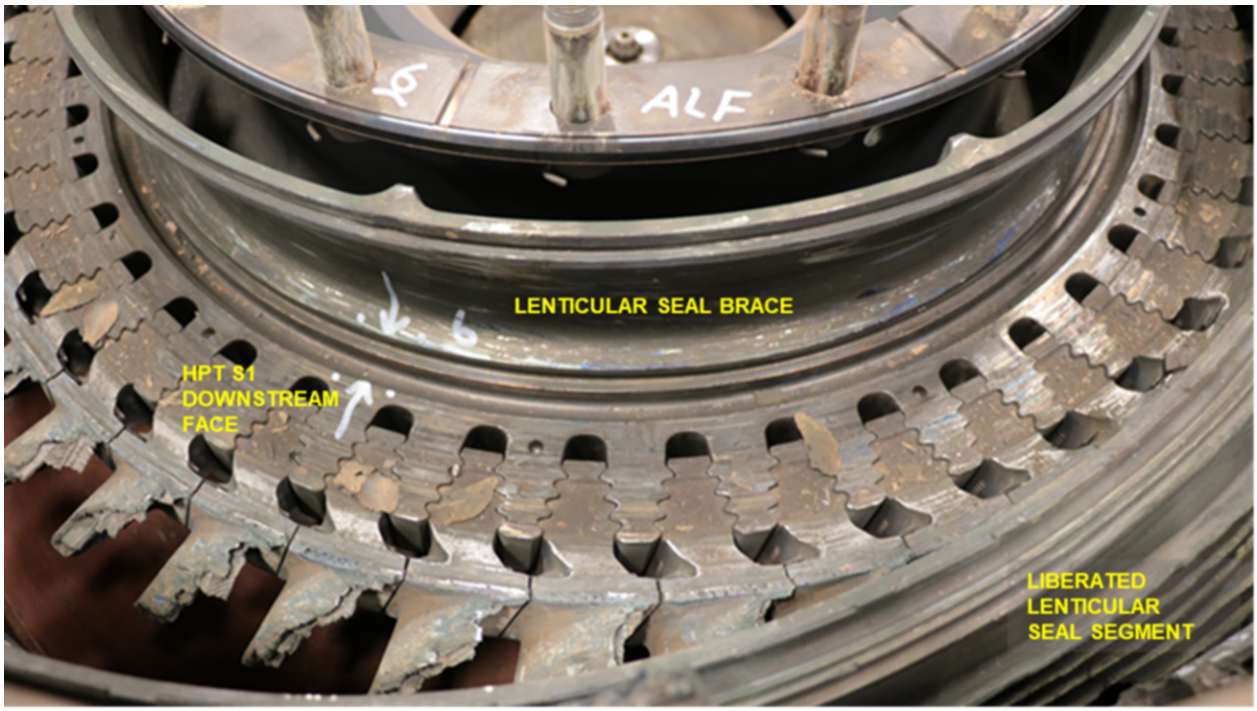

Figure 2. View of the HPT stack with S1 disk removed

Materials examination

Pratt & Whitney examined the seal fragments at their Material & Processes Engineering (M&PE) Lab in East Hartford, Connecticut with NTSB Materials Lab oversight. The metallurgical examination identified an axial separation through the seal barrel as the most likely primary fracture. The fracture included the full cross section of the seal from the forward to the aft snap. The mating side of this fracture was destroyed.

The area forward of knife edge 3 was missing or significantly damaged. The region from knife edge 3 to the aft edge was examined. The remaining knife edges (3-5) had fractured outboard of the pedestal and no significant amount of knife edge remained. See Figure 3.

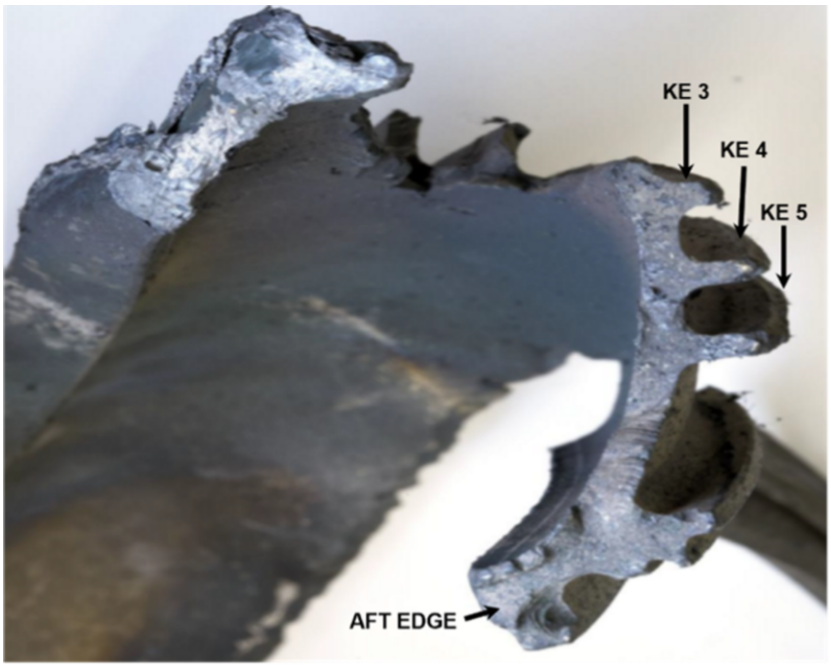

Figure 3. Axial fracture surface, lenticular seal

The fracture surface was oxidized and covered with deposits, obscuring most signs of directionality. However, remnant river lines and beach marks were observed indicating progression from the area of the knife edges toward the aft edge. No origin area was identified.

The fracture path appeared mostly flat in the region of knife edges 3, 4, and 5. Some evidence of shear lips and other topography changes was observed toward the tips of all three knife edges and toward the inner diameter of the seal at knife edge 5. This fracture path suggested an initiation location forward of knife edge 3. Aft of knife edge 5, the crack began to turn circumferentially while continuing to progress towards the aft edge. Scanning electron microscopy (SEM) examination of the fracture surface found no original fracture features.

Examination of a metallographic section prepared through a seal fragment that was shielded from thermal distress found microstructure typical of properly processed IN-100 material and conforming to quality manual requirements for the material. Energy dispersive spectroscopic analysis found material composition conforming to the IN-100 requirement.

The NTSB Materials Lab concurred with the findings and conclusions of the P&W M&PE materials report. The report is available in the public docket.

OTHER INFORMATION

Precursor events

There were 39 previous PW2000 lenticular seal failures. Other than one corrosion-induced case relating to a cleaning process, all the failures were attributed to fatigue cracks originating at the first or second knife edge tip and propagated down the knife edge pedestal to the barrel. Root cause investigation of these failures determined that the knife edge tip temperature is elevated when the knife edge coating is worn and has begun to spall. Continued rub with degraded knife edge coating creates a heat affected zone at the knife edge tip that leads to TMF and crack initiation.

An improved-design lenticular seal with the chromium carbide knife edge coating replaced by a more durable, temperature-resistant aluminum oxide coating was released by PW2000 SB 72-754 in 2011. Bulletin compliance was on an attrition basis.

Corrective actions

On April 30, 2019, Revision 2 of PW2000 SB 72-754 (upgrade to the new-PN lenticular seal with the temperature-resistant aluminum oxide knife edge coating) changed the bulletin compliance category from CAT 7 (do when supply of superseded parts is fully used) to CAT 5 (perform at next module exposure).

On August 14, 2019, Revision 3 to PW2000 SB 72-754 released new part numbers (PNs) and instructions for rework of the lenticular seal with chromium carbide-coated knife edges to the improved-durability aluminum oxide knife edge coating (modify PN 1A8209 to PN 1A8209-002 or PN 1A8209-001 to PN 1A8209-003).

Pratt & Whitney developed a technique sheet (NDIP-1217) for on-wing HPT lenticular seal borescope inspection (BSI) in January 2018 and on March 11, 2020, issued CAT 3 PW2000

SB 72-773 requiring BSI of PN 1A8209 or 1A8209-001 lenticular seals every 500 cycles until a part eligible for installation is installed.

Root cause analysis also identified a PW2000 subpopulation at higher risk of temperature-induced lenticular seal knife edge fatigue - engines configured for unmodulated turbine cooling air (TCA).

On February 24, 2021, 2020 BSI PW2000 SB 72-773 was revised to prioritize the higher-risk subpopulation (PW2000 engines with deactivated TCA systems) and to modify the compliance to require the lenticular seal BSI within 2,500 cycles since the last HPT overhaul beginning March 15, 2022, or in 500 cycles or less after March 15, 2022, if, on March 15, 2022, 2,000 cycles have occurred since the last HPT overhaul.

On July 28, 2021, the FAA published Airworthiness Directive (AD) 2021-14-13, effective September 1, 2021, requiring that PN 1A8209 and 1A8209-001 lenticular seals have the chromium carbide coating removed and a fluorescent penetrant inspection performed at every piece part opportunity. The lenticular seal must be removed from service and replaced with a part eligible for installation if any crack is found. If a crack is found in a critical area defined by the AD and extends toward the knife edge region, the lenticular seal, the S1 disk and the S2 hub must be removed from service. The AD also requires the replacement of PN 1A8209 and 1A8209-001 with a part eligible for installation at the next shop visit after September 1, 2021. The AD compliance identified the unmodulated TCA-configured fleet subset as higher risk.

Information

Certificate:	**Age:**
Airplane Rating(s):	**Seat Occupied:**
Other Aircraft Rating(s):	**Restraint Used:**
Instrument Rating(s):	**Second Pilot Present:**
Instructor Rating(s):	**Toxicology Performed:**
Medical Certification:	**Last FAA Medical Exam:**
Occupational Pilot:	**Last Flight Review or Equivalent:**
Flight Time:	

Aircraft and Owner/Operator Information

Aircraft Make:	Boeing	**Registration:**	N668DN
Model/Series:	757 232	**Aircraft Category:**	Airplane
Year of Manufacture:	1991	**Amateur Built:**	
Airworthiness Certificate:	Transport	**Serial Number:**	25141
Landing Gear Type:	Tricycle	**Seats:**	
Date/Type of Last Inspection:		**Certified Max Gross Wt.:**	248020 lbs
Time Since Last Inspection:		**Engines:**	2 Turbo fan
Airframe Total Time:		**Engine Manufacturer:**	Pratt & Whitney
ELT:		**Engine Model/Series:**	PW2037
Registered Owner:		**Rated Power:**	2000 Horsepower
Operator:		**Operating Certificate(s) Held:**	Flag carrier (121)

Meteorological Information and Flight Plan

Conditions at Accident Site:	Unknown	**Condition of Light:**	Not reported
Observation Facility, Elevation:		**Distance from Accident Site:**	
Observation Time:		**Direction from Accident Site:**	
Lowest Cloud Condition:		**Visibility**	
Lowest Ceiling:		**Visibility (RVR):**	
Wind Speed/Gusts:	/	**Turbulence Type Forecast/Actual:**	/
Wind Direction:		**Turbulence Severity Forecast/Actual:**	/
Altimeter Setting:		**Temperature/Dew Point:**	
Precipitation and Obscuration:			
Departure Point:	Atlanta, GA	**Type of Flight Plan Filed:**	
Destination:	Orlando, FL	**Type of Clearance:**	Unknown
Departure Time:		**Type of Airspace:**	

Wreckage and Impact Information

Crew Injuries:	N/A	**Aircraft Damage:**	Minor
Passenger Injuries:	N/A	**Aircraft Fire:**	None
Ground Injuries:		**Aircraft Explosion:**	None
Total Injuries:	N/A	**Latitude, Longitude:**	33.750141,-84.389007(est)

Administrative Information

Investigator In Charge (IIC):	Horgan, Carol
Additional Participating Persons:	Dave Keenan; FAA; Washington, DC Taylor Smith; Delta Air Lines; Atlanta, GA Dan Marcotte; Boeing; Seal Beach, WA Patrick Paris; Airline Pilots Association; Atlanta, GA Terri Chiong; Delta Air Lines; Atlanta, GA Todd Gentry; FAA; Washington, DC John Koza; Pratt & Whitney; E. Hartford, CT Mike Millat; Pratt & Whitney; E. Hartford, CT Matt Smith; FAA; Burlington, MA Jeff Strausbaugh; Pratt & Whitney; E. Hartford, CT
Original Publish Date:	April 6, 2022 **Investigation Class:** 3
Note:	The NTSB did not travel to the scene of this incident.
Investigation Docket:	https://data.ntsb.gov/Docket?ProjectID=98289