Aviation Investigation Final Report

Location:	Charleston, South Carolina	**Incident Number:**	DCA12IA114
Date & Time:	July 28, 2012, 16:00 Local	**Registration:**	VT-ANJ
Aircraft:	Boeing 787	**Aircraft Damage:**	Minor
Defining Event:	Powerplant sys/comp malf/fail	**Injuries:**	5 None
Flight Conducted Under:	Part 91: General aviation - Flight test		

Analysis

During a taxi test with no intention for flight, as the airplane was approaching 40 knots speed and prior to the engine N1 accelerating beyond 70%, the right engine N1 began to rollback and an EICAS advisory message was displayed indicating an N2 (high pressure rotor speed) exceedance.The flight crew reduced engine power to idle thrust, concluded the taxi test, and shut down the right engine during taxi back to the ramp. Examination of the right engine revealed extensive damage to the low pressure turbine (LPT).

The fan mid shaft (FMS) retaining nut was still connected to the FMS threads but the forward part of the FMS, from the rear of the forward threads, was separated from the remainder of the FMS. Separation of the rotating LPT section from the fan, allowed the LPT section to translate rearward resulting in extensive secondary engine damage.

Examination confirmed separation of the FMS adjacent to the lock nut face located at the aft most full thread root. The fracture exhibited features indicative of multiple failure modes: one progressive, and one instantaneous. About 85 percent of the fracture surface exhibited features consistent with progressive fracture. The remaining fracture surface showed signs consistent with instantaneous failure by overstress. Further examination revealed features consistent with environmentally assisted cracking (EAC) specific to GE 1014 ultrahigh strength steel.

The FMS threads and the retaining nut were coated with a dry film lubricant, and grease or engine oil was used as an assembly aid. Although a lead based dry film lubricant was previously used on GE engine fan mid shafts, during development of the GEnx engine, the design was changed to incorporate a lead free dry film lubricant, and graphite grease instead of the previously used engine oil as an assembly aid.

Testing of specimens taken from the FMS, and comparison to other dry film lubricants used previously on GE 1014 ultrahigh strength steel indicated that the dry film lubricant used on the incident FMS absorbed moisture at a higher rate. Additionally, the combination of dry film lubricant and graphite assembly grease was shown to increase the corrosion rate of GE 1014.

Following the FMS separation that occurred during this taxi test, GE developed an ultrasonic inspection to scan the forward end of the FMS in the area of the threads where the fracture occurred. While conducting the inspections, a GEnx-1B engine installed on another airplane was found to have an indication of a similar crack on the FMS. This airplane had not yet been operated in flight. Follow up testing indicated the crack exhibited features consistent with progressive environmentally assisted cracking.

Probable Cause and Findings

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

The separation of the fan mid shaft resulted from environmentally assisted cracking under static load.

Contributing to the incident was the combination of dry film lubricant applied to the fan mid-shaft and graphite grease used during assembly which made the fan mid-shaft susceptible to corrosion from trapped moisture, and the failure of the engine manufacturer to identify this vulnerability during design/development.

Findings

Aircraft	Reduction gear and shaft - Fatigue/wear/corrosion
Aircraft	Reduction gear and shaft - Design
Organizational issues	Equipment design - Manufacturer

Factual Information

History of Flight

Taxi	Powerplant sys/comp malf/fail (Defining event)

HISTORY OF FLIGHT

On July 28, 2012, at 1600 eastern daylight time, a Boeing 787-8, registration VT-ANJ, experienced an engine failure during a taxi test at Charleston AFB / International Airport (CHS), Charleston, South Carolina. The airplane was being operated by Boeing under the provisions of Chapter 14 *Code of Federal Regulations* (CFR) Part 91 for the purpose of conducting a taxi test with no intention for flight. There were no injuries to the 5 people on board and the airplane sustained minor damage.

The crew taxied on to runway 21 to conduct the first of two taxi tests. The first test was to be conducted at low speed with a planned maximum speed of 60 knots.

At approximately 16:00:32 the flight crew commanded takeoff power of 95.4 % N1 (low pressure rotor speed). As the airplane was approaching 40 knots speed and prior to the engine N1 accelerating beyond 70%, the right engine N1 began to rollback and an EICAS advisory message was displayed indicating an N2 (high pressure rotor speed) exceedance.

At 16:00:40 and about 40 knots, the flight crew reduced engine power to idle thrust and advised air traffic control tower they had completed their test stating "that's going to do it for us today". The crew exited the runway via a left turn on taxiway hotel, and during taxi back to the ramp, shut down the right engine.

The crew of Southwest Airlines flight 2414 was subsequently cleared for takeoff on runway 21 and reported a fire developing in the grass on the right side of the runway. Due to the close proximity of the fire to the runway air traffic control suspended all operations on runway 21 and notified Airlift Wing Operations (AMOPS) at about 1605.

After the fire department extinguished the fire, AMOPS conducted a runway inspection and discovered metal foreign object debris (FOD) on the first 4,000 feet of runway 21 prior to the intersection of taxiway foxtrot.

During post taxi inspection on the ramp, Boeing crew identified damage to the airplane and notified air traffic control.

INJURIES TO PERSONS

There were no injuries to the 5 crewmembers on board.

DAMAGE TO AIRPLANE

There were numerous impact marks and small holes on the underside of the right wing, the right side of the fuselage aft of the wing, and the right side of the horizontal stabilizer. The on-scene examination of the right engine revealed extensive damage to the low pressure turbine (LPT).

The fan mid shaft (FMS) retaining nut was still connected to the FMS threads but the forward part of the FMS, from the rear of the forward threads, was separated from the remainder of the FMS. Separation of the rotating LPT section from the fan, allowed the LPT section to translate rearward resulting in extensive secondary engine damage.

PERSONNEL INFORMATION

The flight crew consisted of two pilots and three additional crewmembers.

The captain reported approximately 12,500 hours total time, including about 9,700 hours as pilot-in-command and 174 hours in the B787. The captain held a valid Federal Aviation Administration (FAA) Airline Transport Pilot (ATP) certificate with type ratings for B737, B747-4, B757, B767, B777, and B787 and a current FAA first-class medical certificate with no limitations.

The first officer reported approximately 6,700 hours total flight time, including about 4,200 hours as pilot-in-command and about 44 hours in the B787. He held a valid FAA ATP certificate with type ratings for DC-9, B737, and B787, and a current FAA first-class medical certificate with a limitation that he must wear corrective lenses.

AIRCRAFT INFORMATION

VT-ANJ, manufacturer serial number 36281, was a Boeing 787-8 equipped with two General Electric GEnx-1B67 engines. The company reported that the airplane had approximately 0 hours total time on the airframe. Recorded data and company records indicated no relevant maintenance issues with the airplane. At the time of the incident the airplane was operating at an estimated weight of 351,441 pounds with 13,455 gallons of fuel on board.

Engine History

The right engine was a GE GEnx-1B, engine serial number (ESN) 956-121. The engine had only been operated on the ground and at the time of the incident, the engine had operated a total of 18:16 hours; 9:21 hours in a test cell, and 8:55 hours after being installed on the airplane.

The engine's fan mid shaft was a tubular shaped shaft made of ultrahigh duplex strengthened steel. The shaft transmits rotational energy of the LPT to the fan and booster.

Fan Mid-Shaft History

The FMS was about 8 feet long and was manufactured of GE1014 ultrahigh strength steel. The FMS included threads on the interior and exterior surfaces which allowed coupling to adjacent components. The inside of the FMS was coupled to the center vent tube (CVT) while the exterior joined the FMS with the forward fan shaft using a locking nut and washer. The shaft threads were coated with a cured dry film lubricant, and petrolatum graphite grease was applied to the threads to aid in assembly.

The FMS was originally forged by ATI-Allvac in Monroe, North Carolina in September 2006. In June 2007, the FMS was shipped to IHI Corporation in Japan where it underwent a number of manufacturing steps including rough turning, finish turning, splining, application of paint, balancing, application of dry film lubricant to threads, and various inspections including the final inspection in June 2008. The FMS was shipped to General Electric in Kentucky in November 2008. Almost two years later, in October 2010, the FMS was shipped to GE in North Carolina where it was installed in the LPT module. The LPT module was installed on the engine in November 2010.

METEOROLOGICAL INFORMATION

The CHS surface observation at 1556 EDT reported wind from 220 degrees at 12 knots gusting to 19 knots, visibility 10 miles, few clouds at 3,000 feet, scattered clouds at 4,200 feet, temperature 33 degrees Celsius, dew point temperature 25 degrees Celsius, and altimeter setting 29.95 inches of mercury.

AERODROME INFORMATION

Charleston AFB / International (CHS), a civilian/military joint-use airport, was located about 9 miles northwest of the city of Charleston, South Carolina. Operations were conducted using 4 runways for military, commercial and general aviation. Runway 21 was grooved concrete, 7,000 feet long, 150 feet wide with a touchdown zone elevation of 40 feet. The runway included precision markings and intersected runway 15/33 about 800 feet from the approach end of runway 21.

FLIGHT RECORDERS

Two Enhanced Airborne Flight Recorders (EAFR) were installed on the airplane. The forward and aft EAFRs were identical except that the forward was equipped with a recorder independent power supply (RIPS) to provide backup power to the recorder for approximately 10 minutes after the primary source of power was lost. The EAFR-2100 was a multifunction recorder which records flight data, audio data, and communication, navigation, surveillance air traffic management (CNSATM) messages.

The forward EAFR, serial number 16PLHY was removed from the airplane and sent to the NTSB Vehicle Recorder Division. The recording contained approximately 35.1 hours of data. The incident recording session was the third session from the end of the recording and was approximately 2 hours and 6 minutes.

The voice recorder included 2 hours, 3 minutes, 59 seconds of recording on four audio channels divided into three segments. The event was captured on the first segment which began at 15:35:48 prior to engine start and ended at 16:55:56. The audio quality of the channels was characterized as good to excellent.

WRECKAGE AND IMPACT INFORMATION

The front portion of the FMS with the attached FMS retaining nut and CVT were removed from the engine and sent to GE Cincinnati for metallurgical examination. The remainder of the engine was then removed from the airplane and sent to GE Cincinnati for disassembly and examination.

TESTS AND RESEARCH

Engine Examination

The exterior examination of the engine showed no indication of uncontainments, case ruptures, or under cowl fires. The fan disk was intact with all fan blades and fan blade platforms in place.

The LPT case was intact but there were numerous outward dents and a hole in the case. From the LPT stage 2 rearward, there was evidence of extensive damage such as fractured or missing blades, nozzles, or shroud segments.

There were no impact marks or holes on the inside of the engine cowls and all impact damage on the airframe, wings, fuselage, and horizontal stabilizer was downstream of the engine's tailpipe.

During examination of the bearings, the number 5 bearing inner retaining nut breakaway torque was found to be 320 foot-pounds compared to the GE assembly procedure requirement of 600 – 720 foot-pounds.

Fan Mid-Shaft Examination

Boroscope inspection confirmed separation of the FMS adjacent to the lock nut face located at the aft most full thread root. The FMS fracture exhibited distinct color differences indicative of multiple failure modes: one progressive, and one instantaneous. About 85 percent of the fracture surface exhibited discoloration consistent with longer exposure time to local environment consistent with progressive fracture. The remaining fracture surface showed signs consistent with instantaneous failure by overstress.

The FMS was sectioned in order to examine the fracture using a scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS). The SEM examination revealed faceted, quasi-cleavage fracture features consistent with environmentally assisted cracking (EAC) specific to ultrahigh strength steel GE1014.

The thread root region adjacent to the cracking had thin dry film lubrication thicknesses that measured less than the prescribed minimums, particularly on the 45° thread flanks with some regions within the thread root appeared bare. The measured dry film lubrication thickness on the 7° thread flanks generally met the required minimum but tapered down to below minimum thickness near the thread root.

Chemical and Mechanical Testing

Several specimens from the FMS were sent to outside laboratories for further testing. Various test methods were used to determine conformance to specifications and GE standards.

Bulk hydrogen analysis revealed the bulk hydrogen content of the specimens was below the maximum allowed per specification. Chemical analysis was performed to determine if there were any contaminants on the fracture surface. The tests indicated elements consistent with those of dry film lubricant, graphite grease, or synthetic engine oil used in the assembly of the engine. No other foreign contaminants were observed.

A series of tests were performed to determine the absorption tendencies of two dry film lubricants: Everlube 9002, used on the incident FMS, and MolyDag 254, a dry film lubricant used in other GE engine assemblies. The percentage of water absorbed by the Everlube 9002 was proportional to the coating thickness, and was 3.5 times greater than the absorbtion measured for the MolyDag 254 specimen.

Mechanical testing indicated the FMS met or exceeded the requirements for ultimate tensile strength.

Test specimens of GE1014 were fabricated to replicate the stress concentration expected at the aft most thread root on the FMS. Dynamic load cycling was applied to simulate the expected fatigue loads. Eighteen tests were carried out at two different laboratories and no fractures were observed after each specimen had undergone 42,000 cycles over 250 days' exposure.

Environmental Testing

A series of 168 static two-point bend tests of the FMS material were conducted in a humid bed inside a plastic container. A variety of combinations of dry film lubricant, grease, and synthetic oil were tested to determine if any could lead to environmentally assisted cracking of the FMS material. The specimens were tested in different configurations including at low and high static stress, controlled ambient humidity, and high humidity. During testing, two GE1014 specimens fractured; one at 43 days with Everlube 9002 dry film lubricant and graphite grease, and the second at 149 days with Everlube 9002 dry film lubricant and synthetic engine oil. Both specimens failed at the lower static stress level and higher humidity.

Corrosion testing of the FMS material was performed to measure the relative corrosion performance with various configurations of dry film lubricant, graphite grease, and synthetic engine oil. The testing revealed that bare GE1014 high strength steel exhibited a lower corrosion rate than GE1014 high strength steel coated with Everlube 9002 dry film lubricant.

ORGANIZATIONAL AND MANAGEMENT INFORMATION

The Boeing Company corporate headquarters was in Chicago, Illinois and they employed about 169,000 people worldwide. Boeing South Carolina fabricated, assembled and installed aft fuselage sections on the 787 Dreamliner and also included the 787 Dreamliner final assembly and delivery facility at CHS.

ADDITIONAL INFORMATION

Following the FMS separation that occurred on ESN 956-121 during the taxi test, GE developed an ultrasonic inspection to scan the forward end of the FMS in the area of the threads where the fracture occurred. The inspections were to be performed on all GEnx engine FMS in service and in storage. While conducting the inspections, a GEnx-1B engine, ESN 956-175, installed on a B787-8 airplane was found to have an indication of a similar crack on the FMS. This airplane had not yet been operated in flight. The engine had only been operated during post-production tests at GE and ground runs after installation on the airplane.

Follow up testing and metallurgical examination indicated the crack found on ESN 956-175 was similar to that of ESN 956-121: features consistent with progressive environmentally assisted cracking emanating from the thread root region.

After discovery of the second cracked FMS, the National Transportation Safety Board issued two urgent recommendations to the Federal Aviation Administration:

- **Issue an airworthiness directive to require, before further flight, the ultrasonic inspection of the fan mid shaft in all General Electric GEnx-1B and -2B engines that have not yet undergone inspection. (A-12-52)**
- **Require operators to accomplish repetitive inspections of the fan mid shaft (FMS) in all (on-wing and spare) General Electric GEnx-1B and -2B engines at a sufficiently short interval that would permit multiple inspections and the detection of a crack before it could reach critical length and the FMS fractures. (A-12-53)**

In response to these urgent recommendations, the FAA issued Airworthiness Directive AD-2012-19-08. The AD required initial and repetitive ultrasonic inspection GE GEnx-1B and -2B engine fan mid shafts for cracks.

GE has ceased use of the Everlube 9002 and graphite grease for the GEnx engine assemblies and all engines assembled with the original dry film lubricant and graphite grease combination have been inspected multiple times and are required by Airworthiness Directive to be inspected within every 100 hours of operation.

Pilot Information

Certificate:	Airline transport	**Age:**	50
Airplane Rating(s):	Single-engine land; Multi-engine land	**Seat Occupied:**	Left
Other Aircraft Rating(s):	Glider	**Restraint Used:**	5-point
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	Airplane multi-engine; Airplane single-engine	**Toxicology Performed:**	No
Medical Certification:	Class 1 Without waivers/limitations	**Last FAA Medical Exam:**	July 20, 2012
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	May 11, 2012
Flight Time:	(Estimated) 12500 hours (Total, all aircraft), 174 hours (Total, this make and model)		

Pilot Information

Certificate:	Airline transport	**Age:**	47
Airplane Rating(s):	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; Instrument airplane	**Toxicology Performed:**	No
Medical Certification:	Class 1 With waivers/limitations	**Last FAA Medical Exam:**	November 29, 2011
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	February 23, 2012
Flight Time:	(Estimated) 6700 hours (Total, all aircraft), 44 hours (Total, this make and model)		

Aircraft and Owner/Operator Information

Aircraft Make:	Boeing	**Registration:**	VT-ANJ
Model/Series:	787 8	**Aircraft Category:**	Airplane
Year of Manufacture:		**Amateur Built:**	
Airworthiness Certificate:	Transport	**Serial Number:**	36281
Landing Gear Type:	Retractable - Tricycle	**Seats:**	
Date/Type of Last Inspection:		**Certified Max Gross Wt.:**	503500 lbs
Time Since Last Inspection:		**Engines:**	Turbo fan
Airframe Total Time:	0 Hrs	**Engine Manufacturer:**	General Electric
ELT:	Installed, not activated	**Engine Model/Series:**	GEnx-1B67
Registered Owner:	Boeing Commercial Airplanes	**Rated Power:**	
Operator:	Boeing Commercial Airplanes	**Operating Certificate(s) Held:**	None

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual (VMC)	**Condition of Light:**	Day
Observation Facility, Elevation:	KCHS,46 ft msl	**Distance from Accident Site:**	
Observation Time:	15:56 Local	**Direction from Accident Site:**	
Lowest Cloud Condition:	Few / 3000 ft AGL	**Visibility**	10 miles
Lowest Ceiling:	None	**Visibility (RVR):**	
Wind Speed/Gusts:	12 knots / 19 knots	**Turbulence Type Forecast/Actual:**	/
Wind Direction:	220°	**Turbulence Severity Forecast/Actual:**	/
Altimeter Setting:	29.95 inches Hg	**Temperature/Dew Point:**	33°C / 25°C
Precipitation and Obscuration:			
Departure Point:	Charleston, SC (KCHS)	**Type of Flight Plan Filed:**	None
Destination:	Charleston, SC (KCHS)	**Type of Clearance:**	None
Departure Time:		**Type of Airspace:**	

Airport Information

Airport:	Charelston AFB / International KCHS	**Runway Surface Type:**	Concrete
Airport Elevation:	46 ft msl	**Runway Surface Condition:**	Dry
Runway Used:	21	**IFR Approach:**	None
Runway Length/Width:	7000 ft / 150 ft	**VFR Approach/Landing:**	None

Wreckage and Impact Information

Crew Injuries:	5 None	**Aircraft Damage:**	Minor
Passenger Injuries:		**Aircraft Fire:**	None
Ground Injuries:	N/A	**Aircraft Explosion:**	None
Total Injuries:	5 None	**Latitude, Longitude:**	32.898612,-80.040557

Administrative Information

Investigator In Charge (IIC):	Helson, David
Additional Participating Persons:	
Original Publish Date:	September 8, 2015
Last Revision Date:	July 8, 2024
Investigation Class:	Class
Note:	
Investigation Docket:	https://data.ntsb.gov/Docket?ProjectID=84481