# Aviation Investigation Final Report

| | | | |
|---|---|---|---|
| **Location:** | Russian airspace, | **Incident Number:** | ENG16IA001 |
| **Date & Time:** | October 2, 2015, 05:10 UTC | **Registration:** | N662US |
| **Aircraft:** | Boeing 747 | **Aircraft Damage:** | Minor |
| **Defining Event:** | Loss of engine power (partial) | **Injuries:** | 367 None |
| **Flight Conducted Under:** | Part 121: Air carrier - Scheduled | | |

## Analysis

The examination of the engine confirmed that there were three holes in the LPT case. But the holes were under the LPT cooling air manifolds and plenum that did not have any damage. In addition, there was no damage to the inside of the engine's cowlings nor did any debris fall out when the cowlings were opened. There was no damage to the LPT cooling air manifolds and plenum that were over the holes and was there was no debris in the cowlings indicating that no debris passed through the LPT case that made this a contained event rather than uncontained.

The disassembly of the engine revealed one 3rd stage turbine vane cluster, No. 29, was missing although the cluster's bolt hole tab with the retaining nut were still in place on the inner transition duct. The missing cluster's inner shroud was found in the bottom of the engine in the path of the 3rd stage turbine blades. The metallurgical examination of the inner shroud revealed fatigue, however the full extent of the fatigue could not be determined because the end of the fracture surface was smeared.

The examination of the remainder of the LPT revealed all the other turbine vane clusters were complete and in place or the inner and outer shrouds were in place with just the airfoils missing. All the LPT blades were fractured and the fracture surfaces were coarse and grainy indicating an overload fracture. The examination of the remainder of the engine between the fan and high-pressure turbine did not reveal any damage. The extensive damage to the LPT and the absence of damage throughout the remainder of the engine indicated that the damage to the engine originated within the LPT.

The visual examination and a dimensional inspection of the LPT case revealed the 3rd stage turbine vane hooks had extensive wear that varied significantly between adjacent hooks. The dimensional inspection revealed the hook for 3rd stage turbine vane cluster No. 29, the missing vane cluster, had the most wear and that wear was tapered. The tapered wear on the hook and indicates that the vane cluster's outer foot disengaged from the LPT case and tilted rearward. It was not possible to determine the cause of the tapered wear on the LPT case vane hook that led to the vane cluster disengaging. The finding of fatigue on the inner shroud further supports that the vane cluster's outer foot disengaged from the LPT case initially and fatigue was caused by either the transfer of the loads to the inner shroud or from the cluster being strummed by the passing 3rd stage turbine blades.

The review of the engine's maintenance showed that it had last been overhauled in October 2005 and since accumulated 35,545 hours and 3,532 cycles of service. Although the engine was overhauled in October 2005, the LPT module's maintenance records show that it had been swapped from another engine and accumulated 17,441 hours and 2,184 cycles since its previous overhaul. So, at that time of event, the LPT module accumulated 52,986 hours and 6,546 cycles since it had been last overhauled. Except for the low cycle fatigue life limits for specific rotating parts that are outlined in the engine manual, there is no prohibition for an engine or LPT module to have operated as long as this module had been in service. The review of the LPT module's maintenance records from the previous overhaul show that the LPT case modification to the anti-rotation slots had been previously complied with. In addition, the records show that the modification to the 3rd stage turbine vane clusters to remove material from the outer platform gussets had been complied with as well. Because of previous contained and uncontained PW4000 LPT events, P&W has revised the engine manual to add extensive inspections and repairs to LPT components as well as limiting the number of strip and recoat repairs that can be done to PW4000 LPT airfoils. The inspections and repairs that were subsequently adopted into an airworthiness directive (AD) included a visual and dimensional inspection of the LPT case's vane hooks. The tapered wear that was noted on the LPT case's 3rd stage turbine vane hooks occurred over time. The records do not list any work on the LPT case's vane hooks at the last overhaul, so it cannot be determined if the wear that resulted in the disengagement of the 3rd stage turbine vane cluster had existed only from the last overhaul or had existed prior to that overhaul. However, the revised inspection and repair procedures that are now mandated by an AD likely would have captured the wear and required it to be repaired or the case replaced.

## Probable Cause and Findings

The National Transportation Safety Board determines the probable cause(s) of this incident to be: The PW4056 engine experienced an in-flight loss of power because of damage to the low-pressure turbine (LPT) because of the inadequate overhaul inspection and repair instructions

that existed at the time of the LPT module's last overhaul.  A vane hook in the LPT case wore to the point to allow a 3rd stage turbine vane cluster to disengage and eventually fall into the path of the 3rd stage turbine blades causing extensive downstream damage to the LPT module.

## Findings

| | |
|---|---|
| **Aircraft** | Turbine section - Fatigue/wear/corrosion |

# Factual Information

## History of Flight

| | |
|---|---|
| **Enroute** | Loss of engine power (partial) (Defining event) |
| **Enroute** | Engine shutdown |

On October 2, 2015, at about 0510 UTC, a Boeing 747-451 airplane, N662US, operated by Delta Air Lines as flight 158, experienced a loss of power from the No. 3 engine, a Pratt & Whitney (P&W) PW4056, while in cruise flight at FL330. About 3:40 hours after taking off from Incheon International Airport (ICN), Seoul, Korea, while operating in Russian airspace on the B241 airway near the GITRU navigation fix, the pilots reported hearing a loud bang that was followed by the No. 3 engine's N1 rpm decreasing while the exhaust gas temperature (EGT) increased. The pilots shutdown the No. 3 engine and declared an emergency with Russian air traffic control in addition to requesting a descent to FL290. The pilots contacted the dispatcher at Atlanta and discussed options for diverting. The pilots considered diverting to Seattle, but the weather for their expected arrival time was forecast to be 800 foot overcast and 2 miles visibility. The weather forecast for Tokyo, Japan was scattered clouds and 25 miles visibility. The airplane diverted to Tokyo-Narita International Airport (NRT), where it made a 3-engine landing without further incident. The airplane was operating on an instrument flight rules flight plan under the provisions of 14 Code of Federal Regulations Part 121 as an international passenger flight from ICN to Detroit Metropolitan Wayne County Airport (DTW), Detroit, Michigan.

## Pilot Information

| | | | |
|---|---|---|---|
| **Certificate:** | Airline transport; Commercial | **Age:** | 59,Male |
| **Airplane Rating(s):** | Single-engine land; Multi-engine land | **Seat Occupied:** | Left |
| **Other Aircraft Rating(s):** | None | **Restraint Used:** | Unknown |
| **Instrument Rating(s):** | Airplane | **Second Pilot Present:** | Yes |
| **Instructor Rating(s):** | None | **Toxicology Performed:** | No |
| **Medical Certification:** | Class 1 Unknown | **Last FAA Medical Exam:** | September 2, 2015 |
| **Occupational Pilot:** | Yes | **Last Flight Review or Equivalent:** | March 21, 2015 |
| **Flight Time:** | 10617 hours (Total, all aircraft), 4449 hours (Total, this make and model) | | |

## Co-pilot Information

| | | | |
|---|---|---|---|
| **Certificate:** | Airline transport; Commercial | **Age:** | 58,Male |
| **Airplane Rating(s):** | Single-engine land; Multi-engine land | **Seat Occupied:** | Right |
| **Other Aircraft Rating(s):** | | **Restraint Used:** | Unknown |
| **Instrument Rating(s):** | Airplane | **Second Pilot Present:** | Yes |
| **Instructor Rating(s):** | | **Toxicology Performed:** | No |
| **Medical Certification:** | Class 1 Unknown | **Last FAA Medical Exam:** | July 20, 2015 |
| **Occupational Pilot:** | Yes | **Last Flight Review or Equivalent:** | |
| **Flight Time:** | 9863 hours (Total, all aircraft), 5628 hours (Total, this make and model) | | |

The captain, age 59, held at Air Transport Pilot certificate with airplane single-engine land, multi-engine land, and airplane instrument ratings. The captain was type rated in the Boeing 747-400 as well as the Boeing 727, 737, 757, and 767 airplanes. The captain held a Federal Aviation Administration (FAA) first class medical certificate that was dated September 2, 2015, with no reported limitations. The captain's most recent proficiency check was dated March 21, 2015, and was accomplished in a Boeing 747-400 airplane. The captain's reported flight time was 10,617 hours with 4,449 hours being in the Boeing 747-400 airplane and 154 hours in the previous 90 days. The captain occupied the left seat and was the pilot monitoring.

The first officer (FO), age 58, held an Air Transport Pilot certificate with airplane single-engine land, multi-engine land, and airplane instrument ratings. The FO was type-rated in the Boeing 747-400 airplane. The FO held an FAA first class medical certificate that was dated July 20, 2015, with no reported limitations. The FO's most recent proficiency check was dated May 14, 2015, and was accomplished in a Boeing 747-400 airplane. The FO's reported flight time was 9,683 hours with 5,628 hours being in the Boeing 747-400 airplane and 257 hours in the previous 90 days. The FO occupied the right seat and was the pilot flying.

Airplane Information

The airplane was a Boeing 747-451, serial number (SN) 23720, registered as N662US, and operated by Delta Air Lines. The Boeing 747-451 airplane is a four-engine transport category airplane. The airplane has a maximum takeoff gross weight of 873,000 pounds and the airplane's takeoff weight from ICN was 837,600 pounds. The airplane was loaded with 49,120 gallons of fuel. The airplane was manufactured in 1988 and was originally delivered to Northwest Airlines. Delta Air Lines acquired the airplane in the merger with Northwest Airlines. According to Delta Air Lines' records, at the time of the incident, the airplane had accumulated 109,167 hours of flying time.

The No. 3 engine was a PW4056, SN P717530. The PW4056 is a dual-spool, axial-flow, high-bypass turbofan engine that features a 1-stage 94-inch diameter fan, a 4-stage low-pressure compressor (LPC), an 11-stage high-pressure compressor (HPC), annular combustor, a 2-stage high-pressure turbine (HPT) that drives the HPC, and a 4-stage LPT that drives the fan and LPC. The PW4056 engine has a takeoff thrust rating of 56,750 pounds, flat-rated to 92°F (33°C). When the PW4056 engine is installed on a Boeing 747 airplane, it has a maximum continuous thrust rating of 47,970 pounds, flat-rated to 86°F (30°C). The PW4056 engine can also be installed on a Boeing 767 airplane where it has a maximum continuous thrust rating of 49.530 pounds, flat-rated to 77°F (25°C). According to Delta Air Lines' maintenance records, engine SN 717530 had accumulated 94,778 hours and 11,814 cycles since new, 35,545 hours and 4,362 cycles since the last heavy maintenance, and 29,194 hours and 3,532 cycles since the last shop visit. The last heavy maintenance on the engine was accomplished in 2005 at P&W's Cheshire Engine Center, Cheshire, Connecticut. P&W's Cheshire Engine Center was an FAA-certificated repair station that ceased operations in 2011.

The LPT module was SN D17579. According to Delta Air Lines' maintenance records, LPT module SN D17579 had accumulated 95,180 hours and 11,623 cycles since new and 52,986 hours and 11,623 cycles since the last heavy maintenance, which had been accomplished at the Cheshire Engine Center in 2005. Engine 717530 had been received at Cheshire with LPT module SN D17531 installed. The records show that Cheshire swapped out LPT module D17531 for D17579 from Northwest Airlines PW4056 engine P717684 to expedite the engine build. The records further show that at the time LPT module D17579 was installed in engine P717530, it had already accumulated 59,635 hours and 7,261 cycles since new and 17,441 hours and 2,184 cycles since the last heavy maintenance.

## Aircraft and Owner/Operator Information

| | | | |
|---|---|---|---|
| **Aircraft Make:** | Boeing | **Registration:** | N662US |
| **Model/Series:** | 747 451 | **Aircraft Category:** | Airplane |
| **Year of Manufacture:** | 1988 | **Amateur Built:** | |
| **Airworthiness Certificate:** | Transport | **Serial Number:** | 23720 |
| **Landing Gear Type:** | Tricycle | **Seats:** | 403 |
| **Date/Type of Last Inspection:** | October 2, 2015 Continuous airworthiness | **Certified Max Gross Wt.:** | 873000 lbs |
| **Time Since Last Inspection:** | 10 Hrs | **Engines:** | 4 Turbo fan |
| **Airframe Total Time:** | 109167 Hrs as of last inspection | **Engine Manufacturer:** | P&W |
| **ELT:** | Installed, not activated | **Engine Model/Series:** | PW4056 |
| **Registered Owner:** | WELLS FARGO BANK NORTHWEST NA TRUSTEE | **Rated Power:** | 56750 Lbs thrust |
| **Operator:** | Delta Air Lines | **Operating Certificate(s) Held:** | Flag carrier (121) |
| **Operator Does Business As:** | Delta Air Lines | **Operator Designator Code:** | DALA |

## 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:** | Seoul (RKSI) | **Type of Flight Plan Filed:** | IFR |
| **Destination:** | Detroit, MI (KDTW) | **Type of Clearance:** | IFR |
| **Departure Time:** | 10:38 Local | **Type of Airspace:** | Class A |

## Wreckage and Impact Information

| | | | |
|---|---|---|---|
| **Crew Injuries:** | 26 None | **Aircraft Damage:** | Minor |
| **Passenger Injuries:** | 341 None | **Aircraft Fire:** | None |
| **Ground Injuries:** | N/A | **Aircraft Explosion:** | None |
| **Total Injuries:** | 367 None | **Latitude, Longitude:** | 55.216388,160.109725 |

## Injuries to Persons

There were no reported injuries to the 4 pilots, 13 flight attendants, and 341 passengers on board.

Damage to Airplane

The airplane sustained minor damage in the forms of nicks and dents to the underside of the right wing and inboard aileron as well as to the leading edge of the right horizontal stabilizer.

There was no damage to the inside of the No. 3 engine's nacelle.

## Other Damage

There was no other damage reported.

## Flight recorders

The airplane was equipped with a cockpit voice recorder (CVR) and a digital flight data

recorder(DFDR), which was returned to the NTSB's Recorder Laboratory for readout. The CVR was not removed from the airplane for readout because of the elapsed time from when the event occurred to when the airplane landed at NRT would have resulted in the event being overwritten.

The DFDR recorded data for the incident flight as well as five previous flights. The DFDR data for the incident flight shows the No. 3 engine was started around subframe reference number (SRN, each subframe is equal to 1 second) that was followed 2 seconds later by the No. 4 engine being started. At around SRN 157079, both the No. 3 and 4 engines stabilized at idle power. Around 157080 and 157090, the Nos. 2 and 1 engines, respectively, were started with the No. 1 engine stabilizing at idle around SRN 157184 and the No. 2 engine stabilized at idle around SRN 157195. The DFDR recorded the following engine performance parameters: engine pressure ratio (EPR), which is a measure of engine power based on ratio of pressure of the exhaust gas in the tailpipe in comparison to the pressure of the air entering the inlet; high pressure rotor speed (N2) in percent; EGT in degrees Celsius (°C), and fuel flow (Wf) in pounds per hour (pph)/

After the engines had started and were stabilized at idle power, the engine's performance parameters were:

Engine power, stabilized idle power after start

No. 1: EPR – 1.014, N2 - 66 %, EGT - 350°C, Wf - 1,696 pph

No. 2: EPR – 1.023, N2 – 66 %, EGT - 343°C, Wf – 1,664 pph

No. 3: EPR – 1.016, N2 – 66 %, EGT – 368°C, Wf – 1,952 pph

No. 4: EPR – 1.016, N2 – 66 %, EGT – 346°C, Wf – 1,824 pph

Between about SRN 157184 and 157672, the Nos. 1 and 4 engine performance parameters: EPR, N2, EGT, and fuel flow intermittently increased and decreased consistent with the airplane taxiing from the ramp out to the runway. Around SRN 157673, the engines' performance parameters began to increase with the No. 3 engine's parameters lagging those of the other three engines by about 2 percent N2. At around SRN 157683, the engines stabilized at takeoff power and the airplane had begun to accelerate. The airplane lifted off at around SRN 157726 at an airspeed of around 184 knots.

During takeoff, the engines' performance parameters were:

Engine power at takeoff

No. 1: EPR – 1.498, N2 - 98 %, EGT - 562°C, Wf – 21,856 pph

No. 2: EPR – 1.498, N2 – 98 %, EGT - 556°C, Wf – 21,248 pph

No. 3: EPR – 1.500, N2 – 97 %, EGT – 595°C, Wf – 22,048 pph

No. 4: EPR – 1,500, N2 – 98 %, EGT –464°C, Wf – 21,281 pph

At around SRN 158451, the airplane climbed through FL 180 and all four engines were at an EPR of 1.408. The engines' performance parameters in the climb through FL180 were:

Engine power at FL 180

No. 1: EPR – 1.408, N2 - 96 %, EGT - 506°C, Wf – 13,344 pph

No. 2: EPR – 1.408, N2 – 95 %, EGT - 492°C, Wf – 12,800 pph

No. 3: EPR – 1.408, N2 –95 %, EGT – 542°C, Wf – 13,888 pph

No. 4: EPR – 1.408, N2 – 95 %, EGT – 505°C, Wf – 13,280 pph

The airplane leveled off at FL 330 at around SRN 159399. Around SRN 159699, about 5 minutes after the airplane had leveled off at FL 330, all four engines were at an EPR of 1.363. The engines' performance parameters at FL330 were:

Engine power at FL 330

No. 1: EPR – 1.363, N2 - 94 %, EGT - 459°C, Wf – 7,488 pph

No. 2: EPR – 1.363, N2 – 93 %, EGT - 449°C, Wf – 7,206 pph

No. 3: EPR – 1.363, N2 – 92 %, EGT – 491°C, Wf – 7,964 pph

No. 4: EPR – 1.363, N2 – 93 %, EGT – 461°C, Wf – 7,552 pph

Between about SRN 159699 and 170166 while the airplane continued to maintain FL 330, the engines' EPRs and N2 speeds varied in unison between 1.273 and 1.359 and 91 and 93 percent, respectively. The engines' EGT and Wf also varied in unison with the EPR and N2 speed.

At around SRN 170166, the No.3 engine's performance indications were: EPR 1.281, N2 91 percent, EGT 458°C, and Wf 7,022 pph. At around SRN 170167, with the EPR remaining at 1.281 and N2 at 91 percent, the EGT began to increase and the fuel flow began to decrease. The EGT continued to increase until around SRN 170813 when it peaked at 659°C before it began to decrease. Concurrently, the EPR decreased from 1.297 to 0.92 in 2 seconds, the N2 began to decrease from 92%, and the Wf continued to decrease. At around SRN 170199, while the EPR was at 0.631 and the N2 and EGT continued to decrease, the Wf began to increase from 3,520 to 18,144 pph in 4 seconds before decreasing down to zero in the next 6 seconds. There was no increase in the N2 rpm or EGT associated with the increase in Wf.

The DFDR contained data from five previous flights. The data show that No. 3 engine's performance indications were comparable to those of the other three engines.

## Fire

There was no fire damage.

## Tests and Research

The engine was removed from the airplane and shipped to Delta's Technical Operations Center, Atlanta, Georgia for disassembly and examination in the presence of the Powerplants Group. The disassembly revealed one 3rd stage turbine vane cluster, No. 29 that was located at about 8 o'clock, was missing. (Photo No. 1) A portion of the missing vane cluster's inner shroud was found at the bottom of the engine in the 3rd stage turbine blades' plane of rotation. (Photo No. 2) The piece of the 3rd stage turbine vane cluster inner shroud had three circumferential grooves that corresponded to the geometry of the 3rd stage turbine rotating inner air seal.

Photo No. 1: View of missing 3rd stage turbine vane cluster from front of LPT. (Delta)

Photo No. 2: View of missing 3rd stage turbine vane cluster with piece of 3rd stage turbine vane cluster inner shroud lying in bottom of engine in location of missing cluster. (P&W)

Although the vane cluster was missing, the cluster's bolt hole tab with the nut remained in place attached to the inner transition duct. (Photo No. 3) During the disassembly of the 3rd stage turbine vane area, the torque on the retaining nuts were checked and all including that for the missing vane cluster were found to be tight.

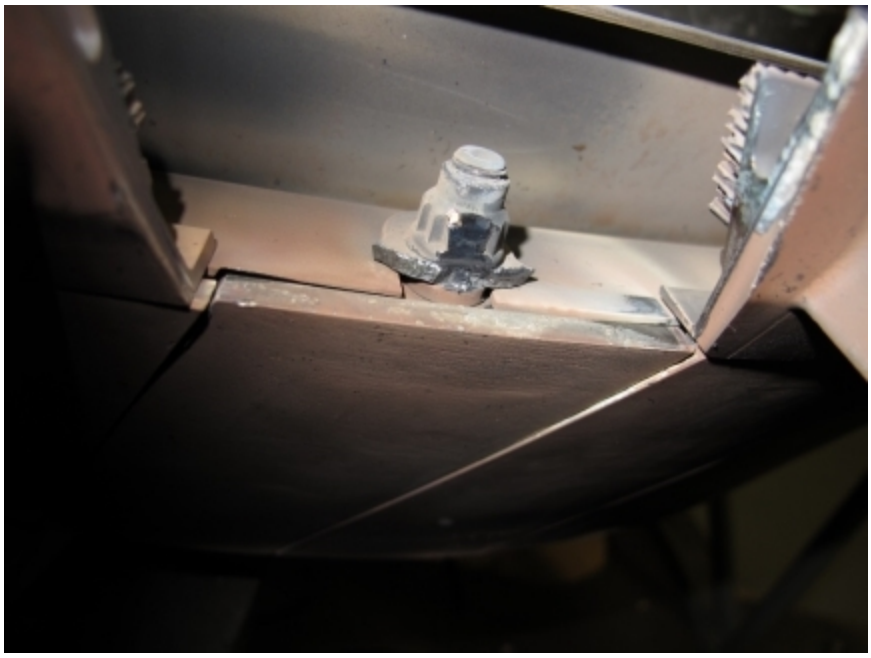

Photo No. 3: Close up of the bolt hole tab with the retaining nut in place for the

No. 29 3rd stage turbine vane cluster. (P&W)

The remaining 3rd stage turbine vane clusters' were all in place and the airfoils were heavily battered with nicks and dents on the trailing edges. (Refer to Photo No. 2)

The LPT case with the inner transition ducts and all of the 3rd stage turbine vane clusters including the No. 29 vane cluster inner shroud fragment were sent to P&W, East Hartford, Connecticut for metallurgical examination and dimensional inspections that were accomplished under NTSB oversight. The metallurgical examination of the No. 29 3rd stage turbine vane cluster's inner shroud revealed remnants of fatigue on the counterclockwise side of the forward flange. The fatigue had progressed forward from multiple origins along the aft surface of the flange to a maximum depth of 0.026 inches. The fracture surface beyond the fatigue was smeared, so it could not be determined if the fatigue had progressed further. The examination of the fragment also revealed two wear patterns that were consistent with contact with the No. 28 3rd stage turbine vane cluster in the normal installed position as well as having moved out of position. The dimensional inspection of the LPT case revealed wear on the 3rd stage turbine vane cluster hooks with the most extensive wear that was also tapered being on the hook for the No. 29 cluster. The examination of the No. 29 inner transition duct revealed wear patterns from the No. 29 3rd stage turbine vane cluster that were consistent with the cluster having moved inward and aft.

The initial report of this event from NRT was that it was an uncontained LPT event because there were several holes in the LPT case. The examination of the LPT case confirmed that there were three small holes, largest about 0.69 x 0.44 inches, in the LPT case, all under the LPT case cooling air tubes. The examination of the cooling air tubes did not show any impact damage and it was reported from NRT that there was no damage to the inside of the No. 3 engine cowling nor did any debris fall out of the cowling when it was opened.

## Administrative Information

| | |
|---|---|
| **Investigator In Charge (IIC):** | Hookey, Gordon |
| **Additional Participating Persons:** | Eric West; Federal Aviation Administration; Washington, DC<br>Joshua Migdal; Delta Air Lines; Atlanta, GA<br>Bemnet Tekeste; Delta Air Lines; Atlanta, GA<br>Van Winters; Boeing; Seattle, WA<br>Douglas Zabawa; Pratt & Whitney; East Hartford, CT<br>Jeff Wait; Air Line Pilots Association; Herndon, VA |
| **Original Publish Date:** | October 20, 2017 |
| **Last Revision Date:** | |
| **Investigation Class:** | Class |
| **Note:** | The NTSB did not travel to the scene of this incident. |
| **Investigation Docket:** | https://data.ntsb.gov/Docket?ProjectID=92117 |