



NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

March 27, 2019

POWERPLANT GROUP CHAIRMAN'S FACTUAL REPORT
NTSB No: ENG17IA028

A. INCIDENT

Location: Chicago-O'Hare International Airport

Date: June 10, 2017

Time: 0850 central standard time (CST)

Aircraft: Bombardier CRJ700, N715SK, SkyWest Airlines Flight 2985

B. POWERPLANTS GROUP

Group Chairman: Robert Hunsberger
National Transportation Safety Board
Washington, DC

Member: John Frost
Federal Aviation Administration
Burlington, Massachusetts

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Cincinnati, Ohio

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GE Aviation
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Bombardier
Montreal, Quebec, Canada

Member: Logan Phipps
SkyWest Airlines
St. George, Utah

C. SUMMARY

On June 10, 2017, at about 1750 central daylight time (CDT), a SkyWest Airlines Bombardier CRJ700, N715SK, equipped with two General Electric CF34-8C5B1 turbofan engines, experienced a No. 1 engine failure during takeoff from Chicago O'Hare International Airport (ORD), Chicago, Illinois. The crew reported hearing a loud bang, followed by a reduction in engine power, and a No. 1 (left) engine fire warning. The crew declared an emergency, shutdown the No. 1 engine, and returned to ORD for an uneventful single engine landing. Aircraft rescue and firefighting (ARFF) crews met the airplane on the runway and did not observe fire or smoke coming from the No. 1 engine, so the airplane was cleared to taxi to the gate. There were no passenger or crew injuries reported. The flight was being operated in accordance with 14 *Code of Federal Regulations* Part 121 as a regularly scheduled flight (flight 2985) from ORD to Bishop International Airport (FNT), Flint, Michigan.

A visual examination of the engine was conducted by maintenance crews at ORD who reported: a hole in the engine cowl, damage to the visible low pressure turbine (LPT) blades, and several small impacts on the fuselage, aft of the No. 1 (left) engine. The No. 1 engine was removed from the airplane at ORD and shipped to the SkyWest maintenance facility at Salt Lake City International Airport (SLC), Salt Lake City, Utah for quick engine change component removal and a preliminary engine borescope inspection (BSI). The engine was then shipped to StandardAero in Winnipeg, Manitoba, Canada for examination and disassembly. Party members from SkyWest Airlines, GE Aviation (GE), Bombardier, the Federal Aviation Administration (FAA), and the National Transportation Safety Board (NTSB) met at StandardAero from July 11-13, 2017.

The LPT case had a hole at the 10 o'clock position, near the forward flange that was approximately six inches circumferentially by four inches axially. The high pressure turbine (HPT) 2nd stage nozzle assembly was missing a vane segment at the 10 o'clock position and the HPT inner case assembly had a burn through hole in the same location as the missing vanes. The HPT 2nd stage rotor blades exhibited thermal and impact damage. All four LPT stages exhibited severe impact damage and missing material. The combustion outer liner had a 12 inch long circumferential crack from the 10 o'clock to 12:30 positions that ran between the cooling air holes on panel P2.¹ The circumferential crack was connected to an axial crack that was 2.5 inches long, from panel P2 to the aft flange/trailing edge of the panel P4 (interface with the HPT 1st stage nozzle). At the junction of the circumferential and axial cracks, the liner surface was displaced about 1.5 inches radially in towards the engine centerline.

According to GE there have been four additional combustion outer liner cracking occurrences, one of which also resulted in a case burn through and engine fire indication. Following the incident, changes were made to the CF34-8 line maintenance manual (LMM) combustion liner BSI procedures to clarify combustor liner crack location and crack length limits. GE also revised customer notification report² (CNR) parameters to provide additional tools for operators to assess core engine health.

¹ GE documentation identifies the combustion outer liner position according to panel numbers, P0-P4. The combustion liner damage is detailed in section 3.3 of this report.

² Customer notification reports are generated from engine trend data that is sent to GE through aircraft communications addressing and reporting system (ACARS). The trend data is compiled and if engine parameters deviate from expected performance thresholds, a report is sent to the operator with suggested corrective actions.

D. DETAILS OF THE INVESTIGATION

1.0 ENGINE INFORMATION

1.1 Engine History/Maintenance

According to SkyWest Airlines maintenance records the engine had accumulated the following hours and cycles at the time of the incident:

Engine Position	Serial Number	Time Since New (hours)	Cycles Since New	Time Since Shop Visit (hours)	Cycles Since Shop Visit
Left/No. 1	965587	35,792.5	21,746	23,066.6	13,769

The last major engine repair was completed at StandardAero, Winnipeg in April 2009. During that shop visit the engine was converted from a CF34-8C1 to an CF34-8C5B1. The last hot section/combustor BSI of the incident engine was completed in May 2016.

According to GE Aviation records, four high priority engine CNRs were sent to SkyWest Airlines due to low or decreasing takeoff exhaust gas temperature hot day margin (EGTHDM) in combination with low or decreasing delta core speed (increasing physical core speed) prior to the incident. The notifications were sent in February 2016, October 2016, March 2017, and May 2017. The probable cause listed on all four CNRs was compressor efficiency, and the first recommended maintenance action listed on the CNR was to perform a core engine water wash in accordance with the GE LMM procedures. SkyWest completed core engine water washes on March 7, 2016, November 2, 2016, April 1, 2017, and May 6, 2017. The first two water washes increased engine margin, but the third and fourth were ineffective (**Figure 1**). Following the water wash on May 6, 2017, SkyWest performed a high pressure compressor (HPC) BSI on June 6, 2017 and no anomalies were observed. On June 9, 2017, SkyWest scheduled the incident engine for removal and replacement on June 14th, 2017.

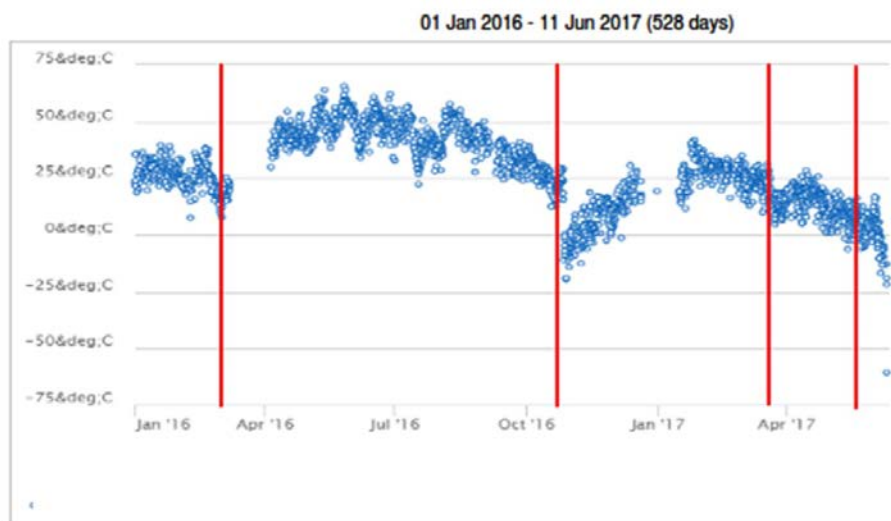


Figure 1- Exhaust Gas Temperature Hot Day Margin, Red Lines Identify CNR Issue Dates

The electronic engine control (EEC) and digital flight data recorder (DFDR) recorded interturbine temperature (ITT) exceedances during the seventh and fifth flights (June 8th and 9th, 2017) prior to the incident. The maximum temperature and time duration of both ITT exceedances were within “Area A” according to the Bombardier CRJ700/900/1000 aircraft maintenance manual (AMM), Maintenance/Inspection Actions for ITT Overtemperature Events (Takeoff). An “Area A” exceedance requires maintenance operators to visually inspect the cases and visible blades through the exhaust nozzle for anomalies. No anomalies were noted following either of the two ITT exceedances, so the airplane was returned to service. Only one of the two exceedances (June 8, 2017) was recorded in the SkyWest aircraft maintenance log.

1.2 Engine Information

The GE CF34-8C5B1 is a two-spool turbopfan engine that has a single stage high-bypass fan driven by a four-stage axial-flow LPT. The high pressure section of the engine includes a 10-stage axial flow compressor with inlet guide vanes and variable stator vanes on stages 1-4, an annular combustor, and a two-stage axial-flow HPT (**Figure 2**). The engine control system is composed of a full authority digital/electronic engine control (FADEC), a fuel metering unit (FMU), a permanent magnet alternator (PMA), engine sensors, variable geometry actuator, and an operability bleed valve (OBV). According to the FAA type certificate data sheet, E00063EN Revision 8, dated November 22, 2016 the engine has a maximum takeoff (5 minute) static sea level thrust rating of 13,790 lbs. and a maximum continuous static sea level thrust rating of 13,280 lbs.³

All directional references to front and rear, right and left, top and bottom, and clockwise and counterclockwise are made aft looking forward (ALF).

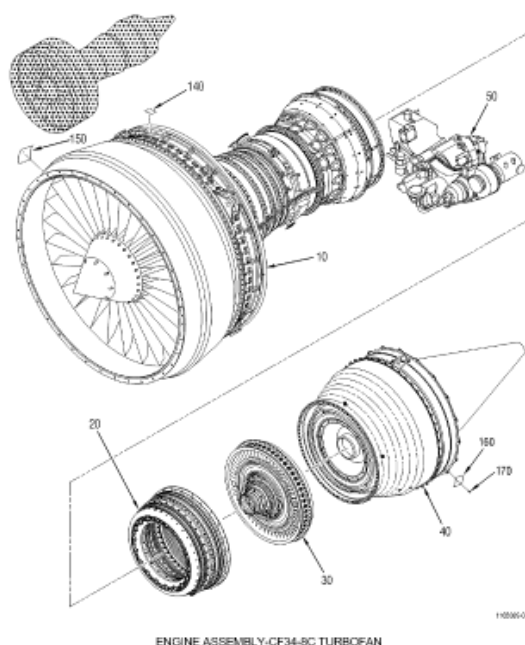


Figure 2- General Electric CF34-8C Module Diagram

³ Engine ratings are based on calibrated test stand performance assuming static sea level standard conditions of 59°F and 29.92 inches Hg. with no aircraft accessory loads or air extraction.

2.0 FUSELAGE AND COWL DAMAGE

SkyWest Airlines reported multiple small fuselage impacts aft of the No.1 engine following the incident event. At the request of the NTSB, SkyWest created a damage map to identify the impact locations (**Photo 1**). All damage was determined to be repairable in accordance with the Bombardier structural repair manual (SRM).



Photo 1- Empennage Damage Map, Impacts Marked with Yellow Tape

The aft core cowl had a hole at the 10 o'clock position, 4 inches aft of the cowl forward flange. The hole measured 7.5 inches circumferentially by 4 inches axially (**Photo 2**).



Photo 2- Aft Core Cowl Damage

3.0 NO. 1 ENGINE, SERIAL NUMBER 965587 EXAMINATION AND DISASSEMBLY

The engine was secured in a shipping container when the investigative team arrived at StandardAero. The engine was transferred to a work stand for examination and disassembly (**Photos 3, 4, and 5**). A cardboard box with engine fragments that were recovered at ORD by airport operations was included in the shipping container (**Photo 6**). A part number was visible on one of the fragments, and it was confirmed that the part was from a CF34 low pressure turbine nozzle.



Photo 3- Left Side of Engine



Photo 4- Right Side of Engine



Photo 5- Engine Data Plate



Photo 6- Debris Recovered by ORD Airport Operations

A visual examination of the engine was conducted beginning at the fan module. The fan blades and fan case were complete and in good condition, but the fan (N1 spool) was seized and could not be rotated by hand. The LPT case had a hole at the 10 o'clock position at the forward flange that measured 6

inches circumferentially by 4 inches axially (**Photo 7**). The edges of the hole were thermally damaged. The material around the hole was not extruded/deformed radially outward. The spiral wrap on the igniter lead that ran directly over the case hole was consumed and the rubber seal located on the LPT case baffle immediately aft of the hole exhibited thermal distress. Minor discoloration was observed around the edges of the LPT case hole, but minimal sooting and discoloration were observed on other exterior engine surfaces.

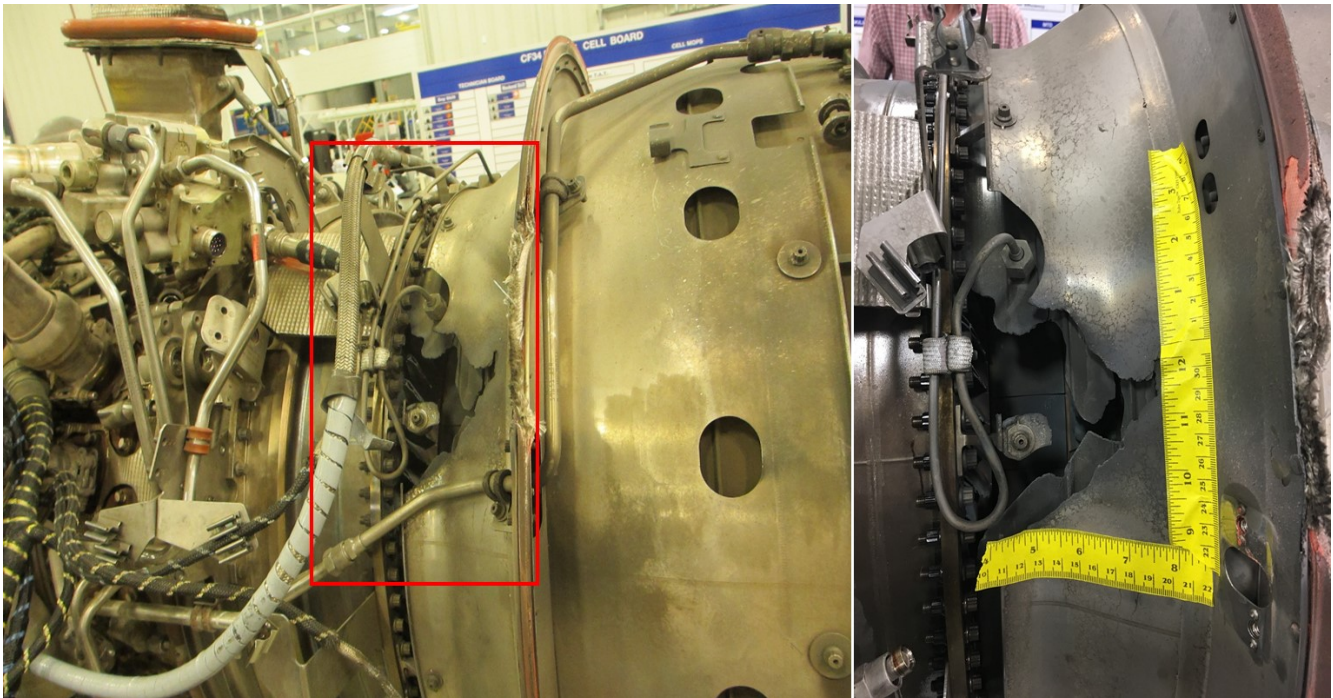


Photo 7- LPT Case Hole

Engine oil from the gearbox, A sump, B sump, C sump, and oil filter housing were run through a paper filter and no debris was visible. The master chip detector plug was removed and had a small amount of debris accumulation that is considered normal for similar service run engines according to StandardAero mechanics (**Photo 8**).



Photo 8- Master Chip Detector Plug

3.1 Low Pressure Turbine

The LPT was removed from the engine and disassembled into stages. All LPT 6th stage rotor blades were separated at locations ranging from the blade platform to three-quarter span. The LPT 6th stage nozzle was missing vane airfoils between the 10 and 12 o'clock positions, and all remaining vane airfoils exhibited impact damage including: deformation on the pressure and suction sides, missing material on the trailing edge, and discoloration (**Photo 9**).

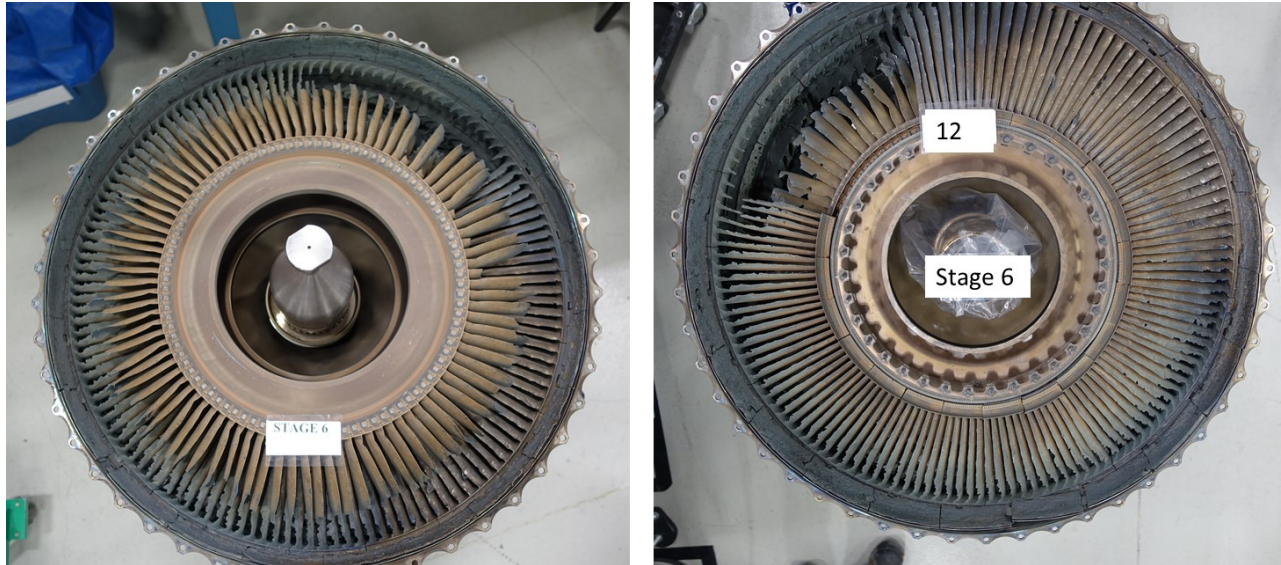


Photo 9- (L) LPT 6th Stage Rotor, (R) LPT 6th Stage Nozzle

All LPT 5th stage rotor blades were separated between the quarter and midspan. The remaining blade stubs exhibited extensive hard body impact damage and material transfer. The LPT 5th stage nozzle vane airfoils were separated at the inner and outer diameter platforms between the 9 and 11 o'clock positions and the 4:30 and 6 o'clock positions. The outer diameter vane platforms between the 9 and 11 o'clock position had a concentrated area of thermal damage (**Photo 10**).

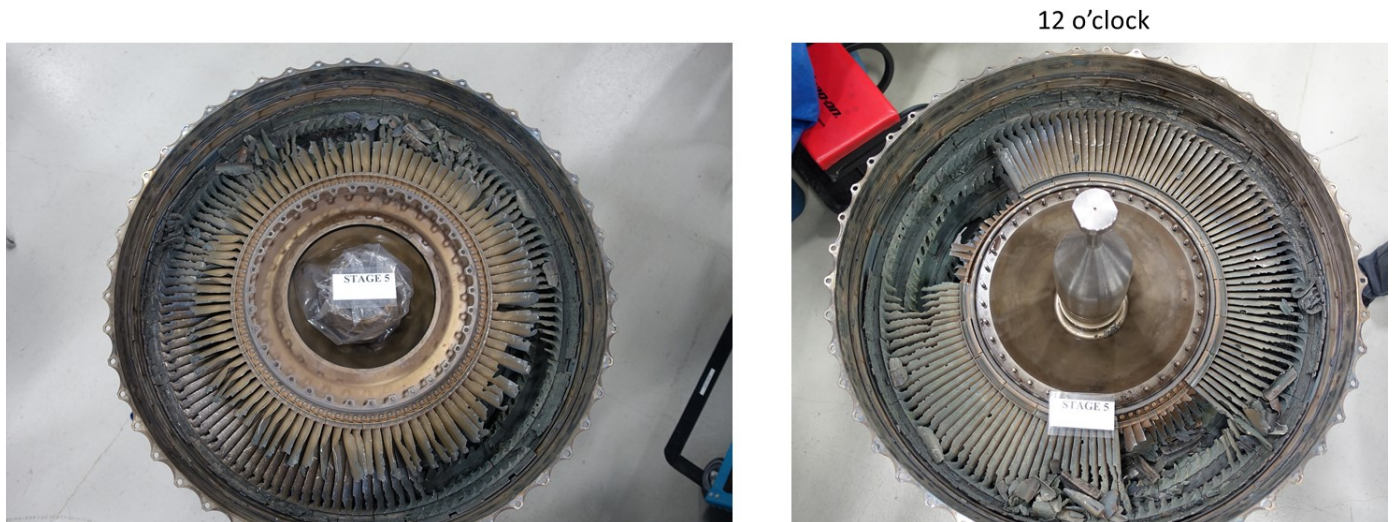


Photo 10- (L) LPT 5th Stage Rotor, (R) LPT 5th Stage Nozzle

All LPT 4th stage rotor blades were separated between the blade platform and one-third span. The remaining blade stubs exhibited impact damage and deformation. The LPT 4th stage vane airfoils were separated and missing at the inner and outer vane platforms between the 8:30 and 11:30 positions and between the 3 o'clock and 7:30 positions. All remaining nozzle vanes had impact damage and deformation. The outer diameter nozzle vane platforms were thermally damaged between the 10 and 11 o'clock positions (**Photo 11**).



Photo 11- (L) LPT 4th Stage Rotor, (R) LPT 4th Stage Nozzle

All LPT 3rd stage rotor blades were separated at about the half span and remaining blade stubs had impact damage. The LPT 3rd stage nozzle vane airfoils were separated at the inner and outer diameter vane platforms between the 9 o'clock and 10:30 positions. The LPT case hole previously mentioned was located forward of the 3rd stage vane nozzle, at the 10 o'clock position. The nozzle vane airfoils between the 2 and 3 o'clock positions exhibited thermal damage at the mid span. The nozzle vanes between the 11 and 1 o'clock position were intact with minor impact damage. All other 3rd stage nozzle vane airfoils exhibited impact damage and were missing material along the trailing edge (**Photo 12**). The ITT probes located at the 4 and 9 o'clock positions were missing material, and the remaining probe pieces were flush with the outer transition liner (OTL). The ITT probe at the 4 o'clock position was also missing material and about a one-inch piece of the probe remained protruding from the OTL. The ITT probe at the 1 o'clock position was intact and in good condition. The OTL had thermal damage at the 3 to 4 o'clock positions and the 9 to 11 o'clock positions.

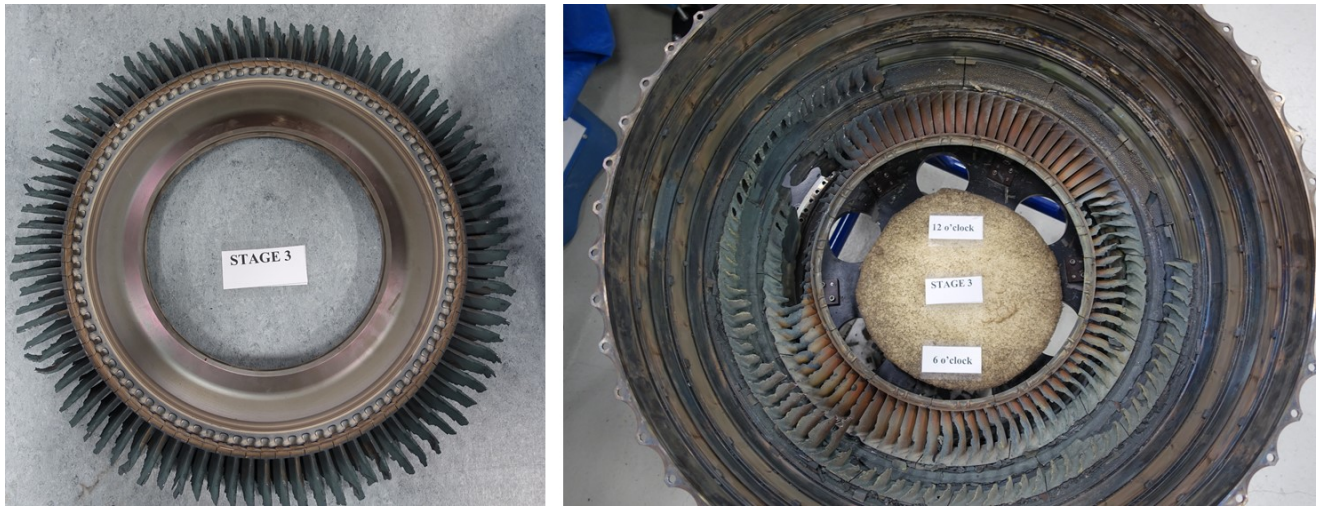


Photo 12- (L) 3rd Stage LPT Rotor, (R) 3rd Stage LPT Nozzle

3.2 High Pressure Turbine

The HPT 2nd stage rotor blades were all present but had a combination of thermal and impact damage to the leading edge that exposed the blade cooling air circuits, as well as trailing edge material loss at the blade tip (**Photo 13**). A groove was rubbed into all blades at the leading edge near the platform, consistent with the HPT 2nd stage nozzle inner platform trailing edge contact. The HPT 2nd stage rotor shroud had thermal damage between the 3 and 4 o'clock positions and more severely between the 9 and 11 o'clock positions. The HPT inner case that houses the HPT 2nd stage nozzle had burn through at the 10 o'clock position coincident with the hole in the LPT case (**Photo 14**). One nozzle vane segment had separated and was missing at the 10 o'clock position. The surrounding vanes exhibited thermal and impact damage. Thermal damage including vane airfoil deformation was also observed at the 3 o'clock position (**Photo 15**).

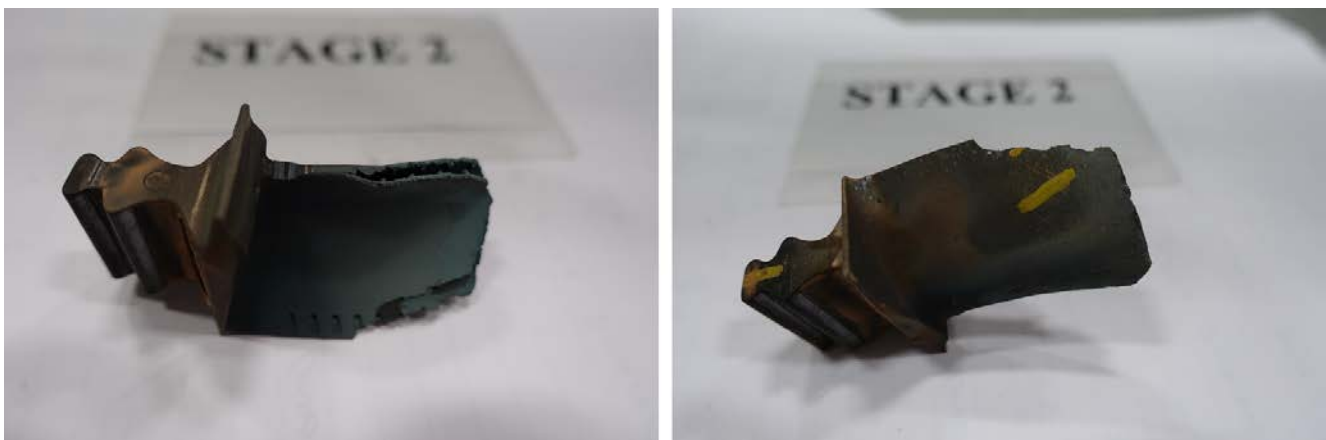


Photo 13- HPT 2nd Stage Rotor Blade

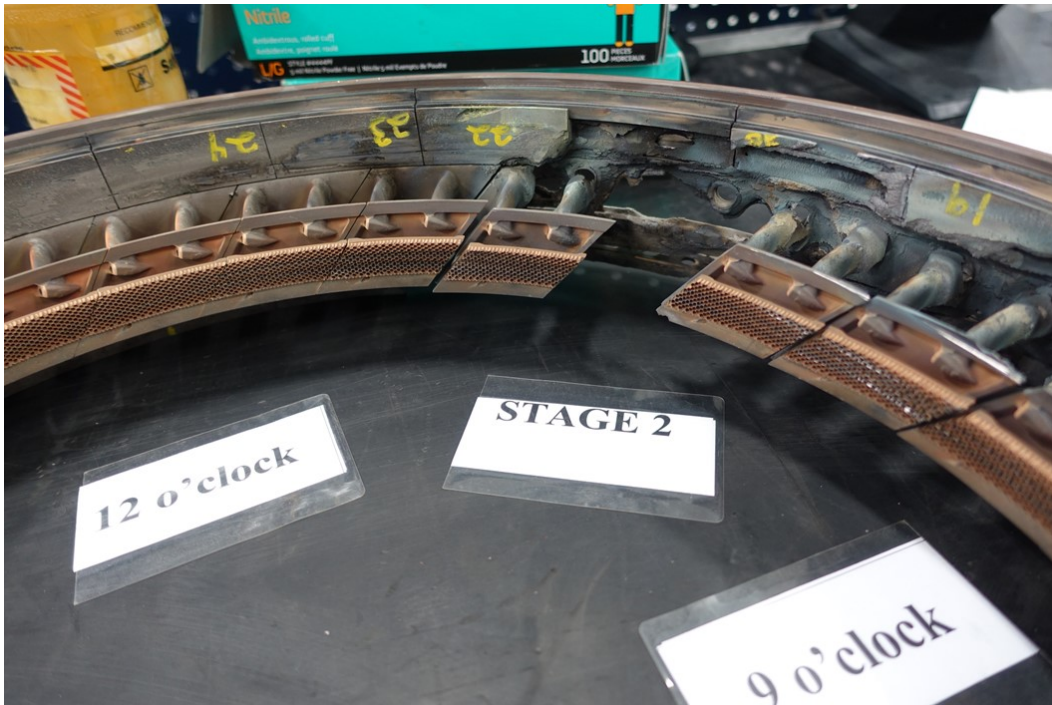


Photo 14- HPT Inner Case Burn Through and Missing HPT 2nd Stage Nozzle Segment

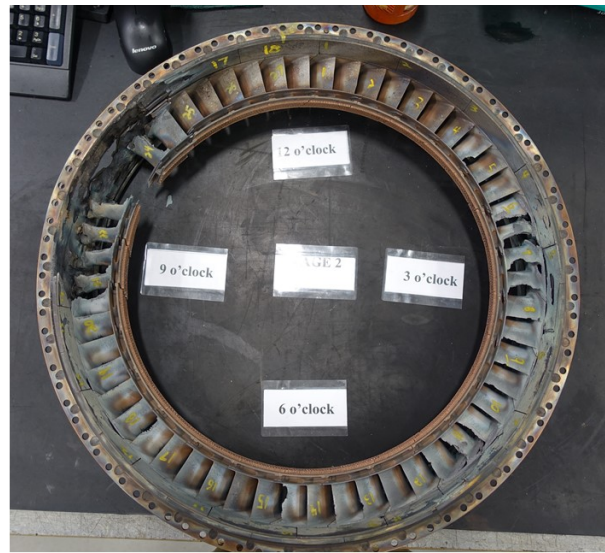


Photo 15- HPT 2nd Stage Nozzle (L) Pressure Side, (R) Suction Side

The HPT 1st stage rotor blades were all present and several blades had minor trailing edge material loss at the tip. The HPT 1st stage blade shrouds exhibited thermal damage between the 9 and 11 o'clock positions and minor thermal damage at the 3 o'clock position. The HPT 1st stage nozzle assembly was removed as part of the combustor liner assembly. The nozzle vane airfoils were intact with minor discoloration that was considered normal for similar service run engines according to StandardAero (**Photo 16**).

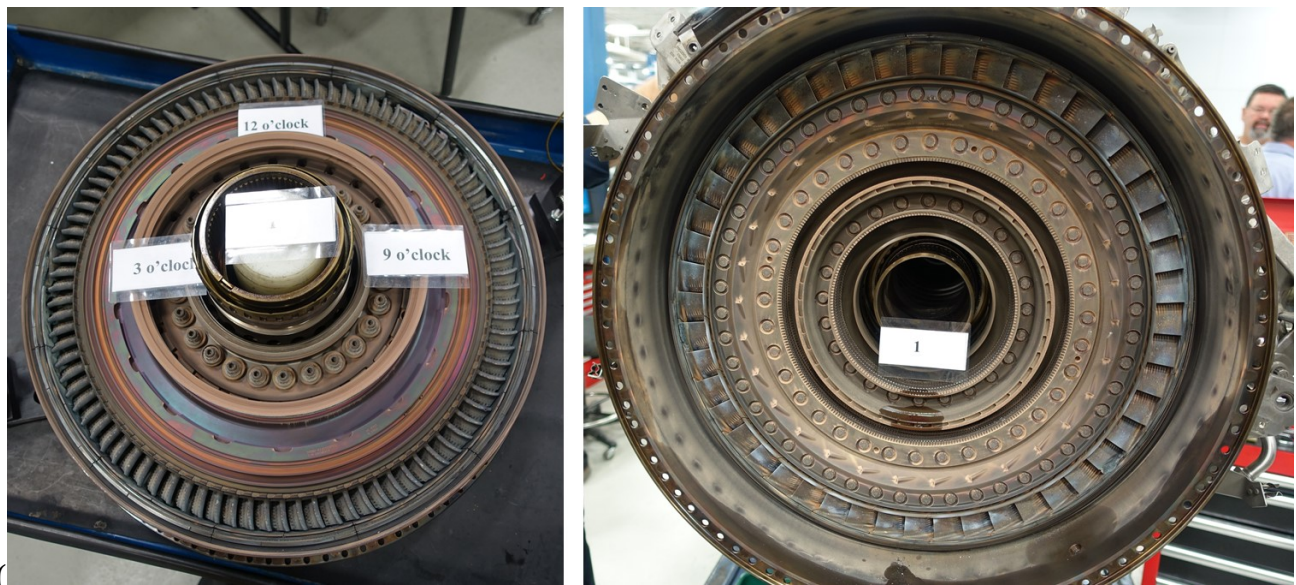


Photo 16- (L) HPT 1st Stage Rotor LE, (R) HPT 1st Stage Nozzle TE

3.3 Combustor

GE documentation identifies the combustion outer liner sections by panel numbers, P0-P4 (**Photo 17**). The combustion outer liner on the incident engine had a 12 inch long circumferential crack that ran between the cooling air holes on panel P2, from the 10 o'clock to 12:30 positions. The circumferential crack was connected to an axial crack that ran approximately 2.5 inches from panel P2 to the aft flange/trailing edge of the panel P4 (interface with the HPT 1st stage nozzle). At the junction of the circumferential and axial cracks, the liner surface was displaced about 1.5 inches radially in towards the engine centerline (**Photo 18**). A second 2.5 inch axial crack was also present at the 2 o'clock position between panel P2 and the trailing edge of panel P4. There was no circumferential cracking in the area around the second crack.

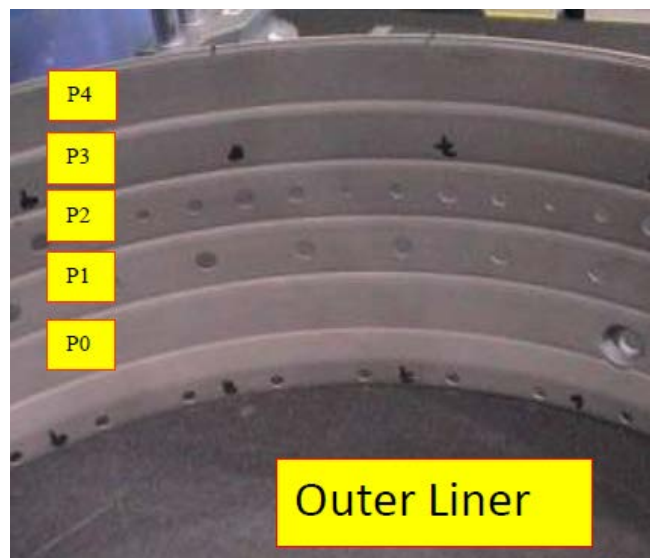


Photo 17- Combustion Outer Liner Panel Identification



Photo 18- Combustion Outer Liner Cracks (L) 12 o'clock, (R) 2 o'clock

The inner combustion liner was intact but exhibited discoloration and thermal barrier coating loss (**Photo 19**). The fuel injector swirlers were intact and moved freely. The combustor baffles were all present but had extensive discoloration/coking accumulation (**Photo 20**). The fuel injectors had minor discoloration but appeared to be in good condition and free of obstructions. Two fuel injectors located at the 11:30 and 7 o'clock positions had a wear step on the metal sleeve around the fuel injector tip that was uncommon according to StandardAero mechanics. The fuel injectors were all removed and shipped to Woodward in Rockford, Illinois to be flow tested.

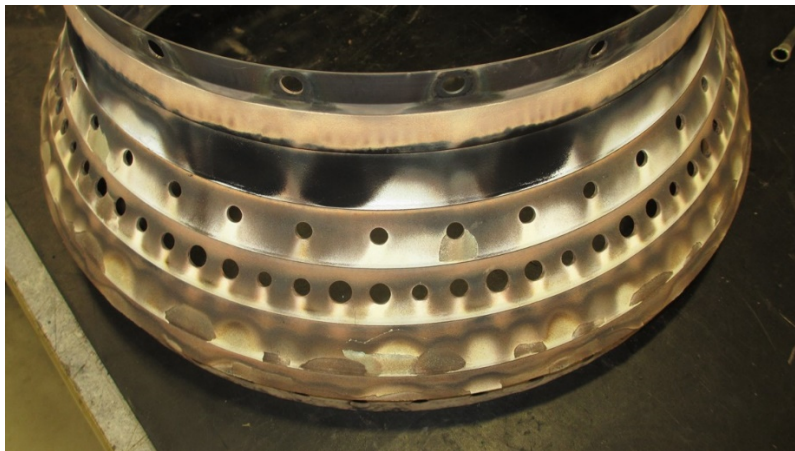


Photo 19- Combustion Inner Liner

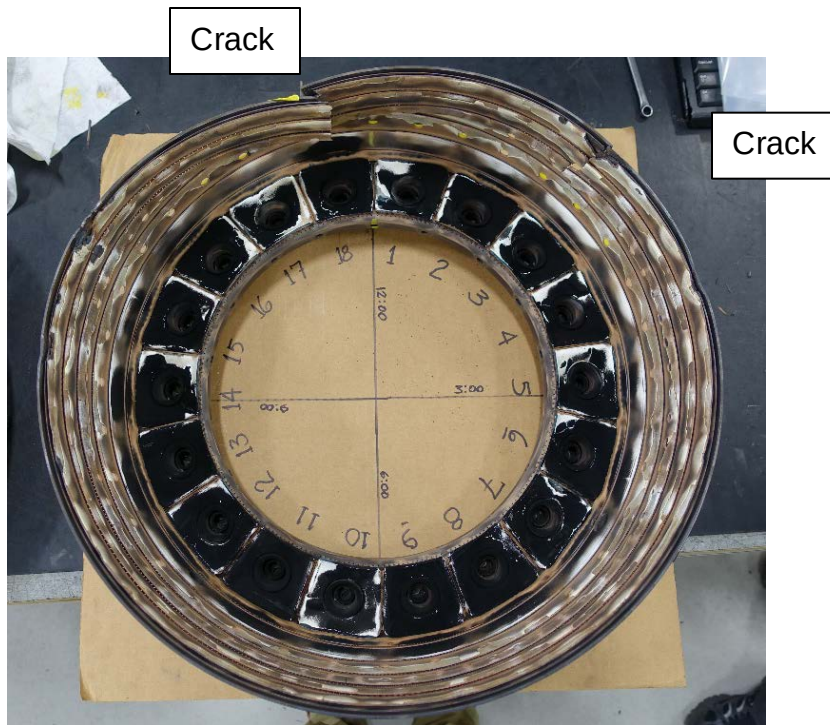


Photo 20- Combustor Baffles and Outer Liner

3.4 High Pressure Compressor

A BSI of HPC stages six through nine was performed to verify there was no additional upstream damage. All four stages were intact and in good condition. The group determined no further disassembly of the HPC was required.

4.0 METALLURGY AND COMPONENT TESTING

The combustion liner fracture surfaces exhibited significant thermal distress and the group determined that fracture analysis would not be beneficial. The GE Materials Laboratory attempted to examine the liners recovered from previous failures and were unsuccessful. All damage aft of the combustion liner, including the thermal damage to the HPT 1st stage nozzle and thermal and impact damage to the remaining stages of the HPT and LPT were deemed to be secondary so no other parts were submitted for metallurgy.

4.1 Fuel Nozzles

All 18 fuel nozzles were shipped to the Woodward facility in Zeeland, Michigan for flow testing in the as received "dirty condition". There were no anomalies noted in spray pressure or spray angle, but 16 of the 18 nozzles failed spray quality testing due to minor streaking. The pass/fail criteria were based on new or repaired nozzles, and according to Woodward engineering, the nozzle spray patterns were consistent with what is expected for other high time service run hardware. The flow testing results are available in the docket under "SkyWest ESN 965587 Fuel Nozzle Test Results."

4.2 Fuel Metering Unit

The fuel metering unit was shipped to the Woodward facility in Rockford, Illinois for testing. Multiple fuel flow test points were recorded below minimum specification for a new unit but were within the expected range for a high time service run component according to Woodward and GE Aviation engineering. Woodward noted leak rates from the variable geometry servo valve of 45 milliliters (ml)/minute (min) at max flow rate, 2 ml/min at a fuel flow rate of approximately 3000 pph (pounds per hour), and 1 ml/min at minimum flow rate⁴. The FMU test results are available in the docket under “SkyWest ESN 965587 FMU Test Results.”

4.3 Main Fuel Pump

The main fuel pump was shipped to Triumph Accessory Services in Grand Prairie, Texas for testing. The fuel pump met testing specifications and no faults were recorded. The bench test results are available in the docket under “SkyWest ESN 965587 MFP Test Results.”

5.0 COMBUSTION LINER FAILURE HISTORY

The NTSB is aware of four other combustion outer liner buckling occurrences, one of which resulted in an operational event that did not necessitate an inflight shutdown of the engine. The remaining buckled combustion outer liners were discovered during engine inspection or repair.

The NTSB investigated a CF34-8C combustion inner liner burn through failure that resulted in a LPT case burn through. The report for this investigation is available in the NTSB docket management system under NTSB investigation number ENG14IA029.

To date, a combustion outer liner failure has not occurred on a liner with fewer than 18,000 hours and/or 12,000 cycles.

6.0 CORRECTIVE ACTIONS

6.1 GE CF34-8C Line Maintenance Manual

Following the prior incident event, GE revised the on wing combustion liner inspection criteria in the LMM to clarify pass/fail criteria for axial cracks and burn through holes. The initial manual revision was issued on April 1, 2018 and the applicable text and figure are shown below in **Figures 3 and 4**.

⁴ The leakage from the variable geometry servovalve end plates is contained within the electrical cavity of the FMU. The test points are chosen to replicate a typical engine flight cycle.

Inspection

(e) Axial (non-circumferential) can be connected with circumferential cracks and dilution/burn through holes

Serviceable Limits

Any amount, if cracks do not go across a second panel. No more than three cracks are permitted to go across two panels and no cracks are permitted to go across three or more panels

Remarks

If a crack goes across a second panel, increase the interval of the borescope inspection to every 600 hours.

If the defect is more than serviceable limits, return the engine to a certified repair facility within 25 hours with instructions to refer to GEK105091 TASK-72-00-00-800-802 (72-00-00, Special Procedures 02) to replace the applicable hardware

In order to validate that an axial crack connects two adjacent panels, it is necessary to view the cold of the inner/outer liner to determine if the crack has gone through the cooling lip.

If the length of a crack on panel P4 of the outer liner only is more than 0.75 in. (19.1 mm), increase the interval of the borescope inspection to every 600 hours.

If a crack on the outer liner only connects across the entire length of panel P4 into panel P3, increase the interval of the borescope inspection to every 300 hours. Refer to Figure 815, Sheet 12. If the defect is more than the serviceable limits, return the engine to an overhaul facility to replace the applicable hardware within 25 hours.

If a crack on the outer liner only connects across the entire length of panel P4 and panel P3 into panel P2, return the engine to an overhaul facility to replace the applicable hardware within 5 hours

Figure 3- LMM 72-00-00 Inspection 003- Borescope Inspection

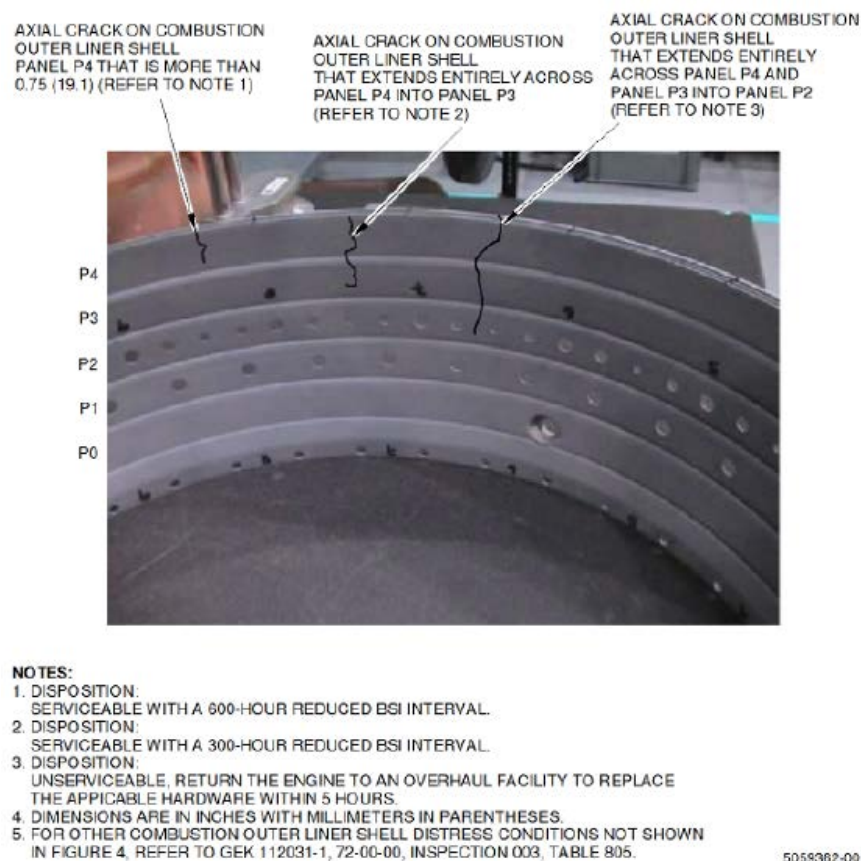


Figure 4- LMM 72-00-00 Inspection 003- Borescope Inspection Figure 815 (Sheet 12) Combustion Liner Assembly

6.2 Service Bulletins

GE released category 2⁵ service bulletins, SB 72-A0326 (CF34-8C engines) and SB 72-A0211 (CF34-8E engines) on October 17, 2018. The SB recommends a one-time BSI of panel P4 on combustion outer liners with more than 15,000 flight hours time since new or time since repair.

5.2 GE Customer Notification Reports

Following the incident event, GE developed a new CNR monitoring parameter for combustor distress. Engine trend data is monitored for sharp decreases in takeoff EGTHDM with corresponding shifts in takeoff delta fuel flow. These shifts are both most relatable to hot section distress, more precisely combustor distress. The following engine core related CNR parameters were also modified to add a recommendation to perform a BSI on the combustion liner as part of the corrective actions: CNR HPC Efficiency, CNR Core Deterioration, CNR Low Engine Performance, CNR exhaust gas temperature (EGT) Indication, and CNR HPC-HPT Distress.

A new Core Health Indicator (CHI) parameter was developed in April 2018. The CHI algorithm uses core speed, fuel flow, and compressor discharge pressure measurements during takeoff to calculate a predicted EGTHDM. CHI is designed to provide a supplemental trend data point to the existing EGTHDM parameter. CHI does not factor EGT or ITT as part of the algorithm and GE believes agreement and/or variation between the two parameters will help maintainers perform more targeted troubleshooting of engine issues.

Robert Hunsberger
Aerospace Engineer
Propulsion

⁵ According to the service bulletin compliance paragraph, GE recommends completion of the SB as soon as possible without effect on revenue service but before 1,000 flight hours from the issue date of the bulletin.