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

# POWERPLANT GROUP CHAIRMAN'S FACTUAL REPORT

## NTSB No: ENG14IA001

## A. INCIDENT

| | |
|---|---|
| Location: | Dallas, Texas |
| Date: | October 15, 2013 |
| Time: | 1451 central daylight time (CDT) |
| Aircraft: | Spirit Airlines Airbus A319, Registration No. N516NK, Flight 165 |

## B. POWERPLANTS GROUP

| | |
|---|---|
| Group Chairman: | Robert Hunsberger<br>National Transportation Safety Board<br>Washington, DC |
| Member: | Martin Adler<br>Federal Aviation Administration<br>Burlington, Massachusetts |
| Member: | Christopher Demers<br>International Aero Engines<br>East Hartford, Connecticut |
| Member: | Jeffrey Perin<br>Airline Pilots Association, International<br>Ypsilanti, Michigan |
| Member: | Donald Wade<br>Spirit Airlines<br>Miramar, Florida |
| Member: | Jerome Real<br>Airbus<br>Toulouse, France |

## C. SUMMARY

On October 15, 2013 at about 1451 CDT, a Spirit Airlines (NKS) Airbus A319, registration number N516NK, experienced a No. 1 (left) engine failure during climb out from Dallas-Fort Worth International Airport (DFW), Dallas, Texas. The airplane was equipped with two International Aero Engines (IAE)[1] V2524-A5 turbofan engines. The flight crew reported that about ten minutes after takeoff, at FL190, the electronic centralized aircraft monitor (ECAM) displayed a No. 1 engine pressure ratio (EPR) fault, N2[2] over limit warning, and an exhaust gas temperature (EGT) over limit warning. The ECAM notifications coincided with heavy vibrations that could be felt throughout the cockpit and cabin. The No. 1 engine was left at a high power setting and four minutes later a No. 1 engine fire warning registered and smoke was detected in the cockpit. The crew donned oxygen masks, declared an emergency, shut down the No. 1 engine, and discharged one of the fire suppression bottles. The airplane returned to DFW and executed an uneventful single engine landing. Aircraft Rescue and Fire Fighting (ARFF) personnel met the aircraft on the runway and determined the fire had been extinguished. A visual examination of the No. 1 engine was conducted and extensive damage to the low pressure turbine (LPT) was observed through the engine exhaust. The thrust reverser cowls were opened and large sections of the LPT and turbine exhaust cases (TEC) were missing. The flight was being operated in accordance with *14 Code of Federal Regulations Part 121* as a regularly scheduled flight from DFW to Atlanta Hartsfield International Airport (ATL), Atlanta, Georgia.

An on scene evaluation of the aircraft and No. 1 engine was conducted at DFW on October 16-17, 2013 with members from IAE, NKS, the Air Line Pilots Association (ALPA), the Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB). During the evaluation it was confirmed that the LPT 3$^{rd}$ and 4$^{th}$ stage disks, turbine exhaust case center body, and the No. 5 bearing housing were jettisoned from the engine. The LPT 5$^{th}$ stage disk had separated from the 6$^{th}$ stage disk and was hanging on the LPT shaft. There was extensive damage to all remaining high pressure turbine (HPT) and LPT hardware but the engine cowlings were in good condition without indications of radial uncontainment.

Several days after the event, the NTSB Central Region office received a call reporting a possible aircraft component in the front yard of a home in a rural area northwest of DFW. Photographs were provided by the homeowner and it was confirmed that the part was a section of the missing LPT 3$^{rd}$ stage disk from the incident engine. Radar data, flight data recorder (FDR) parameters, and meteorological reports were used to map out a search grid to locate additional parts in the area. Members from IAE, NKS, the Delta County Sheriff's Department, and the NTSB met in Ben Franklin, Texas to conduct a search from October 30-31, 2013. The search recovered an additional section of the LPT 3$^{rd}$ stage disk.

The engine was shipped to the Pratt & Whitney (P&W) Columbus Engine Center in Columbus, Georgia for examination and teardown from November 5-7, 2013. The LPT shaft exhibited bending and heavy circumferential scoring. The LPT 6$^{th}$ and 7$^{th}$ stage disks remained intact but had substantial impact damage. All 6$^{th}$ stage blades were missing and all 7$^{th}$ stage blades were fractured at the root. The HPT 2$^{nd}$ stage disk had three blades separated below the platform with blade attachments secure in the hub slots and two blades were missing entirely. All remaining blades exhibited hard body impact damage on both the leading and trailing edge surfaces. The No. 4 bearing compartment was

[1] International Aero Engines is a joint venture between Pratt & Whitney, Pratt & Whitney Aero Engines International (a wholly owned subsidiary of Pratt & Whitney), Japanese Aero Engine Corporation, and MTU Aero Engines.

[2] N2 is is the high pressure spool of the engine consisting of the HPC and HPT.

disassembled and multiple items including the No. 4 bearing seal and aft air seal were fractured. The No. 4 bearing was intact, oil wetted, and in good condition.

Engine hardware from the LPT, HPT and No. 4 bearing compartment were shipped to the P&W Materials Lab in Hartford, Connecticut. Metallurgical analysis of the HPT 2$^{nd}$ stage blade fracture surfaces identified a series of stress corrosion cracks (SCC) in the internal J-channel cooling air cavities below the blade platform. Probe spectrometry of the cracks found sulfur deposits in each blade along the corrosion front. The remaining intact blades were examined by x-ray and borescope and 38 of the 67 blades were found to have varying levels of SCC within the J-channel cooling air cavities. The blades were subsequently sectioned for a more thorough examination and a total of 41 of the 67 blades exhibited some level of SCC.

A hardness profile of all recovered turbine hardware was completed. The LPT disks had measured hardness values that indicated exposure to temperatures that exceeded the materials annealing temperature. The hardness values were lowest (softest) along the outer diameter of the components and were progressively higher (harder) near the inner bore.

The No. 4 bearing compartment component fracture surfaces were examined and features were consistent with overload without indications of fatigue. None of the bearing compartment components exhibited signs of fire exposure or thermal distress.

In response to the findings from this incident, IAE developed and released additional inspection and repair procedures for V2500 series engine HPT 2$^{nd}$ stage blades. The new procedures require x-ray and borescope inspections of the J-channel cooling air cavity for cracks. IAE also proposed coating the internal passages with an aluminide corrosion preventative coating beginning in late 2014.

## D. <u>DETAILS OF THE INVESTIGATION</u>

## 1.0 ENGINE INFORMATION

### 1.1 ENGINE HISTORY/MAINTENANCE

According to maintenance records the engine had accumulated the following hours and cycles:

| Engine Position | Serial Number | Time Since New (hours) | Cycles Since New | Time Since Repair (hours) | Cycles Since Repair |
|---|---|---|---|---|---|
| Left/ No. 1 | V12069 | 28,626 | 13,800 | 3,076 | 1,500 |

Maintenance records provided by NKS stated that the last engine hot section overhaul was completed at Rolls Royce- East Kilbride, Scotland, United Kingdom on November 20, 2012. Relevant maintenance activity performed on the engine was removal and replacement of the LPT 6$^{th}$ stage inner air seal and the HPT 2$^{nd}$ stage air seal. The HPT 2$^{nd}$ stage rear plate retainer was removed and replaced with a refurbished component. The No. 4 bearing compartment service records indicate incorporation of three service bulletins (SB) 72-0497 REV 1, 72-0541 REV 4, 72-0592 REV 1, and 72-0617 REV 1. The requirements of Airworthiness Directive (AD) 2008-14-15 were met by completing SB 72-0541 REV 4 in advance of AD release.

### 1.2 ENGINE TYPE

The IAE V2524-A5 is a dual rotor, axial flow, high bypass turbofan engine. The engine has a single-stage fan; four-stage low pressure compressor (LPC), ten-stage high pressure compressor (HPC), annular combustor, two-stage HPT, and five-stage LPT.

According to the FAA Type Certificate Data Sheet E40NE, Revision 9, dated June 22, 1999, the IAE V2524-A5 engine has a maximum continuous sea level thrust rating of 19,200 pounds and a takeoff sea level thrust rating of 24,480 pounds[3].

All directional references to front and rear, right and left, top and bottom, and clockwise and counterclockwise are made aft looking forward (ALF). The engine flange positions are illustrated in **Figure (1)**.

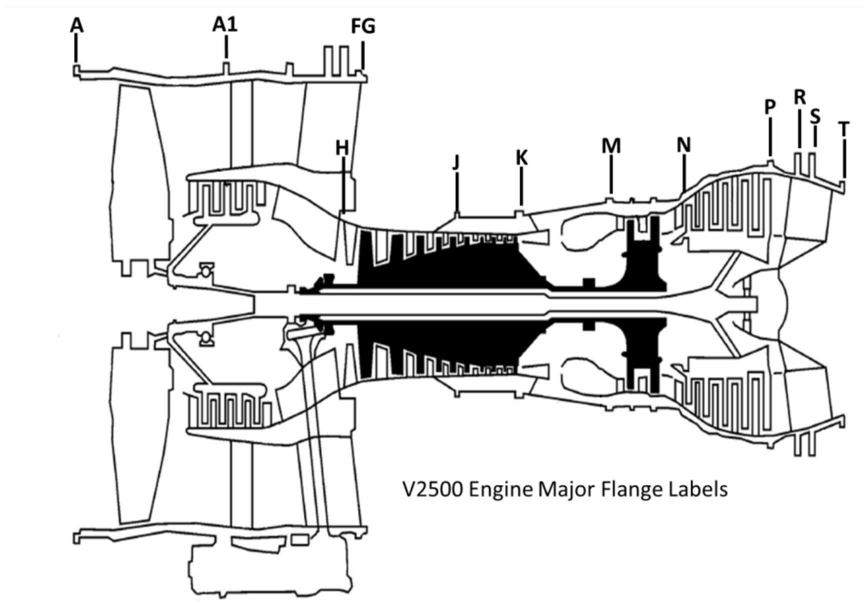



**Figure 1- V2524-A5 Engine Flange Diagram**

## 2.0 ON SCENE AIRCRAFT AND ENGINE EXAMINATION

The investigative team arrived at DFW on October 16, 2013 to document the condition of the aircraft and No. 1 engine. The aircraft was quarantined on the tarmac in front of the NKS maintenance hangar. Prior to the team's arrival, the engine cowls had been raised and the engine borescope and magnetic chip detector plugs had been removed by NKS maintenance crews (**Photo 1**). The master magnetic chip detector plug located in the oil tank had accumulated a significant amount of metal shavings and debris (**Photo 2**).

[3] The ratings are based on Sea Level Static test stand operation under the following condition:
- Engine inlet air at 59°F and 29.92 in.Hg.
- No fan or compressor air bleed or load on accessory drives.

**Photo 1- No. 1 Engine**

**Photo 2- Main Chip Detector Plug with Metal Shavings and Debris**

## 2.1 AIRCRAFT EXAMINATION

Minor impact damage was observed on the aft engine fairing, left wing fairing (canoe) and the leading edge of the left horizontal stabilizer (**Photo 3**). The impacts did not penetrate the outer panel or affect the underlying structure.

**Photo 3- Impact Marks on the Horizontal Stabilizer Leading Edge**

The No. 1 engine pylon exhibited sooting and substantial metal splatter in areas above the LPT (**Photo 4**). The pylon structure was deemed to be beyond repair limits by Airbus and was removed and replaced.

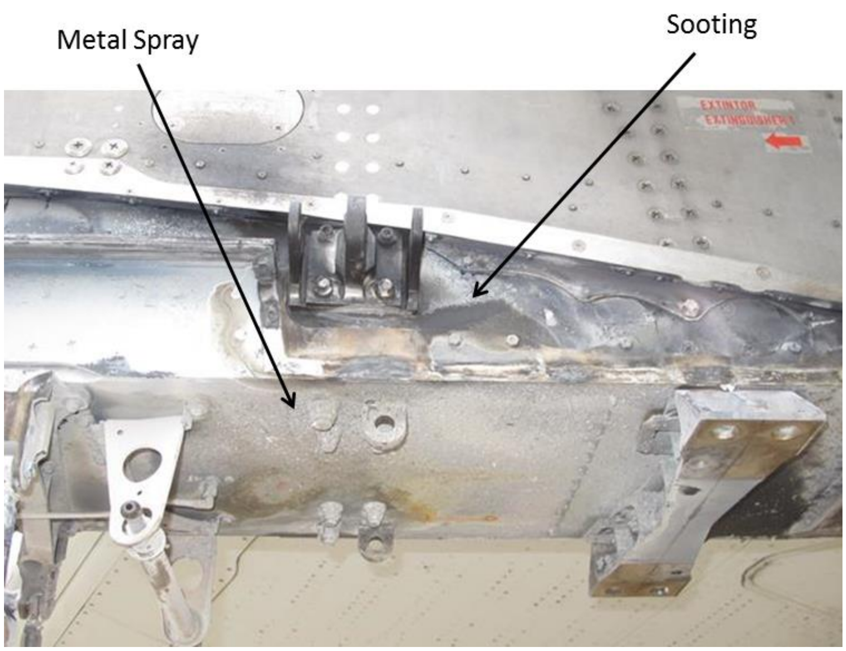



**Photo 4- No. 1 Engine Pylon Damage Including Sooting and Metal Spray**

## 2.2 ENGINE EXAMINATION

### 2.2.1 Fan and Low Pressure Compressor

The fan was intact and spun freely without binding. The fan case rub strip exhibited light tip rub circumferentially from the 4 to 11 o'clock positions along the fan blade leading edge and 360 degrees around at the trailing edge (**Photo 5**). Visible fan exit guide vanes and LPC inlet guide vanes were in good condition.

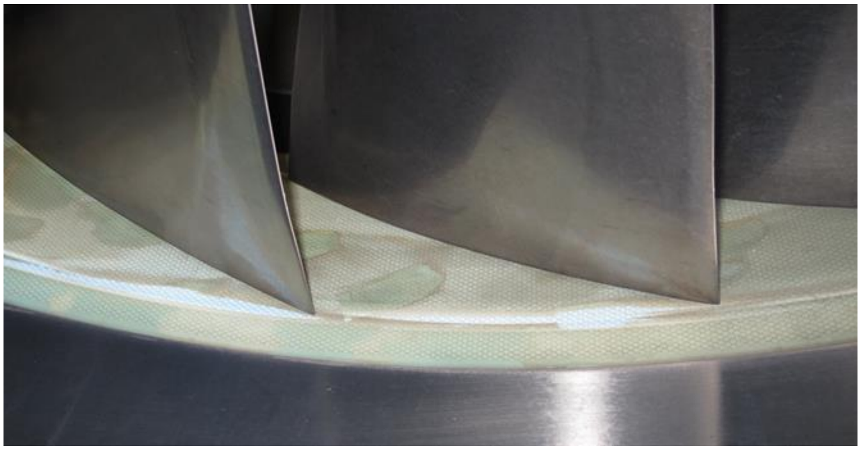


**Photo 5- Fan Rub Strip Damage**

2.2.2 Intermediate Fan Case

The intermediate fan case and external lines were in place and undamaged. The surrounding engine cowl and internal heat blanket were in good condition. The HPC and combustion cases were sooted but did not exhibit thermal damage and the silicone sleeves and wire clamps remained pliable.

2.2.3 High Pressure Turbine Case

The HPT case was intact and in good condition between the M and N flanges. The HPT case surfaces and lines were sooted but did not exhibit thermal damage.

2.2.4 Low Pressure Turbine Case

The LPT case was missing material from the 8:30 to 4 o’clock positions circumferentially and axially from the N flange to 10 inches forward of the P flange (**Photo 6**). A fragment of the LPT case remained attached to the P flange from the 11 to 1 o’clock positions when the exhaust was separated from the engine (**Photo 7**). The remaining sections of the LPT case had metal splatter on external surfaces. The LPT cooling case manifold exhibited impact damage and was fractured at the lug position 3 inches forward of the P flange.

**Photo 6- LPT and TEC Damage (L) Left Side of Engine (R) Right Side of Engine**

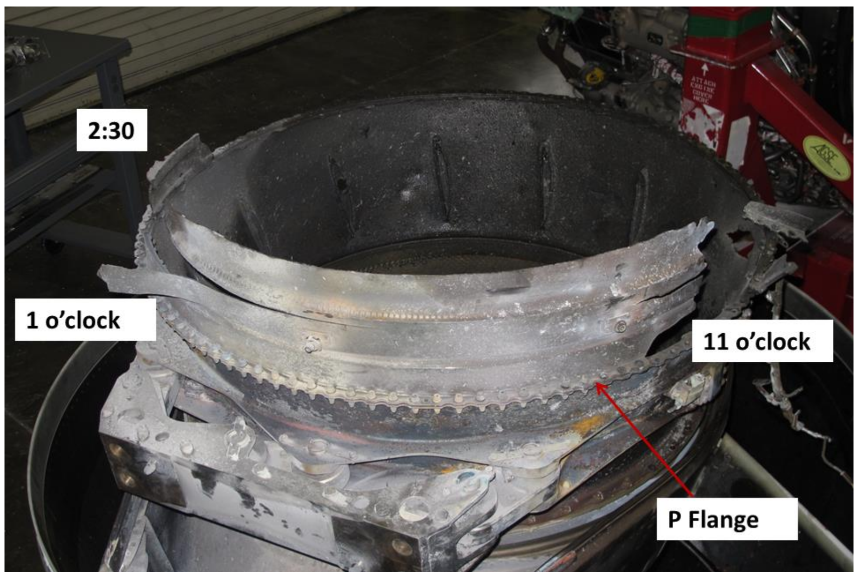



**Photo 7- LPT Case Material Attached to P Flange**

### 2.2.5 Turbine Exhaust Case

The TEC struts, center body and No. 5 bearing compartment were separated and missing from the engine. The EGT harness was severed in multiple locations and the wire insulation was damaged with metal splatter adhered to the remaining probes and wire. The EGT harness junction box was detached from the flange and resting at the 6 o'clock position on the No. 4 bearing buffer cooler exhaust tube (**Photo 8**). The fire detection loop around the turbine exhaust case was intact but the support brackets were loose. The No. 5 bearing oil scavenge line was detached but the safety wire connection remained intact and no damage was noted to the male fitting threads. A hole was present in the TEC at the oil scavenge tube fitting (**Photo 9**). The TEC had a 1.5 inch puncture at the 7:30 position, 2.5 inches aft of the P flange with cracks extending from the puncture consistent with thermal damage. The P flange was missing 5 bolts at the 10:30 position and all bolts were missing from the 1 to 9 o'clock positions. All but 6 of the remaining 29 P flange bolts were loose and the attaching nuts had started to back off the bolt threads. When the P flange was viewed from below it was noted that the LPT case had shifted below the turbine exhaust case so the case flanges no longer lined up (**Photo 10**).The bottom of the turbine exhaust case was oil wetted.


**Photo 8- EGT Harness Junction Box, Damaged Harness**


**Photo 9- No. 5 Bearing Oil Scavenge Line**

**Photo 10- P Flange Shift Between LPT Case and Turbine Exhaust Case**

The inner barrel C-duct was breached and missing material coincident with the material missing from the LPT case. The material breaches measured 25 inches circumferentially and 5 inches axially on the left side of the engine and 19 inches circumferentially and 11 inches axially on the right hand side of the engine (**Photo 11**).

**Photo 11- Missing Material and Thermal Damage to Left Side C-Duct**

The left and right hand thrust reverser (TR) cowls were intact without breaches or indications of thermal damage. An impact mark into the left hand TR cowl was present at the 9 o'clock position but it did not breach the cowl and no bulging was noted on the outer cowl surface. The right hand TR cowl had an impact mark at the 2:30 position, approximately 16 inches from the aft edge that did not breach the cowl but did result in a bulge on the outside surface (**Photo 12**). A second impact mark was identified at the 4:30 position, approximately 3 inches from the aft edge and did not result in any deformation to the cowl outer surface.

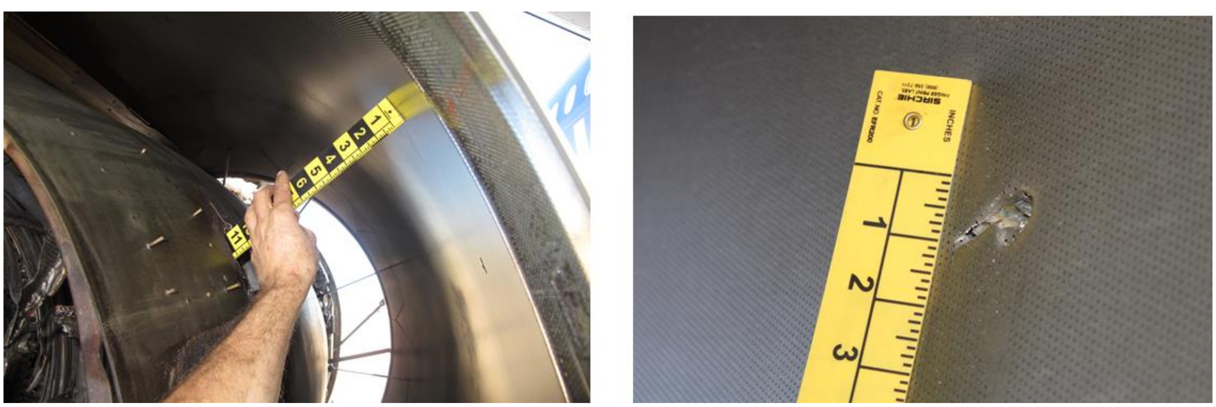


**Photo 12- Right Hand Thrust Reverser Cowl Trajectory and Impact**

Loose metal debris was found resting in the tailpipe. Dents and gouges were noted 360 degrees around the circumference of the exhaust.

2.3 Turbine Inspection

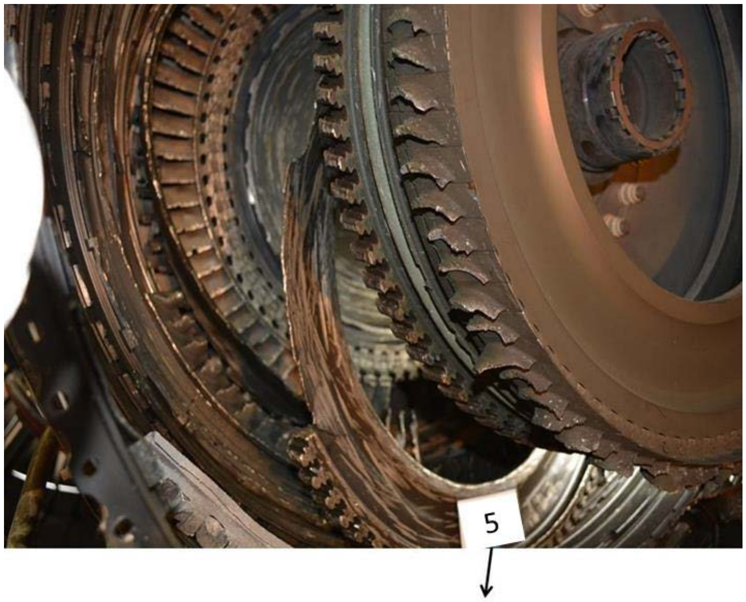
After removal of the engine from the airframe a more thorough evaluation of the turbine sections was conducted. The HPT 2nd stage vanes were visible through the HPT 2nd stage blades and were intact and in good condition with light uniform metal splatter 360 degrees around. The HPT 2nd stage blades were present but exhibited impact damage and smearing against the direction of rotation, concentrated on the trailing edge around the disk (**Photo 13**). Three HPT 2nd stage turbine blade airfoils were fractured transversely at the platform but the blade roots remained in the disk slots. Six blades, including the blade roots were separated from the disk. Four of the six blades were later found loose within the engine. The HPT 2nd stage disk web and bore exhibited circumferential gouging and scoring 360 degrees around. The HPT 2nd stage rear side plate was fractured, deformed, and out of position. The side plate locks were gouged and missing material. The HPT nut and lock ring were in place. The HPT outer air seal was missing from the 5:30 to 11:30 positions.

**Photo 13- HPT 2nd Stage Turbine Disk Damage**

The LPT inner transition duct was separated and missing. The outer transition duct segments were missing from the 5:30 to 11:30 positions and the remaining segments exhibited impact damage from the 11:30 to 3:30 positions. The outer transition duct segment was punctured at the 2:30 position. The LPT 3rd stage vanes were missing from the 8 to 11 o'clock positions and the remaining vanes exhibited impact damage and were missing material. The LPT 3rd stage vane inner diameter platform was missing with the exception of a three vane cluster at the 5 o'clock position. Damage to the 3rd stage vanes was concentrated on the trailing edge in the direction of rotation.

The LPT 4th stage vanes were missing in two segments from the 2 to 4 o'clock and 6 to 11 o'clock positions. The vanes that were present were fractured near the vane platform and remaining material exhibited impact damage and smearing. The 4th stage vane heat shield visible under the missing vane segments was intact without indications of thermal damage. The LPT 4th stage disk was missing and was not recovered.

The LPT 5th stage vanes were only present from the 12 to 1 o'clock positions with all remaining vanes missing. The LPT 5th stage disk was missing approximately 270 degrees of the outer blade attachments. The disk was detached from the LPT $6^{th}$ stage disk and was hanging on the LPT shaft (**Photo 14**).




$5^{th}$ Stage Disk

**Photo 14- LPT $5^{th}$ Stage Disk Displaced and Hanging on LPT Shaft**

The LPT $6^{th}$ stage vanes were not present. The LPT $6^{th}$ stage disk and blade attachments were intact but all the blades were missing. The LPT $6^{th}$ stage disk front attachment flange was present but heavily damaged and folded under the blade slots 270 degrees around the disk. The front face of the LPT $6^{th}$ stage disk hub was circumferentially scored 180 degrees around with minimal scoring over the remainder of the disk. The $6^{th}$ stage disk hub attachment bolts to the LPT shaft were heavily smeared over the same 180 degree section as the disk hub.

The LPT shaft was heavily scored/gouged 360 degrees around axially from the HPT $2^{nd}$ stage bore to the LPT $6^{th}$ stage disk (**Photo 15**). The knife edge seal between the LPT $6^{th}$ and $7^{th}$ stage disks was present with minor nicks and dents around the circumference.

**Photo 15- LPT Shaft and LPT 6th Stage Disk Hub Scoring Damage**

The LPT 7th stage vanes were missing and not recovered. The LPT 7th stage disk was present but all airfoils were sheared at the blade root just above the platform with blade roots secure in the disk. The aft side of the 7th stage disk was in good condition. Carbon seal fragments were found resting at 6 o'clock inside the 6th to 7th stage bore cavity. The aft end of the LPT shaft was in good condition and the internal plug was intact and secure. The No. 5 bearing rollers and outer race were missing. The inner race was present and undamaged. The No. 5 bearing lock nut and ring were in good condition but slightly displaced in the aft direction (**Photo 16**). The No. 5 bearing and bearing housing were not recovered.


**Photo 16- No. 5 Bearing, Rollers and Outer Race Missing. No. 5 Bearing Lock Ring and Nut Intact**

## 2.4 Combustor and High Pressure Turbine Borescope

The combustion chamber and HPT module were examined by borescope. The inner and outer combustion liners, fuel nozzles, and HPT 1st stage vanes were in good condition with no thermal or mechanical damage noted. The HPT 1st stage blade airfoils exhibited loss of thermal coating material but were otherwise in good mechanical condition with the exception of a group of approximately six consecutive airfoils with various amounts of material missing from the tip (**Photo 17**). The HPT 1st stage blade outer air seal appeared to be in good condition with no significant rub. The HPT 2nd stage vanes were intact and in good condition.


**Photo 17- HPT 1st Stage Blade Airfoil Tip Damage**

## 3.0 ENGINE EXAMINATION AND DISASSEMBLY

Extensive damage to the aft engine mount, LPT case, and turbine exhaust prohibited shipment in a standard shipping container. NKS and IAE created a modified container to ship the engine to the P&W Columbus, GA facility (**Photo 18**). The turbine exhaust case and common nozzle assembly were shipped in a separate crate (**Photo 19**).

The remaining magnetic chip detector plugs were removed and evaluated for metal debris. The main engine oil tank and de-oiler plugs had a buildup of metal shavings and the remaining plugs were clean (**Photo 20**).

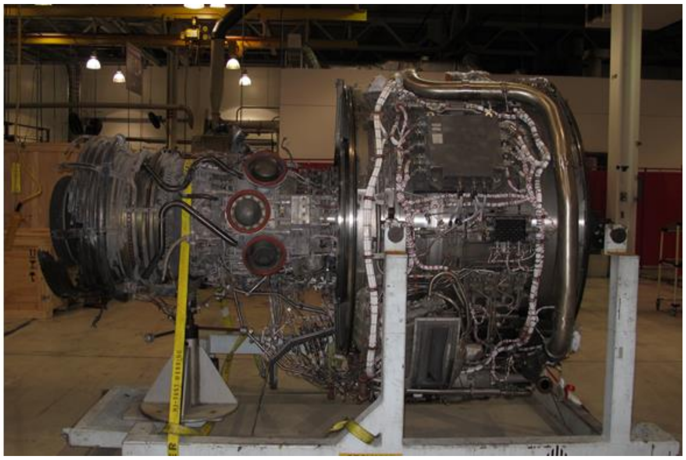



**Photo 18- Engine- As Received (L) Left Side (R) Right Side**

**Photo 19- Turbine Exhaust Case and Common Nozzle Assembly- As Received**


**Photo 20- Magnetic Chip Detector Plugs, Main Oil Tank (1) and De-Oiler Plugs (7) With Debris**

### 3.1 LOW PRESSURE TURBINE

The LPT shaft and attached $6^{th}$ and $7^{th}$ stage disks were removed from the engine. The LPT $5^{th}$ stage disk was detached from the LPT $6^{th}$ stage disk and hanging freely from the LPT shaft (**Photo 21**). The LPT shaft exhibited circumferential rubs at multiple points along its length. Measurements were taken of each rub location and compared against engine drawings to determine which internal surfaces had contacted the shaft at each location. A series of four rubs on the forward half of the shaft aligned with the HPC $4^{th}$ through $7^{th}$ stage disk bores. The rub aligning with the HPC $4^{th}$ stage bore was a light single point rub with no material loss. The rub aligning with the HPC $5^{th}$ stage bore was approximately 180 degrees around with light material loss that could be felt. The rubs aligning with the HPC $6^{th}$ and $7^{th}$ stage disk bores were both 360 degrees around and depth increased with each stage (**Photo 22**). The circumferential rub aligning with the HPC $7^{th}$ stage disk bore also exhibited material bluing around the circumference. The HPT shaft was borescoped and matching rubs were confirmed on the HPC disk bores (**Photo 23**). Rub/scoring was also present in positions that aligned with the high pressure shaft rear heat shield and HPT shaft below the $1^{st}$ and $2^{nd}$ stage disks (**Photo 24**). The points where the HPT shaft contacted the LPT shaft exhibited material transfer. The aft end of the

LPT shaft where the LPT disks are normally positioned exhibited heavy gouging and scoring 360 degrees around with material damage most concentrated over a 180 degree area. A ruler was placed on each side of the shaft and a gap comparison check confirmed that the shaft was bent (**Photo 25**).

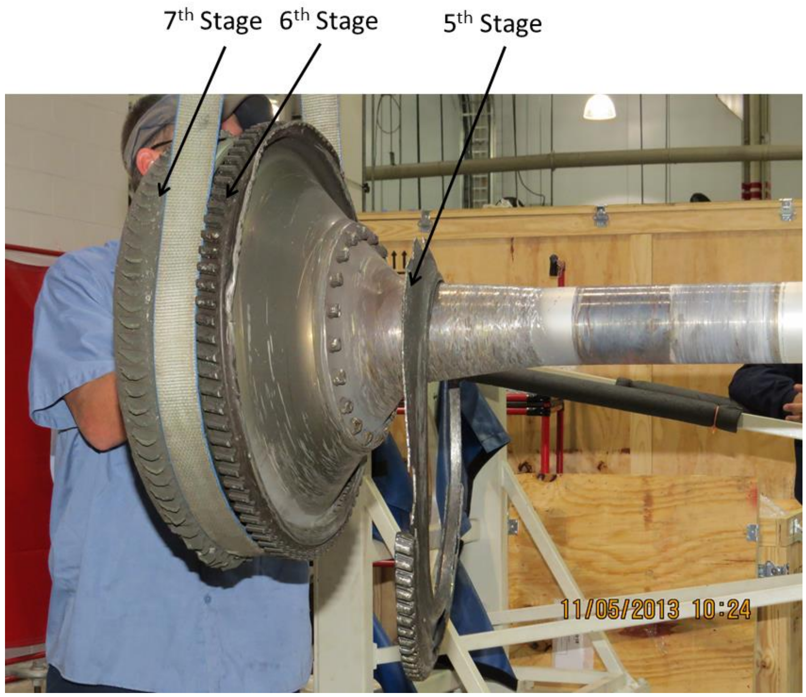



**Photo 21- Removal of the LPT Shaft From the Engine**

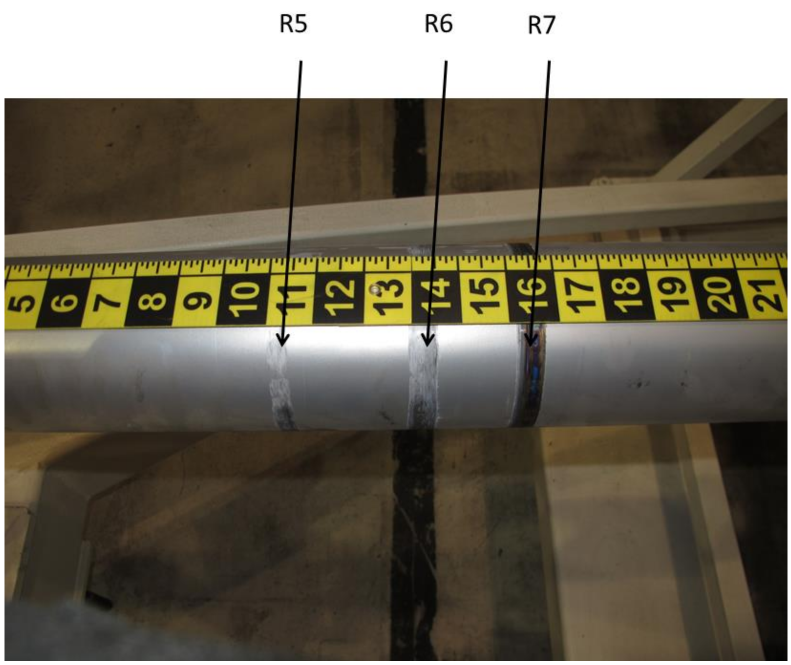



**Photo 22- Circumferential Rubs on the FWD End of the LPT Shaft, Corresponding Contact Points Labeled**

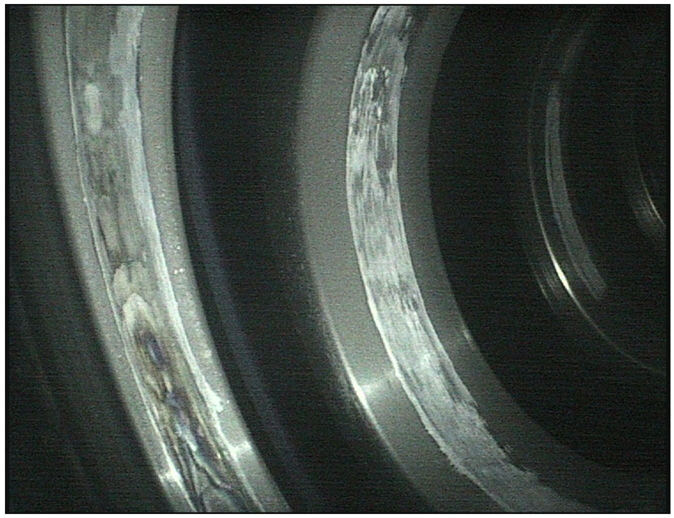


**Photo 23- Borescope Photos Inside High Pressure Shaft, Rubs on HPC Disk Bores**

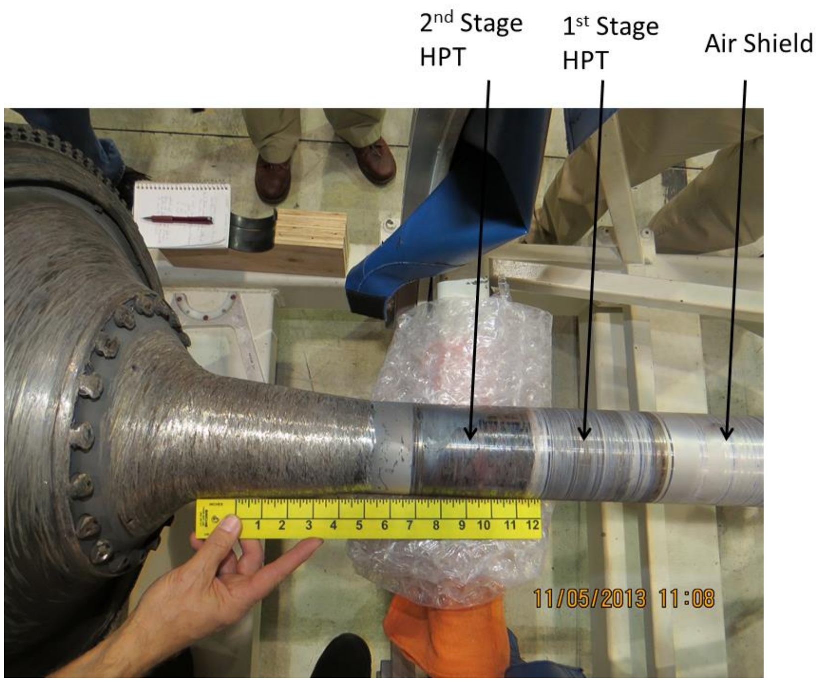



**Photo 24- Circumferential LPT Shaft Rub/Scoring, Corresponding Contact Points Labeled**


**Photo 25- LPT Shaft- Gap Between Ruler and Shaft to Show Shaft Bend**

The LPT 5th stage disk was missing 240 degrees of blade attachment slots (**Photo 26**). The disk webbing exhibited heavy gouging on the forward and aft sides. The inner diameter disk bore was mushroomed consistent with LPT shaft impact. Multiple cracks were present on the disk web originating from the outer rim. The forward disk attachment wing was present in two sections, 30 degrees and 20 degrees in circumference. Both sections exhibited impact damage that flattened the wing into the disk web. The aft disk attachment wing was present over a 30 degree section and exhibited impact damage that caused it to roll inward towards the blade attachments (**Photo 27**).

**Photo 26- LPT 5th Stage Disk, (L) As Removed From Engine (R) New Disk**

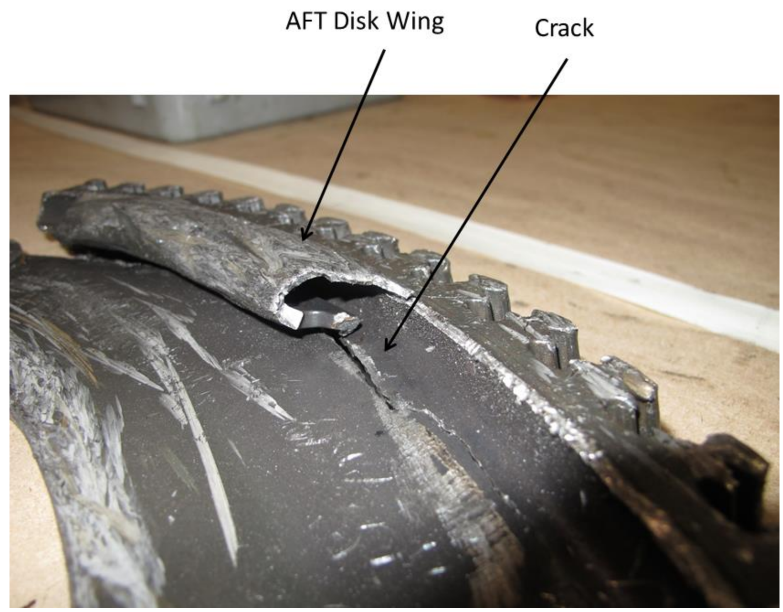



**Photo 27- LPT $5^{th}$ Stage Disk Damage, Disk Wing Rolled Inward**

### 3.2 LOW PRESSURE TURBINE CASE[4]

The LPT $3^{rd}$ stage vane fracture surfaces were shiny and less oxidized than other fracture surfaces within the case. Impact marks were identified on the LPT $3^{rd}$ stage vane heat shield and LPT case where vane segments were missing (**Photo 28**). Impact mark spacing on the LPT $3^{rd}$ stage vane heat shield was consistent with LPT blade attachment spacing based on caliper measurements.

**Photo 28- Impact Marks Along $3^{rd}$ Stage Vane Track, Vanes, and Heat Shield Missing**

[4] The LPT case condition is documented in the on scene section of this report because damage allowed for removal of the engine cases at DFW. Section 2.2 addresses additional findings during the engine teardown.

## 3.3 High Pressure Turbine

The HPT 2nd stage blade retaining ring had separated allowing it to expand into a "U" shape. The ring exhibited impact deformation 360 degrees around with material loss and rub noted along the separated edges (**Photo 29**). All 32 bayonet tabs were present, confirming that the entire ring circumference was recovered.

**Photo 29- HPT 2nd Stage Blade Retaining Ring**

Removal of the HPT retaining nut was difficult due to binding. Galling was noted on the forward nut surface and discoloration was present along the forward outer diameter. After removal of the retaining nut, the HPT shaft aft edge was notably flared.

The HPT 2nd stage turbine blades had trailing edge impact damage and material loss around the rotor (**Photo 30**). The aft surface of the disk web and blade attachment slots exhibited scoring 360 degrees around. Three HPT 2nd stage blades were fractured transversely below the platform at positions 45, 51, 52, as numbered during teardown, and the blade roots remained within the disk blade slot. Six consecutive blades were missing located at positions 2-7, four of which were found in the debris just aft of the HPT. The forward side of the HPT 2nd stage disk was oil streaked. The HPT 2nd stage metering plugs were intact and in place.

**Photo 30- HPT 2nd Stage Blade Damage, Blades Secured in Fixture**

The HPT 2nd stage nozzle vanes had rub on the forward inner vane platform around the circumference, consistent with HPT 1st stage turbine blade discourager seal (guitar pick) contact. All vanes had metal spray on both pressure and suction surfaces. Multiple vanes exhibited impact damage along the trailing edge outer diameter (**Photo 31**).

**Photo 31- HPT 2nd Stage Nozzle, Trailing Edge Impact Damage and Metal Spray**

Ten consecutive HPT 1st stage turbine blades were missing material. The greatest material loss occurred at approximately 50% of blade span and material loss on subsequent nine blades decreased progressively to only the leading edge tip. All remaining blades exhibited heavy tip rub. The circumferential location of the fractured blades was consistent with heavy rub identified on other rotating components. All blades had metal spray on the leading and trailing edges. The trailing edge blade platform had rub 360 degrees around the disk. The trailing edge discourager seal (guitar pick) had 360 degree rub most concentrated over a 180 degree arc (**Photo 32**). The HPT stage 1-to-2 air seal web had baked on oil residue and sooting on the forward and aft surfaces. Baked oil residue had collected along the outer seal diameter lip and flaked off to the touch (**Photo 33**). Oil wetting was also noted along the seal inner bore. The knife edge seals along the 1-to-2 air seal outer diameter were intact with evidence of rub. The HPT 1st stage air seal (Tangential On Board Injector - TOBI) exhibited approximately a 180 degree rub on the forward surface consistent with contact from the static discourager seal. The aft side of the disk was oil streaked. The HPT 1st stage metering plugs were intact and in place.

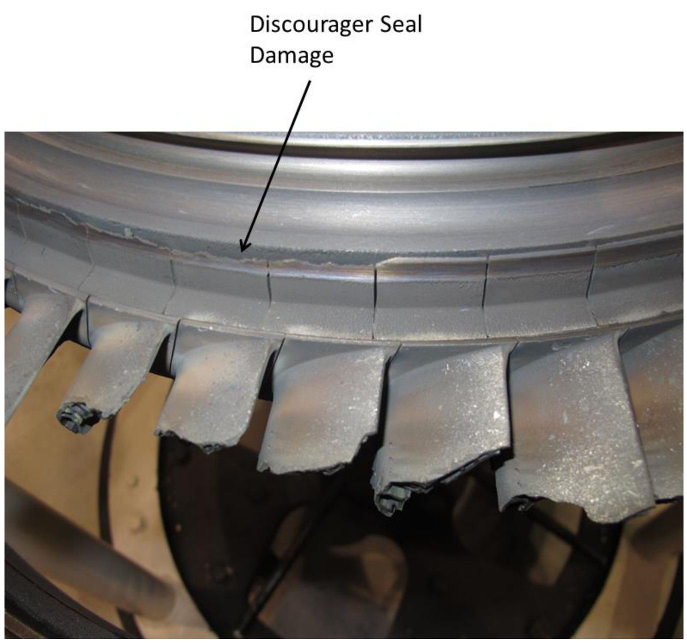



**Photo 32- HPT 1st Stage Blade Tip Damage**


**Photo 33- 1-to-2 Seal Oil Residue**

## 3.4 COMBUSTOR/DIFFUSER

Damage to the No. 4 bearing housing and heat shield was noted during a borescope inspection. The HPT 1st stage nozzle guide vane (NGV) assembly and inner burner were removed to expose the outer combustion liner and No. 4 bearing housing. The NGV was intact and in good condition. Multiple feather seals were dislodged between guide vanes consistent with a vibration event according to IAE engineering. The combustion liner assembly was intact and its thermal barrier coating was in good condition without evidence of uneven combustion or fuel nozzle streaking. The fuel nozzles did not exhibit coke buildup and collars were intact and in good condition. Debris including metallic flakes, carbon seal fragments, and safety wire were found between the No. 4 bearing support and No. 4 bearing rear cooling duct at the 6 o’clock position. A length of uncoiled carbon seal carrier spring was found between the carrier and seal land (**Photo 34**). Oil wetting was noted at 6 o’clock running down the rear No. 4 heat shield cover originating from the No. 4 bearing housing. The aft No. 4 bearing carbon seal was fragmented and seal springs were dislodged and bundled at 6 o’clock. The external No. 4 bearing compartment surfaces were coated in soot.

The No. 4 bearing forward compartment heat shield was fractured and missing material. Multiple heat shield studs were found fractured with nuts still attached. One heat shield stud with nut attached remained intact securing remaining sections of the heat shield in place. Two buffer air tubes heat shields were found loose with safety wire present but not in place on the cooling duct end. One buffer air tube heat shield was missing safety wire on the cooling duct end (**Photo 35**).

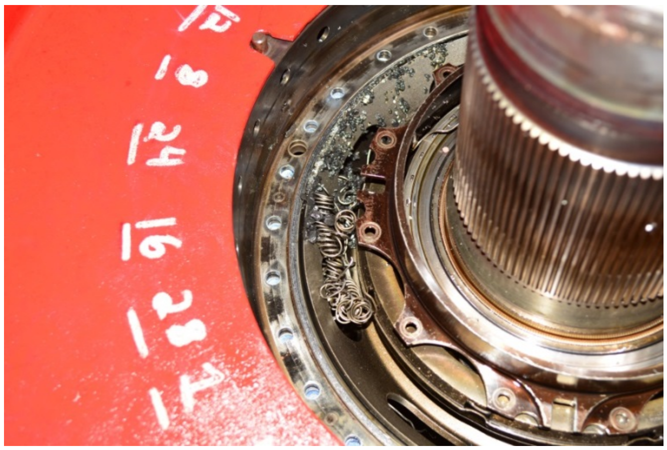


**Photo 34- No. 4 Bearing Aft Compartment Debris**

**Photo 35- No. 4 Bearing Forward Compartment Heat Shield Damage**

## 4.0 METALLURGY

Multiple components from the HPT, LPT, turbine exhaust case, and No. 4 bearing compartment were shipped to the P&W materials lab in East Hartford, CT for materials analysis. A complete list of hardware sent to the lab with a brief workscope for each item is available as **attachment (1)** to this report. The full P&W metallurgy report is available as **attachment (2)**.

## 4.1 HIGH PRESSURE TURBINE

### 4.1.1 HPT 1st Stage Rotor

The HPT 1st stage hub and all 64 HPT first stage blades were submitted for lab analysis. A visual examination of the blades identified 10 consecutive blades that exhibited span wise airfoil fractures. The fracture surfaces were examined under magnification and determined to all have occurred due to overload. The remaining 53 blades exhibited evidence of tip rub. A random sample set of blades were examined and there was no evidence of microstructural changes that would indicate metal temperature exposure in excess of $2050^{o}$F ($1121^{o}$C).

The forward side of the HPT 1st stage hub web and bore were oil wetted with streaks that extended from the bore inner diameter out to the underside of the aft snap land (outer diameter). Oil streaking observed on the hub is consistent with an oil leak from the No. 4 bearing compartment. The hub did not exhibit any indications of sooting or oil fire.

### 4.1.2 HPT 2nd Stage Disk

Seventy of the 72 HPT 2nd stage blades were submitted for analysis. Three of the 70 blades exhibited below platform fractures. The fracture surfaces were covered with dark deposits with low aspect ratio cracks in the trailing edge cavity of the J-channel rib (**Photo 36**)[5]. According the P&W materials lab, the crack morphology was consistent with SCC of nickel superalloys. Electron microprobe (EMP) and scanning electron microscope (SEM)/energy dispersive spectroscopy (EDS) were used to analyze the oxidation/corrosion products on the fracture surfaces and secondary cracks. The product was found to be predominantly comprised of oxidized base metal elements but sulfur deposits were found on each crack location that was examined. The source of the sulfur could not be determined.

[5] In the photo PS stands for pressure side (concave) of the blade, SS stands for suction side (convex) of the blade, and SCC stands for stress corrosion cracking.

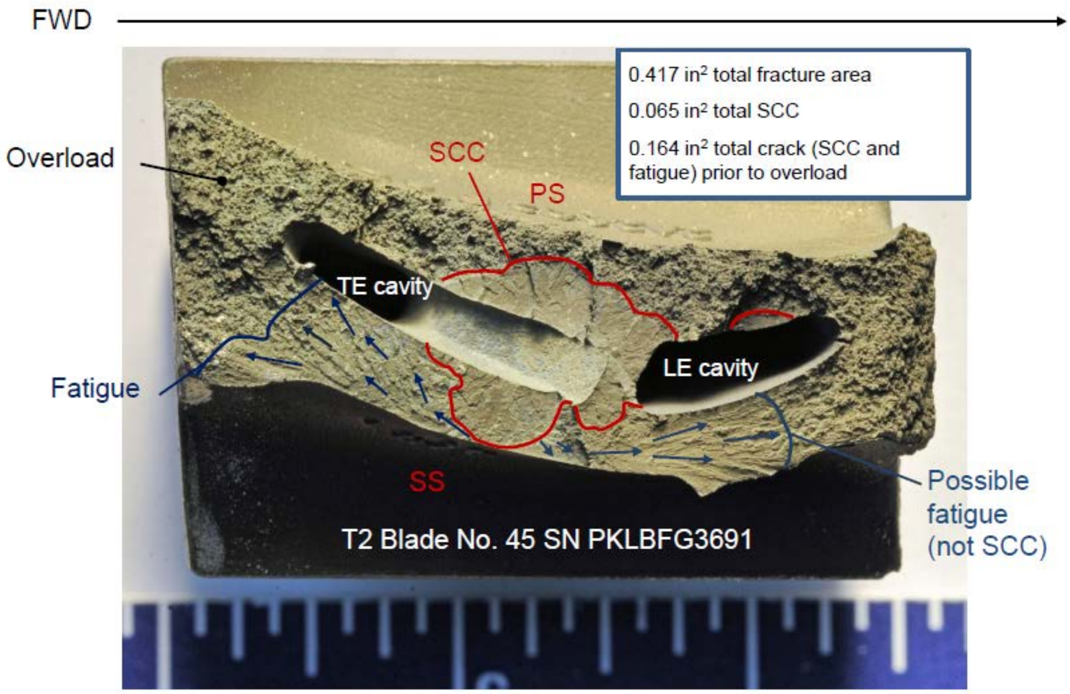



**Photo 36- HPT 2nd Stage Blade Fracture Surface, Stress Corrosion Cracks Labeled**

Non-destructive examination methods including x-ray and borescope of the remaining 67 blades identified various levels of SCC in the J-channel cooling air cavity of 38 blades. All 67 blades were subsequently sectioned for more thorough examination and a total of 41 were found to exhibit under platform cracks.

All HPT 2nd stage blades exhibited multiple impact fractures along the blade span on both the leading and trailing edges. The blades also had indications of severe thermal distress concentrated on the forward section of the blade platform and along the leading edge. Damage was consistent with a blade failure event and subsequent overtemperature due to insufficient cooling airflow.

#### 4.1.3 HPT 2nd Stage Hub Heat Shield

The HPT 2nd stage hub heat shield exhibited dark discoloration and evidence of oil deposition. A hardness survey[6] was conducted by collecting three axial sections. Hardness values ranged between 44-46 Rockwell Hardness on the C scale (HRC) which are expected values for precipitation heat treated Inconel 718[7]. Changes in Inconel 718 occur at temperatures greater than 1450°F (788°C) and these changes were not observed in any of the samples.

[6] The Rockwell Hardness Test presses a steel or diamond hemisphere-conical penetrator against a test specimen and measures the resulting indentation depth as a gage of the specimen hardness. The harder the material, the higher the HR reading. For softer materials the Rockwell B Scale (HRB) is used and for harder materials (>100 HRB) the HRB scale is used.

[7] Inconel 718 is a wrought precipitation hardened nickel base alloy.

## 4.2 LOW PRESSURE TURBINE

### 4.2.1 LPT 3rd Stage Disk

Two fragments of the LPT 3rd stage disk were recovered during a search in rural Texas and shipped to P&W for analysis. The larger of the two fragments measured 52 inches circumferentially and was twisted. The smaller fragment measured 9.5 inches circumferentially. The ends of the smaller piece mated with those on the large piece and the total circumference of the two fragments accounted for the entire disk outer rim (**Photo 37**). Binocular examination of the fracture surfaces found rough, granular features consistent with a mixture of tensile overload and stress rupture failure modes with no evidence of fatigue.

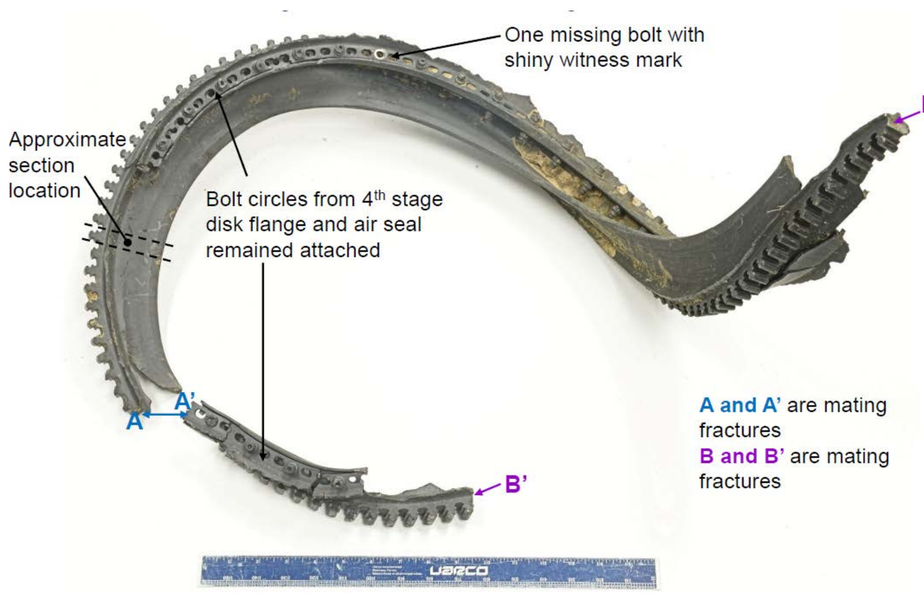



**Photo 37- Recovered HPT 3rd Stage Disk Rim**

Hardness measurements were taken at multiple points along the disk rim and ranged from 87.5-95.3 HRB, well below the 40 HRC minimum for heated treated Inconel 718. The recorded hardness values are consistent with metal temperature exposure in excess of 1700°F (927°C).

Additional evaluation of grain boundaries found evidence of grain growth consistent with temperature exposures in excess of 1825°F (996°C) but there was no evidence of incipient melting which occurs between 2200-2450°F (1204-1343°C) in Inconel 718.

### 4.2.2 LPT 5th Stage Disk

The LPT 5th stage disk outer rim was intact but exhibited severe damage including deformation and heavy impact damage. Binocular examination of the disk fracture surfaces identified features consistent with overload with no evidence of fatigue.

Hardness measurements were taken at multiple points along a cross section of the disk and values ranged from 96 HRB - 28.5 HRC, below the minimum level for heat treated Inconel 718. These values correlate to maximum metal temperature exposure in excess of 1600°F (871°C).

#### 4.2.3 LPT 6th Stage Disk

The LPT 6th stage disk remained intact but all blades and attachments were missing and the disk was severely damaged including the forward side arm fracture over approximately 40% of the circumference. The remaining 60% of the arm was deformed inward and the aft side of the disk exhibited dark discoloration.

Two metallographic cross sections were collected to conduct a hardness survey of the disk. Hardness measurements along the cross sections ranged from 20.1–42 HRC, below the minimum expected level for Inconel 718. Hardness measurements along the thickest sections of the disk near the bore and in the forward flange were greater than 40 HRC indicating that these areas were not exposed to temperatures in excess of 1450$^{o}$F (788$^{o}$C). In thinner areas where hardness measurements were recorded in the lower levels were consistent with exposure to temperatures in excess of 1600$^{o}$F (871$^{o}$C).

#### 4.2.4 LPT 7th Stage Disk

The LPT disk was fully intact but exhibited dark discoloration. Hardness measurements were taken at the disk rim, web and bore and ranged from 21.8-31.7 HRC, below the minimum expected levels for Inconel 718. These hardness measurements are consistent with temperature exposure in excess of 1600$^{o}$F (871$^{o}$C).

All 89 LPT 7th stage blades were recovered but exhibited fractures near the platform. The remaining blade roots exhibited thermal distress including discoloration and dark deposits 360 degrees around the rotor. Visual and binocular examination of blade fracture surfaces identified features consistent with overload and no evidence of fatigue.

### 4.3 LPT Hardness Profile

To better understand how the LPT 3rd and 4th stage disks separated from the engine, hardness measurements were compared at each stage. These measurements provide an approximate gas path temperature exposure for each disk as well a temperature gradient at multiple points radially along each disk to estimate the LPT bore cavity temperature profile. The LPT 3rd stage disk exhibited the largest drop of hardness across the entire component. Hardness levels in each stage further aft in the LPT were progressively higher with the bore section of each stage exhibiting higher hardness values than the outer rim sections (**Figure 2**).

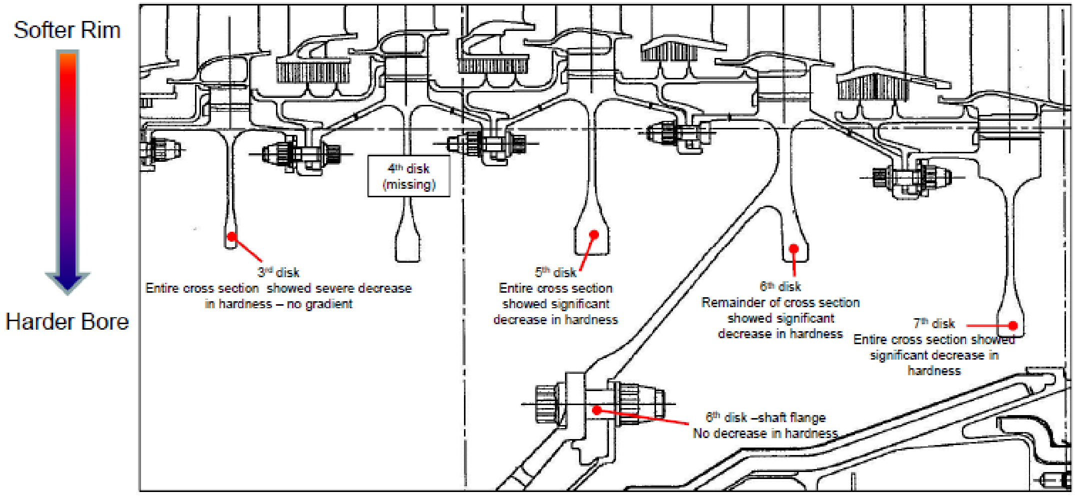



**Figure 2- Low Pressure Turbine Hardness Along the Gaspath**

### 4.4 Low Pressure Turbine Case

The remaining section of the LPT case was submitted for a hardness profile to provide additional information on gas path temperature exposure through the turbine. A section was removed from the 6 o'clock location because it was the most intact location circumferentially around the case. Using the removed section, nine metallographic sections were prepared for hardness checks. Hardness measurements in front of the LPT 3$^{rd}$ stage ranged from 40-46 HRC which is typical for precipitation heat treated Inconel 718. Measurements in the area of the LPT 3$^{rd}$ stage ranged from 19.4-39 HRC. The hardness measured on the remainder of the cross sections, aft of the LPT 3$^{rd}$ stage ranged from 92.1 HRB-22.8 HRC indicating maximum metal temperatures in excess of 1600$^{o}$F (871$^{o}$C) at the upper end of the range and in excess of 1700$^{o}$F at the lower end. Areas of the case closer to the gas path and locations with thinner cross sections exhibited the greatest degree of softening.

### 4.5 Turbine Exhaust Case

A visual examination of the TEC revealed that all of the case support struts fractured and separated from the case at approximately the same radial location, about 0.25-0.50 inch from the case inner diameter surface. The fracture surfaces exhibited mechanical and thermal damage but were consistent with overload/stress rupture failure.

The TEC is manufactured from Greek Ascoloy with a minimum hardness requirement for the specified tempered condition of 30-38 HRC. A section of the TEC was collected and hardness measurements were recorded as 50HRC at the forward flange and 39HRC at the aft flange. The hardness values are consistent with case exposure to temperatures that re-austenitized the material so that it was no longer tempered. From data previously collected at IAE/P&W the values indicate that the case was exposed to temperatures in excess of 1700$^{o}$F (927$^{o}$C) at the forward flange and 1500$^{o}$F (816$^{o}$C) at the aft flange.

### 4.6 No. 4 Bearing Compartment and Hardware

Multiple components from the No. 4 bearing compartment were collected for precautionary examination. The No. 4 bearing compartment scavenge tube was inspected for evidence of an oil leak. The examination focused on the inboard end tube to end fitting weld joint. A visual examination of the tube noted discoloration consistent with exposure to elevated temperatures but there was no evidence of an oil leak. The heat shields were removed from the tube for inspection and had no indications of oil soaking. A binocular examination of the tube to end fitting weld found no evidence of cracking.

The No. 4 bearing front heat shield had multiple intersecting cracks that allowed almost 50% of the cover to separate. The separated pieces of the heat shield were contained within the bearing compartment and were also submitted for review. An examination determined that the heat shield fracture surfaces had granular features consistent with stress rupture. The fragments also exhibited thermal distress including discoloration and localized bulging.

The No. 4 bearing compartment front buffer cooling duct was submitted for confirmation of the weld stud material and examination of the stud fracture surfaces. All weld stud fracture surfaces were consistent with overload failure and did not exhibit signs of fatigue. One stud was examined using scanning electron microscope/energy dispersive spectroscopy and the composition was consistent with Inconel 718 as required by design specification.

## 5.0 RECORDED DATA

### 5.1 Flight Data Recorder

The incident airplane was equipped with a Honeywell solid state FDR. The FDR was collected on scene at DFW and shipped to NTSB headquarters in Washington, DC for download and analysis. Key engine parameters were plotted by the NTSB recorders division and a full report including parameter plots are available in the docket.

#### 5.1.1 ECAM Warnings

The aircraft took off at about 13:36:22 CDT. At 13:47:18 CDT as the aircraft was climbing through approximately 19,500 feet the crew received a sequence of warnings shown in **Table (1)**.

| Timestamp (CDT) | ECAM Message |
|---|---|
| 13:47:18 | Engine Pressure Ratio (EPR) Mode Fault |
| 13:47:22 | No. 1 Engine EGT Overlimit<br>No. 1 Engine N2 Overlimit |
| 13:48:00 | Master Warning |
| 13:51:14 | No. 1 Engine Fire Warning |
| 13:51:50 | Avionics Smoke Warning |
| 13:51:45 | No. Engine Low Oil Pressure Warning |
| 13:51:54* | Lavatory Smoke Warning<br>Cargo Smoke Warning<br>Forward Lower Cargo 1 Smoke Warning<br>Forward Lower Cargo 2 Smoke Warning<br>Aft Lower Cargo 1 Smoke Warning<br>Aft Lower Cargo 2 Smoke Warning |

*Smoke warnings occurred over a 2.5 minute period beginning at 13:51:54

**Table 1- ECAM Warning Sequence**

#### 5.1.2 No. 1 Engine Vibration Levels

At 13:47:21 CDT, the No. 1 engine N1 vibration levels increased from a steady state value of 1.1 to 7.2 units and the N2 vibration levels increased from 0.3 to 2.1 units. At 13:50:34 CDT, the No. 1 engine N1 vibration levels decreased and fluctuated at values between 2.2 and 4.5 units and the N2 vibration levels increased to 9.9 units.

#### 5.1.3 Thrust Lever Angle Adjustments

At 13:47:27 CDT, the thrust lever angle (TLA) on both engines were manually advanced to maximum continuous thrust setting and then about fifteen seconds later to takeoff/go-around (TO/GA) position. The engine parameters indicate that at the time of the increase, the No. 1 engine was N2 speed limited and therefore the change in TLA position did not increase fuel flow. The No. 2 engine responded to the TLA adjustment and commanded increased fuel flow per design. The TLA for both engines remained at TO/GA until the No. 1 engine was shutdown following the fire warning and the No. 2 engine was retarded to cruise level.

#### 5.1.4 Exhaust Gas Temperature Indication

At 13:47:21 CDT, the No. 1 engine EGT indication became invalid as indicated by fluctuating values between $0^{o}$C and $2,560^{o}$C. Airbus confirmed that the cockpit EGT gage displayed amber X’s in place of temperature values beginning at 13:47:21CDT and continued throughout the event.

### 5.2 Quick Access Recorder

The quick access recorder (QAR) memory card was collected on scene and shipped to NTSB headquarters for analysis. NKS and Airbus informed the NTSB that the incident aircraft QAR did not have a customized parameter list or increased sample rate so all parameters gathered on the QAR memory card were identical to FDR data and were therefore not downloaded.

### 5.3 COCKPIT VOICE RECORDER

The Cockpit Voice Recorder (CVR) was gathered on scene at DFW and sent to NTSB Headquarters for audition. A summary transcript of the recording is available in the docket.

## 6.0 OPERATIONS

### 6.1 CREW INTERVIEW

Immediately after the event, statements were collected from the Captain, First Officer and Flight Attendants by NKS and provided to the NTSB. An interview with the Captain and First Officer was conducted by the NTSB on January 9, 2014 at NKS headquarters in Miramar, FL. A record of conversation is available in the docket.

During the interview the captain and first officer stated that shortly after they received the EPR mode fault ECAM message, the autopilot and auto-thrust disengaged. They did not recall hearing an audible signal or display message indicating that the functions had disengaged. The first officer stated that while troubleshooting the EPR mode fault indication, the ECAM priority item located at the top of the fault list was replaced with an EGT overlimit warning and then an N2 overlimit warning. The EGT overlimit and N2 overlimit warnings then repeatedly switched positions on the ECAM priority list making troubleshooting difficult. The captain stated he did not remember advancing the throttles to TO/GA shortly after the initial warnings but said that he was concerned with navigating between thunderstorm cells on both sides of the flight path. Both flight crew members confirmed that there were was a significant vibration that could be felt throughout the cabin during the event.

### 6.2 NKS Crew Operating Manual

The NKS Crew Operating Manual (COM) abnormal/emergency procedures for EPR mode fault, EGT Overlimit, and N2 Overlimit warnings were reviewed. The applicable abnormal/emergency procedures from the February 27, 2013 version of the NKS COM are included as **attachment (3)** to this report.

The maximum value for N1 and N2 speeds are specified in the COM and are as follows: N1 109.4% or above and N2 105.7% or above. Exceedance of these values requires engine shutdown. The maximum EGT value called out in the COM is $635^{o}$ C ($1175^{o}$F). The COM states that the crew may continue operation until next landing but maximum temperature and duration at temperatures above the limit should be recorded. The COM then states, "if unable to maintain engine within limits, affected engine should be shut down. If conditions do not permit engine shutdown, land ASAP using the minimum thrust required to sustain safe flight."

The high engine vibration abnormal/emergency procedure does not have an associated ECAM warning. The NKS COM procedure states, "the VIB advisory on ECAM (N1 $\geq$ 5 units, N2 $\geq$ 5 units) is mainly a guideline to induce the crew to monitor engine parameters more closely." and "VIB detection alone does not require engine shut down."

## 7.0 ADDITIONAL INFORMATION

### 7.1 HIGH PRESSURE TURBINE 2ND STAGE BLADE REPAIR HISTORY

The engine repair records indicated that all 72 HPT 2nd stage blades had previously been repaired prior to the incident at Turbine Overhaul Services (TOS)[8], Singapore or Japan Turbine Technologies (JTT), Taipei, Japan. All 41 blades that exhibited SCC were last repaired at TOS.

### 7.2 SPIRIT FLEET GROUNDING FOR NO. 5 BEARING OIL SCAVENGE TUBE

On October 24, 2013 NKS voluntarily grounded all 51 aircraft in their fleet after discovering a discrepancy in the No. 5 bearing oil scavenge line b-nut torque in the latest revision of the inspection manual. Previous editions of the manual listed the b-nut torque at 300-325 lbs.-in and a newer edition had the torque value decreased to 200-225 lbs.-in. NKS anticipated being able to inspect all airplanes to ensure the b-nut torque was at the higher value without causing disruptions to their flight schedule but ran into unexpected delays. The subsequent flight delays due to the inspection received national media attention. The FAA Certificate Management Office was not notified of the planned inspections in advance.

The maintenance manual is currently at revision 6 and a review of all previous revisions by IAE found the torque value was lowered (200-225 lbs.-in) in revisions 4 and 5 before being adjusted back to the original value in the most recent revision (300-325 lbs.-in). According to standard practice design manuals, 200-225 lbs.-in of torque are applicable for nuts which have anti-seize on the threads, 320-350 lbs.-in of torque are for oil lubricated nuts without anti-seize. The No. 5 oil scavenge b-nut is not supplied with anti-seize and therefore 300-325 lbs.-in of torque is required. The lower torque values listed in manual revisions 4 and 5 are believed to be an error according to IAE.

### 7.3 EGT PROBE AND COCKPIT INDICATION

According to IAE, the EGT probes installed on the V2524-A5 are temperature rated to 1238$^{o}$F (670$^{o}$C). The maximum EGT temperature demonstrated during the certification program was 1328$^{o}$F (720$^{o}$C) for a duration of 5 minutes. According to design specification, the probe is capable of functioning at temperatures up to 1400$^{o}$F (760$^{o}$C). The engine electronic control (EEC) is capable of receiving an EGT signal up to 1830$^{o}$F (999$^{o}$C) with temperatures exceeding that value being rejected as out of range. Airbus confirmed that in an event where the EGT probes are exposed to temperatures above 1830$^{o}$F (999$^{o}$C), the cockpit indication will display amber X's. The EGT probe range used on the V2524-A5 engine is consistent with other engines across the IAE and P&W product line.

### 7.4 IAE ALTERNATIVE CREW ACTION ANALYSIS

IAE performance engineers conducted an analysis to determine how the engine would have responded if TLA had been reduced to idle position at the onset of vibration and warning indications. The analysis was performed with the assumptions that moving the TLA to the idle position would reduce fuel flow to minimum levels and damaged LPT efficiency calculations were based on N1 speed compared to a normal engine as recorded by the FDR during the event. The predicted minimum idle values for N1 speed, N2 speed, burner pressure, and fuel flow are shown in (**Figure 3**). The analysis

[8] Japan Turbine Technologies and Turbine Overhaul Services are Pratt & Whitney owned facilities.

concluded that the $T_{45}$[9] (HPT discharge temperature) levels would decrease to approximately 710°F (377°C) shortly after TLA was decreased to idle.

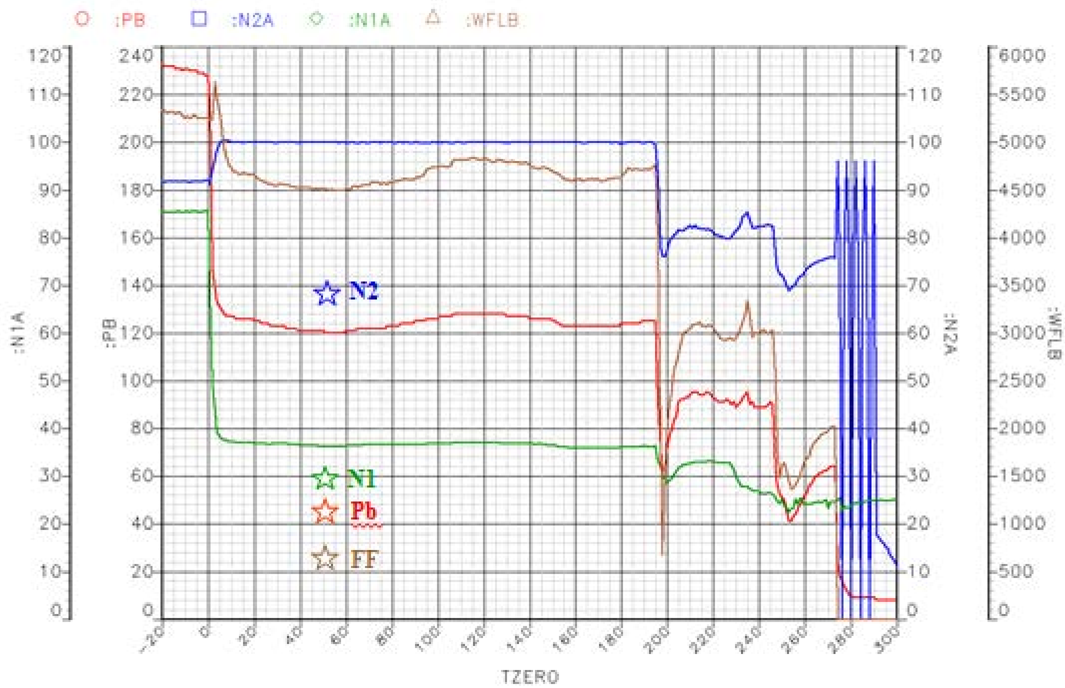



**Figure 3- Performance Plots, Stars Indicate Engine Parameter Levels if Throttle was Retarded to Idle**

### 7.5 SIMILAR HPT 2ND STAGE BLADE FAILURE EVENT

On October 12, 2013, a A319 with IAE V2524-A5 engines experienced a similar failure as the incident event. The engine was shutdown shortly after ECAM warnings began to register and the airplane was able to divert for an uneventful landing. During a post shutdown inspection metal fragments were found in the tailpipe. A materials lab examination determined a HPT 2nd stage blade had failed due to SCC. Examination of the remaining blades under magnification found SCC in the J-channel cooling air cavity of nine additional blades. The crack locations were identical to those seen in the NKS engine.

The event was not a reportable in accordance with NTSB guidelines and was not investigated by NTSB personnel. According to IAE, a limited internal investigation was conducted but testing was not done to check for the presence of sulfur on fractured HPT 2nd stage blade surfaces.

### 7.6 NO. 4 BEARING COMPARTMENT SERVICE BULLETINS AND AIRWORTHINESS DIRECTIVES

IAE released a series of SB's addressing failures related to the No. 4 bearing compartment. As noted in the maintenance section of this report, all applicable SB's had been completed on the incident engine. SB 72-0497 was released on March 22, 2006 to address failures of the No. 4 bearing compartment oil nozzle retention bolt. Liberation of this bolt can result in damage to surrounding components and oil leaks. IAE redesigned the bearing nozzle with a tab washer locating feature to eliminate bolt failure.

[9] $T_{45}$ is measured between the HPT and LPT turbines. It is commonly referred to as inner turbine temperature (ITT)

SB 72-0541 was released on March 12, 2008 and later mandated by the FAA with AD 2008-14-15. Both documents address oil leakage from the bearing compartment primarily due to oil accumulation during windmilling. The No. 4 bearing compartment is not actively scavenged during windmill/sub-idle operation and relies on gravity oil drainage to remove oil that is fed to the compartment. The drainage issue was corrected with a rerouting of the oil weep tube and addition of weep holes in the rotating hardware. As stated previously, compliance with SB 72-0541 satisfied the requirements of AD 2008-14-15.

SB 72-0592 was released on August 11, 2009 to address No. 4 bearing oil pressure tube cracks. Tube cracks can result in oil leaks and subsequent fire that could damage the HPT. The SB calls for installation of a redesigned oil tube that eliminates cracking issues.

SB 72-0617 was released on December 9, 2010 to address No. 4 bearing oil scavenge tube fractures due to incomplete weld penetration. The SB calls for a one time x-ray inspection of the tube to check weld integrity and replace the tube as necessary.

### 7.7 IAE/P&W Corrective Actions

Following the event P&W/IAE revised their HPT 2nd stage blade inspection criteria in an effort to better detect internal cracks during blade repair/overhaul. Blades are x-rayed and then the internal cavities are borescoped to inspect for evidence of surface defects (**Figure 3**). P&W is also developing an aluminide coating for the internal cavities of HPT 2nd stage blades to protect against corrosive deposits that they hope to field in late 2014.

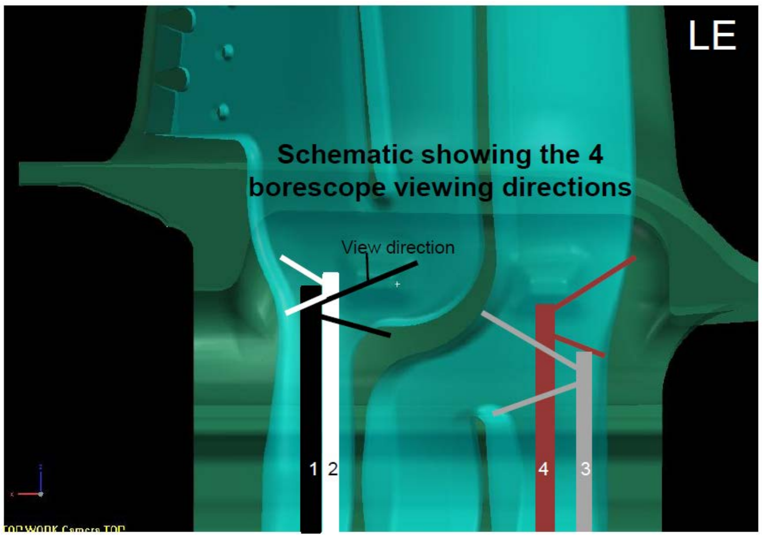



**Figure 4- HPT 2nd Stage Blade J-Channel Cooling Air Cavity Borescope Inspection**

ATTACHMENTS

1. IAE Engine S/N V12069 Components Shipped to Pratt & Whitney Materials Lab with Workscope.

2. Pratt & Whitney Materials and Processes Engineering Metallurgical Investigation of Spirit Airlines V2500-A5 Engine No. V12069

3. Spirit Airlines A320 Series Abnormal/Emergency Procedures- Feb 27, 2013
   ENG 1 (2) EPR MODE FAULT
   ENG 1 (2) N1/N2/EGT OVERLIMIT
   High Engine Vibration