

**NATIONAL TRANSPORTATION SAFETY BOARD
OFFICE OF AVIATION SAFETY
WASHINGTON, D.C. 20594**

NTSB ID: ENG18IA036
POWERPLANT GROUP CHAIRMAN'S FACTUAL REPORT

March 4, 2022

A. INCIDENT

Location: Atlanta, Georgia
Date: September 5, 2018
Time: 2332 Eastern Daylight Time
Aircraft: Boeing 757-232, N668DN, MSN 25141, operated by
Delta Air Lines

B. POWERPLANTS GROUP

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C. SUMMARY

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

Post-incident airplane inspection noted holes in the right nacelle inboard¹ core cowl and engine, and minor damage to the right wing and fuselage.



Figure 1. View of inboard side of right nacelle

A Powerplants Group was formed at Delta TechOps Atlanta, Georgia on September 6, 2018. The airplane damage and initial assessment of the engine uncontainment were documented.

An engine disassembly examination found that a rotating seal located between the HPT stage

¹ Directional references are as viewed from the rear of the engine looking forward unless otherwise noted.

1 (S1)² disk and S2 hub (the lenticular seal) had failed and unwrapped from its inner brace, destroying the turbine, and resulting in debris radially exiting the turbine cases. A segment of the seal displaced forward through the S1 blade path, penetrating the S1 turbine nozzle assembly and combustor, and damaging a fuel nozzle stem.

Metallurgical examination of the lenticular seal fragments identified a primary fracture surface, but the origin area was obliterated by secondary damage. However, the failure shared attributes with prior PW2000 lenticular seal failure events. Root cause investigations of those events led to the release of an improved-design lenticular seal. As a result of this investigation further corrective actions were taken to accelerate the update the PW2000 fleet with the improved-design seal.

D. DETAILS OF THE INVESTIGATION

1.0 Engine information

The incident airplane is powered by two Pratt & Whitney PW2037 turbofan engines.

1.1 Engine description

The PW2037 is a dual rotor, axial flow, high bypass turbofan engine featuring a single stage fan and four-stage low pressure compressor driven by a five-stage low pressure turbine (LPT), a twelve-stage high pressure compressor (HPC) driven by a two-stage high pressure turbine (HPT), and an annular combustor. The PW2037 is takeoff rated at 37,530 pounds thrust.

1.1.1 HPT lenticular seal

The HPT S2 air seal assembly (lenticular seal) is a labyrinth-type rotating seal located between the HPT S1 disk and HPT S2 hub. An outer seal piece includes five knife edges and forward and aft snap surfaces. The seal piece fits to an inner brace piece that includes forward and aft rails. See Figure 2.

² Engine stages are referred to as stage (S)1, S2, and subsequent.

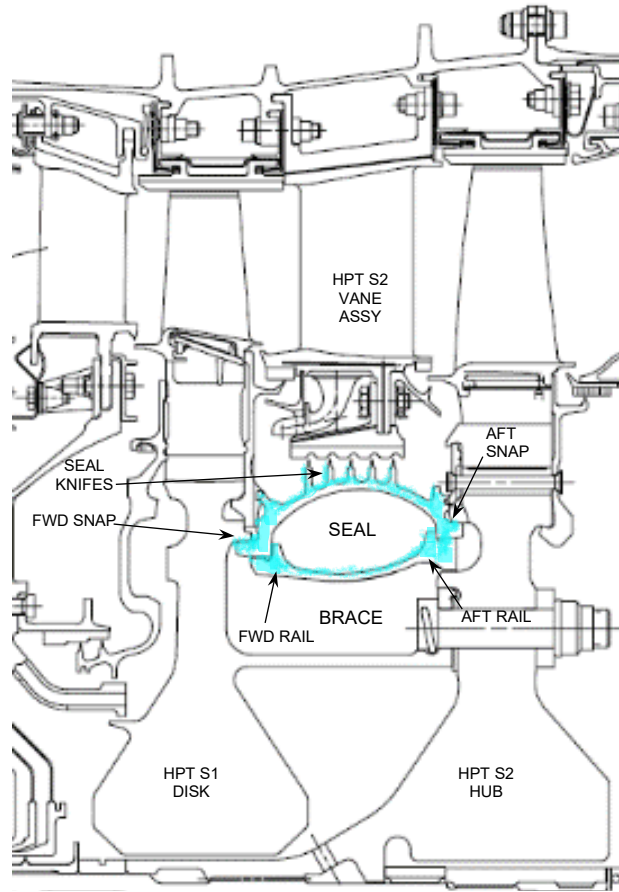


Figure 2. HPT rotor cross section with lenticular seal highlighted

Both pieces are IN-100 alloy. The two pieces become an inseparable assembly during manufacture.

The lenticular seal knife edges run against honeycomb-surfaced seal lands attached at the HPT S2 vane assemblies.

1.2 Engine data

model	serial number (S/N)	time since new (TSN)	cycles since new (CSN)	time since overhaul (TSO)	cycles since overhaul (CSO)
PW2037	716415	88,547	38,161	14,505	6,460

Table 1. Engine data

1.3 Engine service history

The engine was overhauled in 2008 at 61,385 TSN and 25,462 CSN. HPT life limited parts were replaced and the incident lenticular seal, P/N 1A8209, S/N DKLBF7327, was installed new. The HPC, HPT and diffuser/combustor underwent heavy maintenance.

The last shop visit was in June 2013 at 74,042 TSN and 31,701 CSN following an unscheduled removal for a No. 3 carbon seal leak repair. Heavy maintenance was performed on the HPC, HPT and diffuser/combustor. The HPT work included renewal of some of the honeycomb seal land material. The lenticular seal knife edges were not stripped; the seal was inspected and reinstalled.

2.0 Airplane damage assessment

The Powerplants Group documented the airframe damage and assessed the engine on September 6, 2018.

2.1 Engine uncontainment

There was a 27 1/2-inch circumferential by 10 1/2-inch axial³ hole in the right inboard core cowl just forward of the HPC S14 overboard bleed port between 7 and 10 o'clock.⁴ The edges of the hole were petaled outward. Dents were noted 7 1/2 inches forward of the thrust reverser cowl aft end at 9 o'clock, 3 1/2 inches forward of the thrust reverser cowl aft end at 8 o'clock, and 10 inches aft of the forward core cowl edge at 6 o'clock. See Figure 3.



Figure 3. Two photographs of the right nacelle showing hole through inboard side with local dents noted

There was a 14-inch circumferential by 3-inch axial hole in the engine HPT case along the plane of the HPT S2 vanes at 7 o'clock. A 6-inch-long debris fragment identified as lenticular seal

³ Measurements taken at the widest hole dimension.

⁴ O'clock refers to approximate circumferential locations in the clockwise direction as viewed from the rear of the engine looking forward.

material was protruding from this breach. There was a 7-inch circumferential by 2 1/2-inch axial hole in the LPT case in plane with the outer transition duct at 8 o'clock. See Figures 4 and 5.

There was a 6-inch circumferential by 1 1/2-inch axial breach in the HPT case along the plane of the HPT S1 blades at 5 o'clock. See Figure 6.

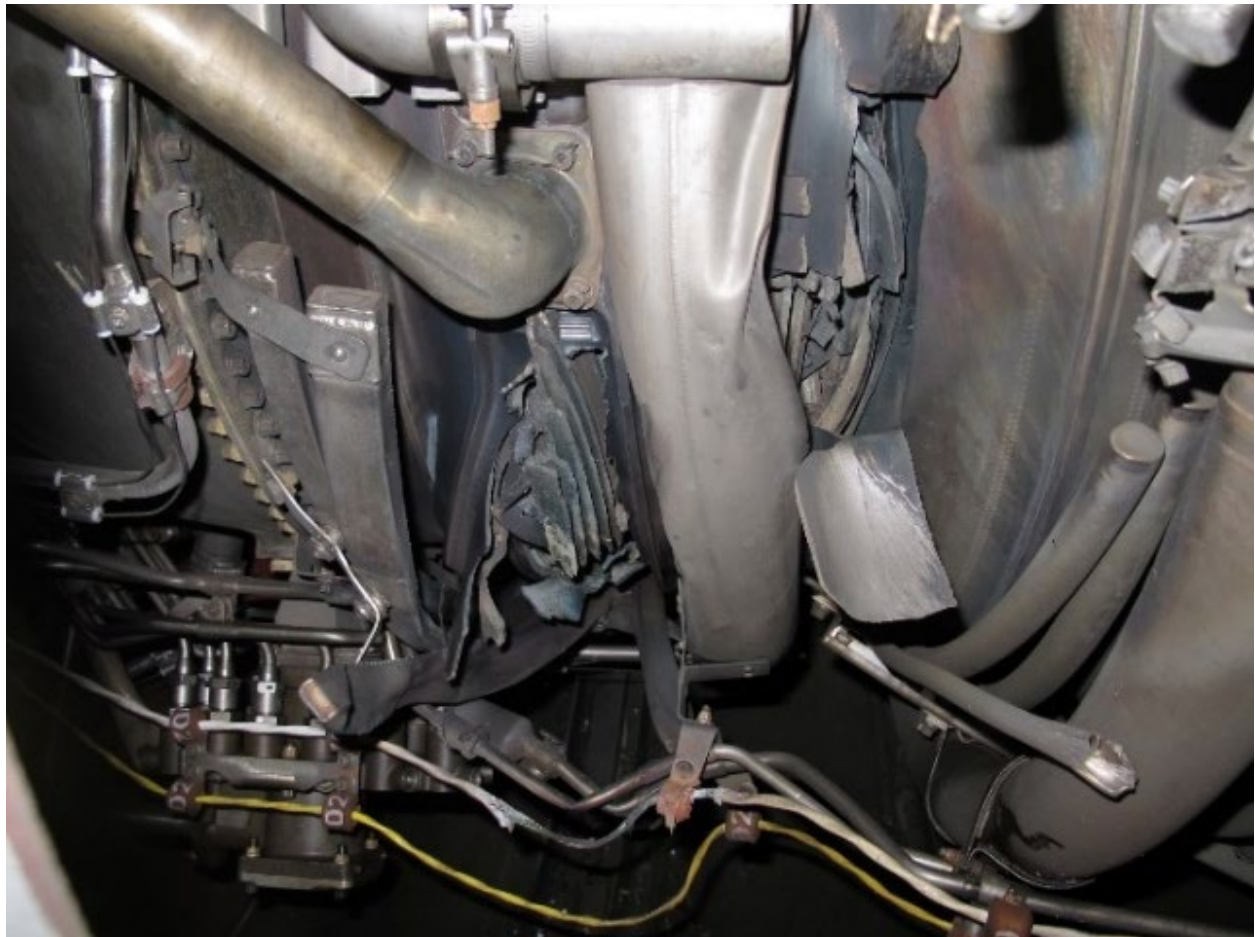


Figure 4. HPT and LPT case breaches. A fragment of lenticular seal is protruding from the HPT



Figure 5. Debris fragment

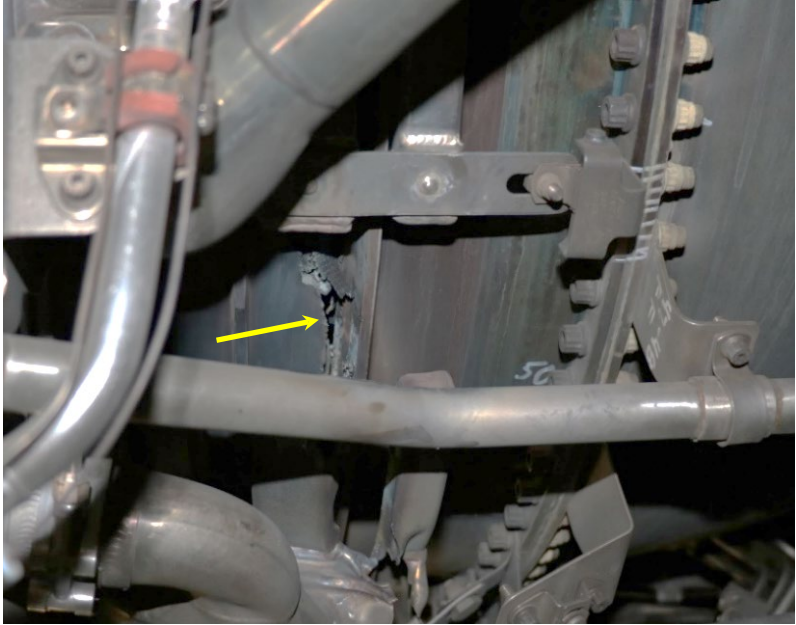


Figure 6. HPT case breach at 5 o'clock

The external engine plumbing in the vicinity of the case breaches was outwardly crushed and deformed consistent with impacts from debris exiting the engine. The affected hardware included the HPT active clearance control and LPT turbine clearance control (TCC), the HPT-to-LPT flange (N-flange) cooling duct and the LPT TCC bridge bracket. See Figure 7. An LPT TCC plenum tube manifold coupling was liberated at 5 o'clock. See Figure 8. The TCC tube coupling was recovered from inside the thrust reverser.

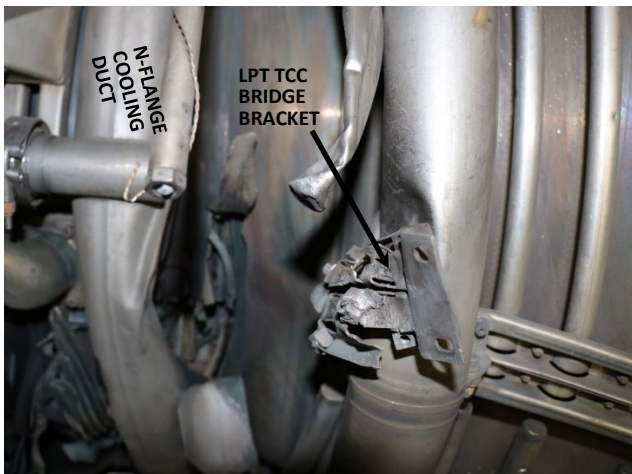


Figure 7. Damage to externals



Figure 8. LPT TCC plenum tube manifold with liberated coupling

Thermal distress was noted to a P-clamp and a small length of EGT signal wire insulation in the

vicinity of the larger HPT case hole, and to the inboard thrust reverser cowl aft end. See Figures 9 and 10.

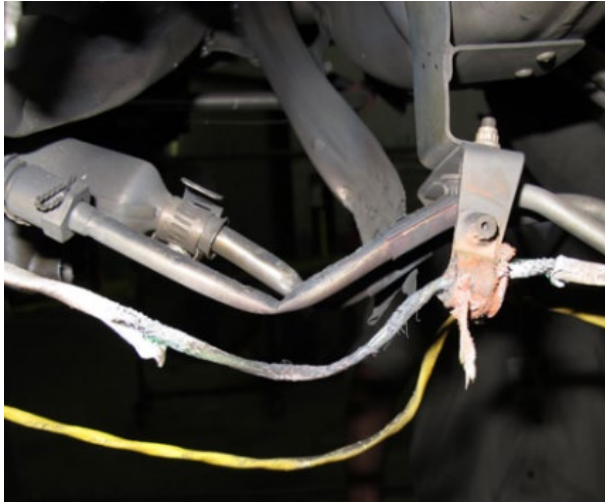


Figure 9. Degraded wire coating and P-clamp cushion



Figure 10. Inboard thrust reverser cowl thermal damage

2.2 Other nacelle damage

A 5-inch-long piece of debris protruded from a 5-inch circumferential by 8-inch axial hole in the thrust reverser outer structure at 5 o'clock. An axially coincident 2-inch circumferential by 3-inch axial hole in the thrust reverser inner structure was found when the thrust reverser was opened. The edges of these holes were petaled outward. See Figure 11.

A line of small dents extended horizontally at 4 o'clock from 6 inches aft to 11 1/2 inches aft of the outboard core cowl forward edge. There was a through-crack in the aftmost dent. See Figure 12.

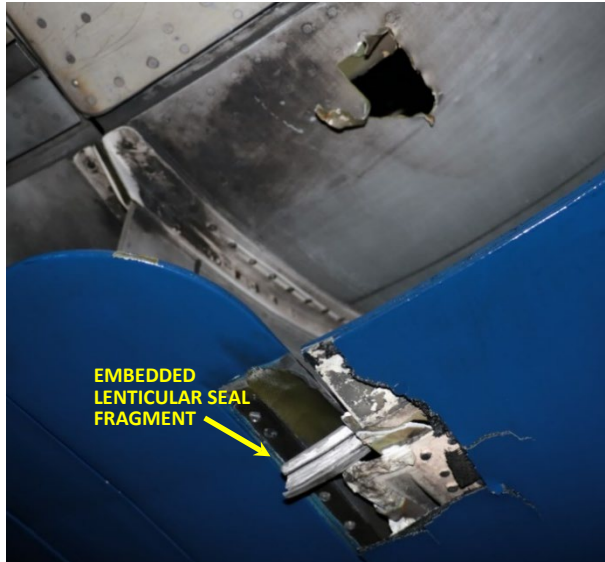


Figure 11. Holes through the inner and outer outboard thrust reverser structure.



Figure 12. Row of dents in outboard core cowl

2.3 Airframe damage

There was a cluster of small scrapes and a 6-inch-long horizontal scuff at the aft end of the trunnion fairing. Local scratches and gouges were found on the underside of the right wing inboard and outboard of the trunnion fairing. There were three small sites of impact damage, including a through-puncture, on the right wing-to-body fairing. The right main landing gear (R MLG) door outer surface displayed two small nicks/scratches. See Figure 13. Light impact damage was also observed along the right horizontal stabilizer leading edge. All the damage was consistent with external impact.



Figure 13. Airplane damage

The engine was removed and transported to the Delta TechOps engine shop.

3.0 Engine disassembly examination

A partial engine disassembly was performed at Delta TechOps September 8 – 11, 2018.



Figure 14. Left side view of ESN 716415

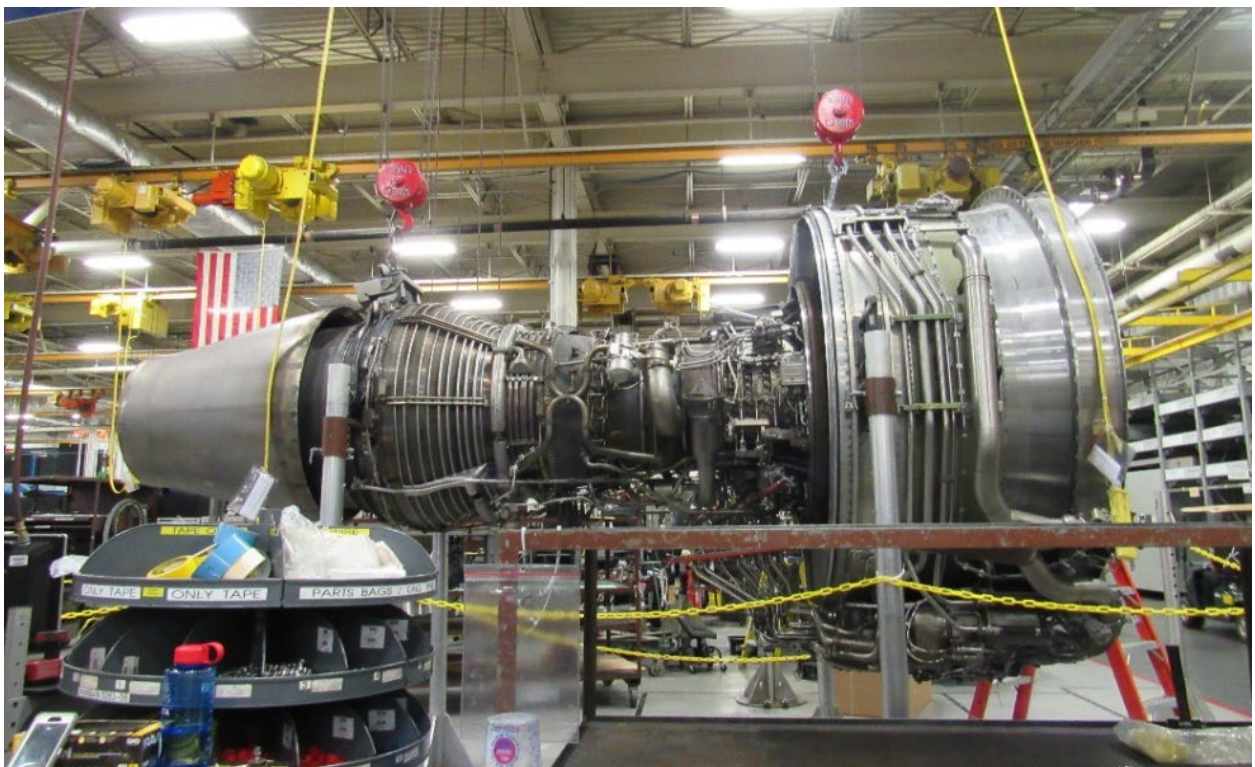


Figure 15. Right side view of ESN 716415

There was no obvious fan blade damage. The LPT S7 turbine blades were intact. Metal debris was collected from inside the tailpipe. See Figures 16 and 17.



Figure 16. Engine inlet



Figure 17. Engine exhaust with intact S7 airfoils

Oil was present in the oil tank fill neck, consistent with a full tank. The oil had a normal appearance and odor. The magnetic chip detectors and last chance filters were inspected and found in normal/clean condition.

3.1 Engine disassembly

The engine external components were removed as required to separate the LPT module from the engine. The turbine cooling system externals were inspected for pre-incident discrepancies with no anomalies noted. No secondary damage to flammable fluid tubes was found. See Figure 18.

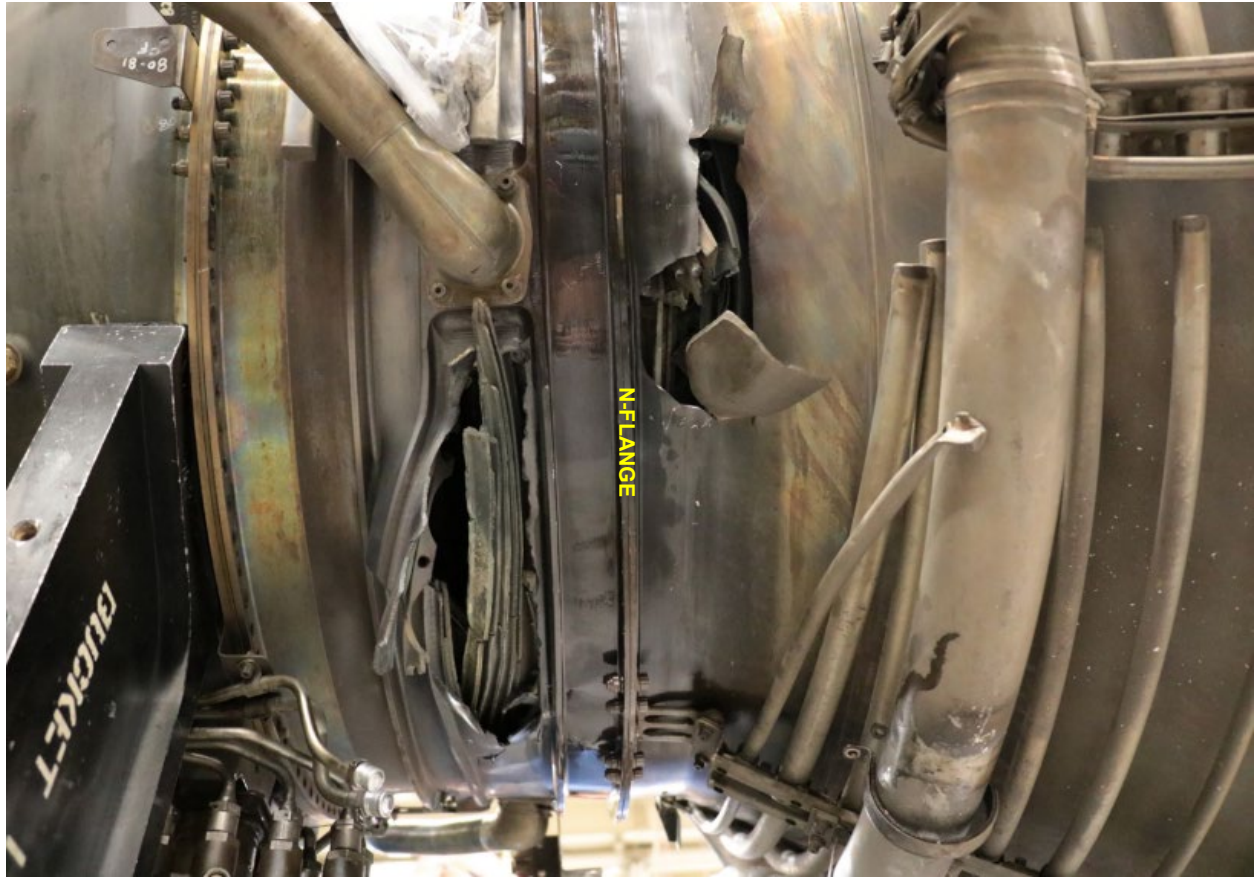


Figure 18. View of the primary engine case breaches following externals removal

The LPT was removed from the engine at the N-flange. The LPT-to-HPT spring seal was dislodged from the HPT case between 6 and 1 o'clock. It was cut to facilitate LPT removal. See Figure 19.

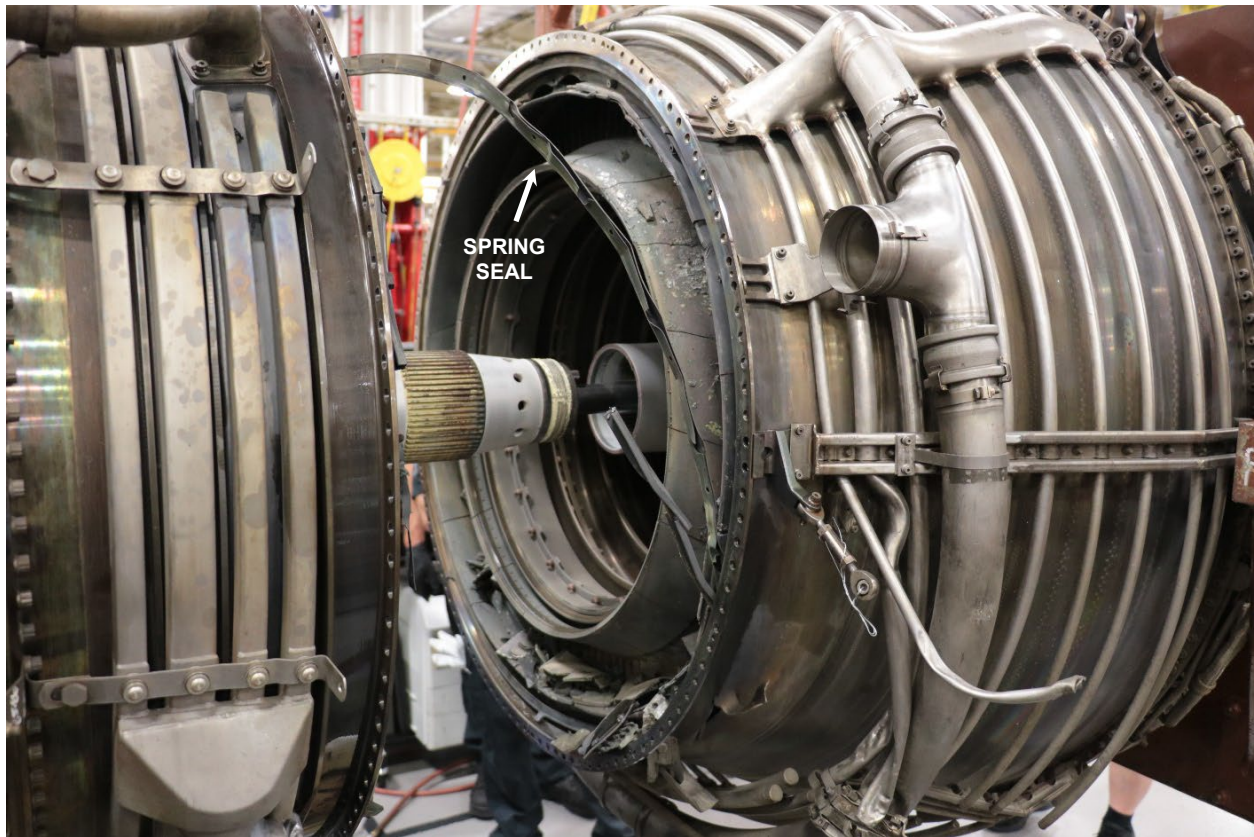


Figure 19. LPT separation from HPT, showing displaced spring seal and loose debris lying in the LPT case at 6 o'clock

A large amount of loose debris fell out of the engine when the flange was separated. Remnants of HPT S2 vanes, HPT S2 blade outer air seals (BOAS), HPT S2 hub front cover plates and HPT S1 disk rear side plates were identified in the debris.

3.2 LPT module

The LPT gas path components over a 30° arc of the LPT centered on 9 o'clock were thermally consumed or had the appearance of re-hardened slag. See Figure 20. This damaged extended from the LPT S3 vanes to the S5 vane leading edges. See Figure 21.

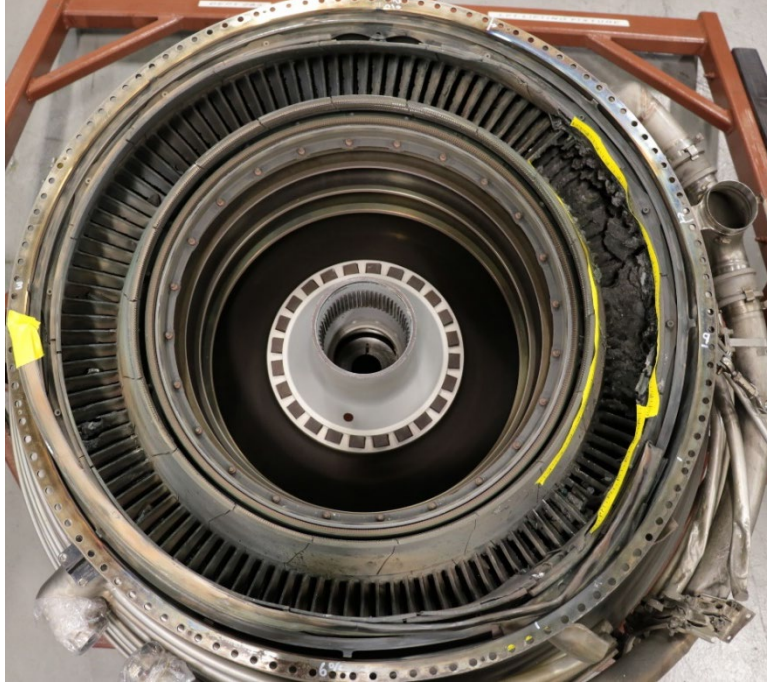


Figure 20. LPT module forward end



Figure 21. LPT gas path thermal damage

The LPT was not disassembled.

3.3 HPT module

The HPT rotor was indexed, and the hardware was labelled in the clockwise direction.

Inspection of the HPT aft end found that all but two of the HPT S2 blades were fractured about one inch above the platform. Blade 29 was fractured 1/4 inch above the platform and blade 16 was fractured below the platform. Secondary damage obscured the fracture surfaces of the above-platform fractures. The below-platform fracture surface was clean and uniformly granular. See Figure 22.



Figure 22. HPT S2 blade below-platform fracture surface

The HPT S2 hub was intact. Eight of the 32 side plate rivets, rivets 25, 26, 28, 29, 30, 31, 32, and 1, were loose. S2 BOAS supports 12 through 16 were liberated; all other supports were present. The S2 BOAS were liberated between 6 and 11 o'clock; all other BOAS were intact. The HPT S2 vanes between 3 and 11 o'clock were liberated. A large amount of debris was lying inside the case at 6 o'clock. See Figure 23.

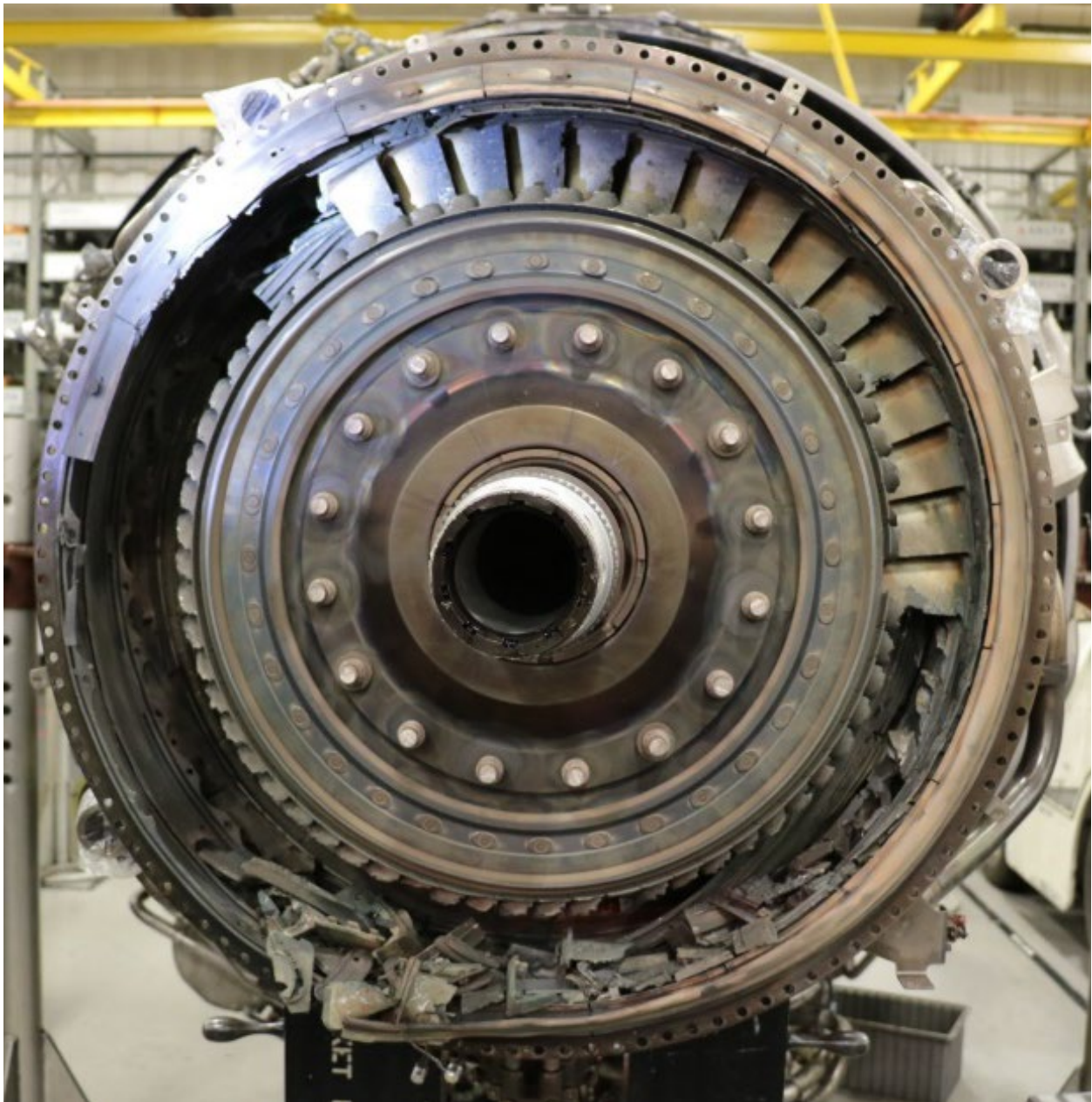


Figure 23. Aft view of HPT module

The HPT module was separated from the engine and its forward end was inspected. The HPT S1

disk was intact. All HPT S1 blades were fractured approximately one inch above the platform. A 30° arc of the tangential on-board injector (TOBI) seal knife edges were slightly damaged. The HPT S1 BOAS supports were intact. The HPT S1 BOAS were liberated between 5 and 1 o'clock and the other BOAS were intact. See Figure 24. A piece of lenticular seal was spiralled over the S1 blade stubs at 10 o'clock and extended forward about 12 inches. See Figures 24 and 25.

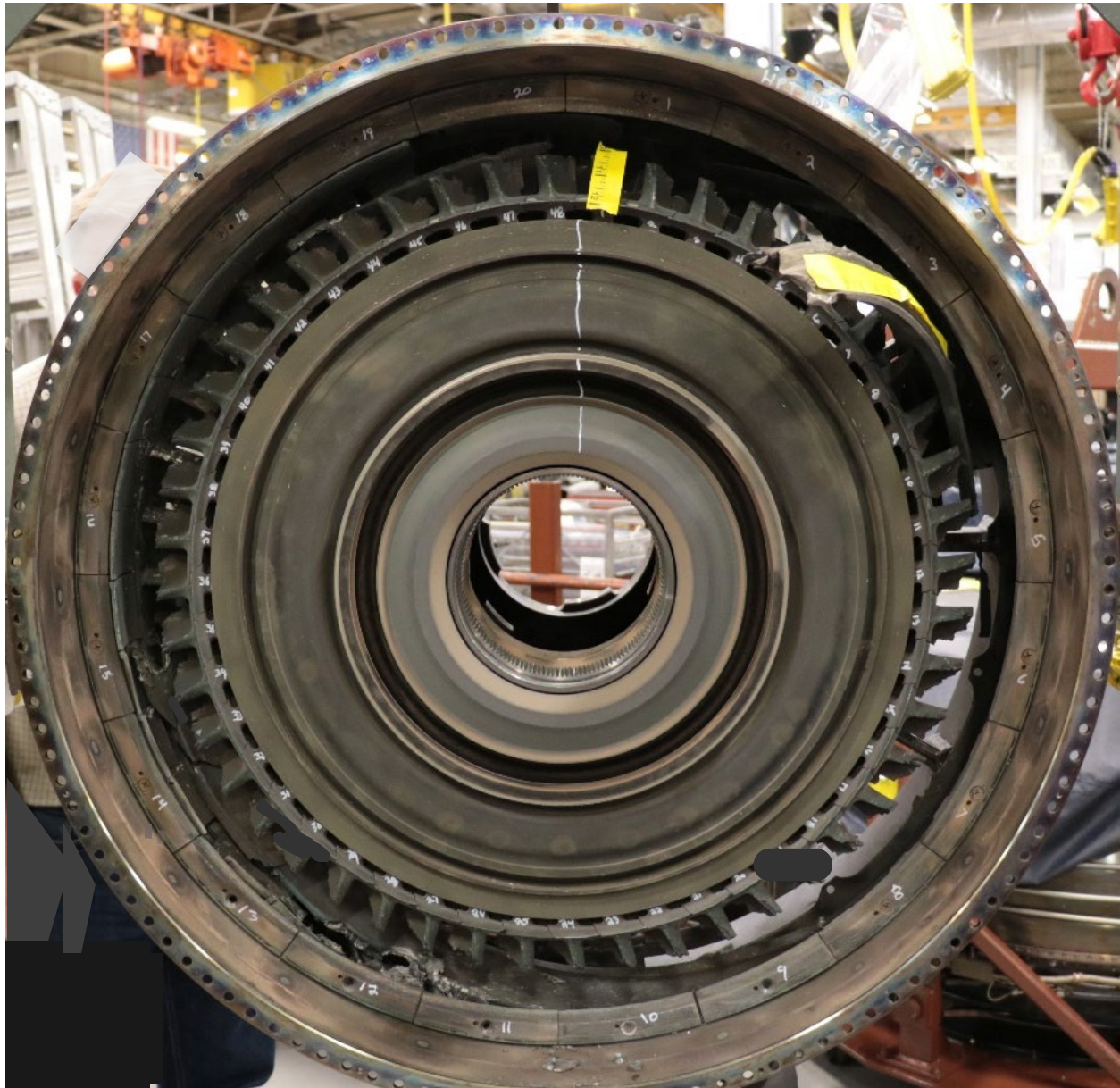


Figure 24. HPT forward end showing HPT S1 damage and S2 air seal fragment extending over S1 HPT



Figure 25. Air seal fragment protruding from forward end of the HPT module

The HPT S1 vanes between 9 and 12 o'clock were fractured or liberated where the lenticular seal segment protruding from the front of the HPT case had penetrated. Combustor damage was observed forward of the HPT S1 turbine vane assembly penetration. See Figure 26.

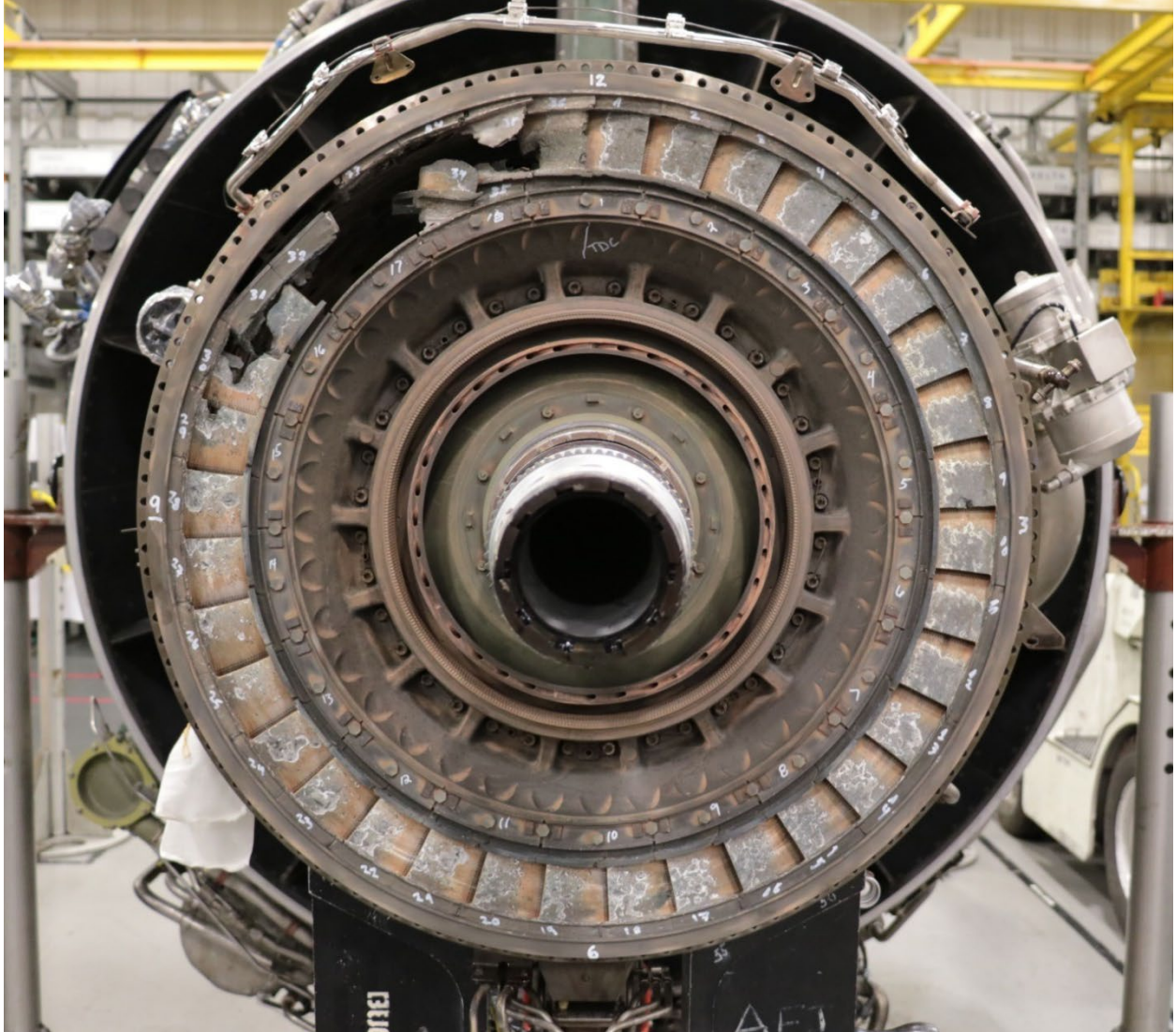


Figure 26. HPT S1 turbine vane assembly, showing penetration by lenticular seal

The HPT S1 turbine vane assembly was removed. Two lenticular seal pieces were found lying between the outer liner and the diffuser case at 6 o'clock. These pieces lacked the darkened color of the other lenticular seal fragments. The combustion outer liner dome was inwardly deformed at 10 to 11 o'clock and there was a 5-inch circumferential by 2 1/2-inch axial hole in the deformed area. Two fuel nozzles in line with the penetration were damaged. See Figure 27.

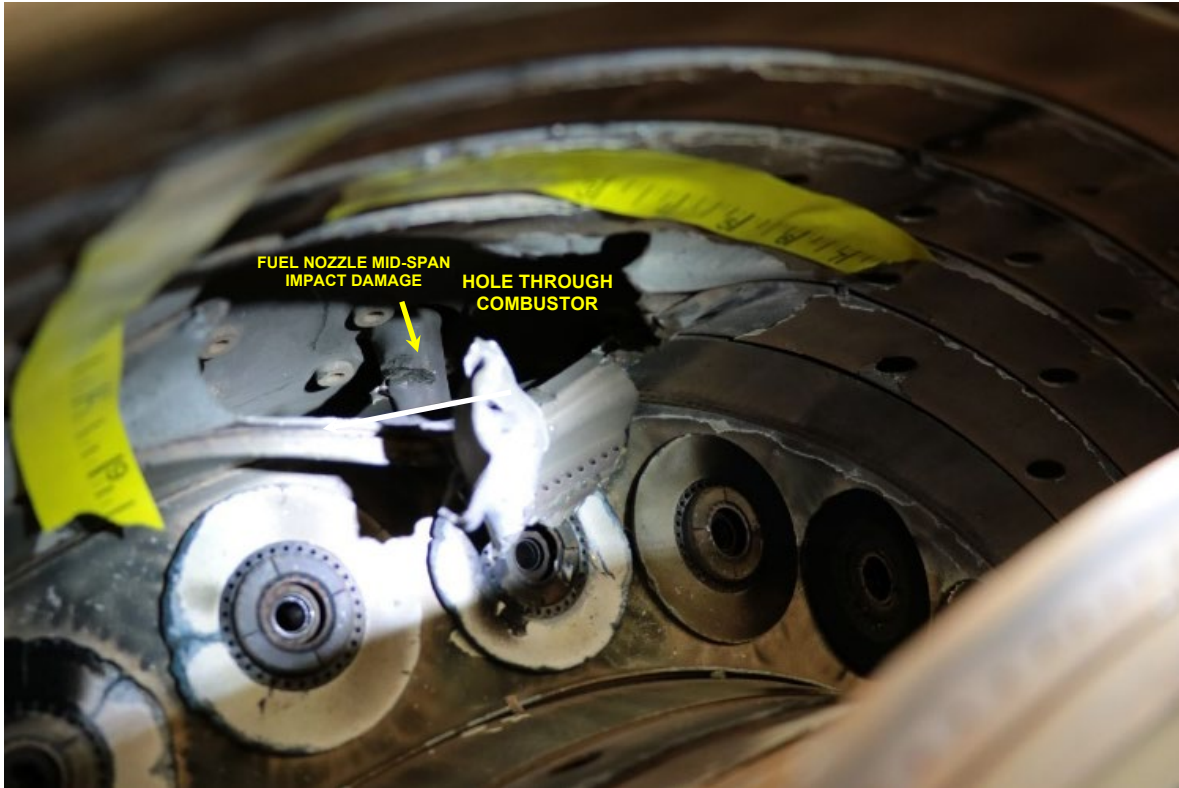


Figure 27. Combustion chamber showing liner penetration and damaged fuel nozzle

Fuel nozzles 23 and 24 were damaged mid span. Fuel nozzle 24 was punctured through the stem and heat shield and leaked when shop air was applied. Fuel nozzle 23 did not leak when shop air was applied. Stoddard solvent at 150 psig was applied to the inlet of fuel nozzle 24 and solvent sprayed from damaged stem portion of the nozzle. See Figure 28.



Figure 28. Mid-span impact damage to fuel nozzles 23 and 24 and leakage observed through stem of fuel nozzle 24

Soot-like deposits were noted on the end of the lenticular seal fragment. The fragment was removed from the HPT by hand. The length of the seal fragment was 17 inches.

3.4 HPT rotor disassembly

The 16 HPT rotor tie rod nuts were removed with a torque wrench set at 155 in-lbs. No torque exceeded the 155 in-lb setting. Nuts 5, 7, 9, 13 and 15 required less effort to remove. See Figure 29.

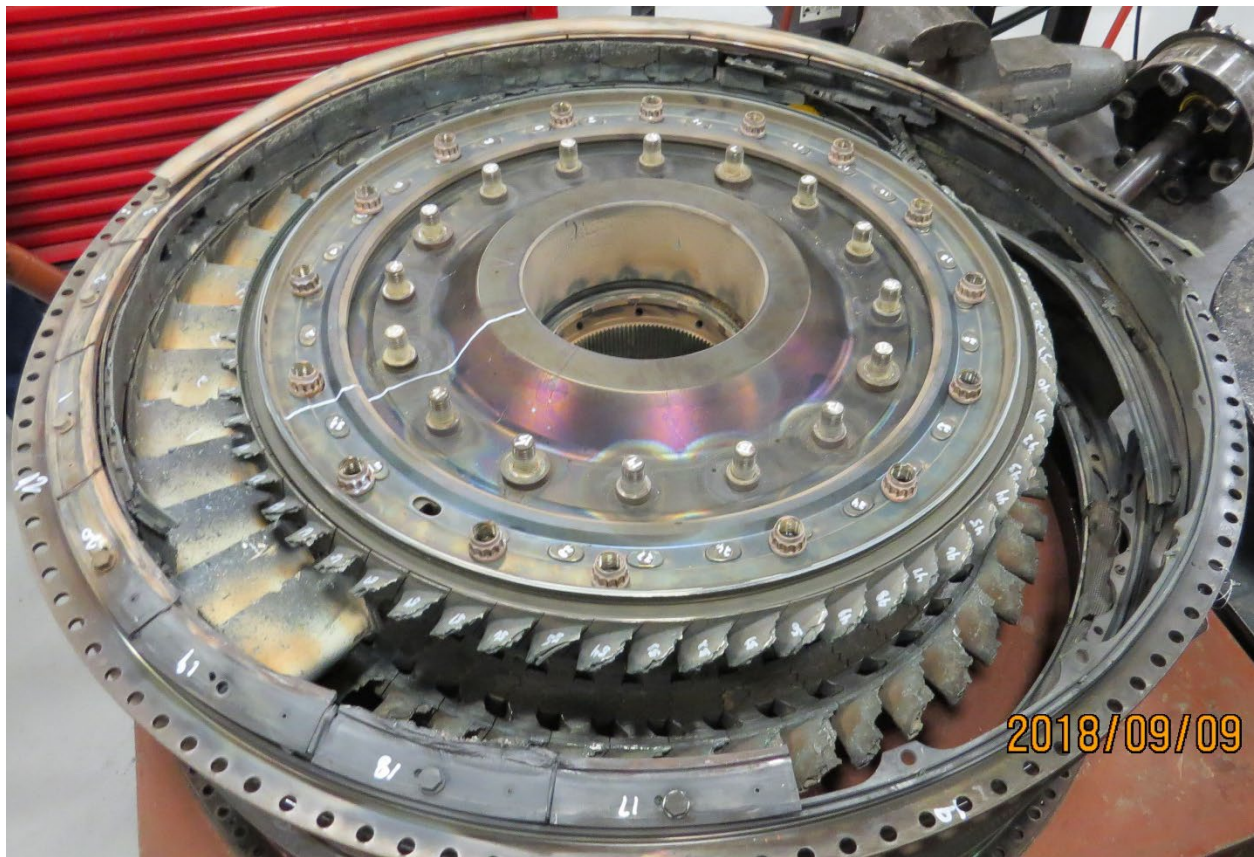


Figure 29. Aft view of HPT with HPT S2 hub retention nuts removed

The disk classified spacers were intact.

3.4.1 HPT S2

The upstream face of the HPT S2 hub exhibited heavy circumferentially oriented scoring from the radial snap and outboard. See Figure 30.

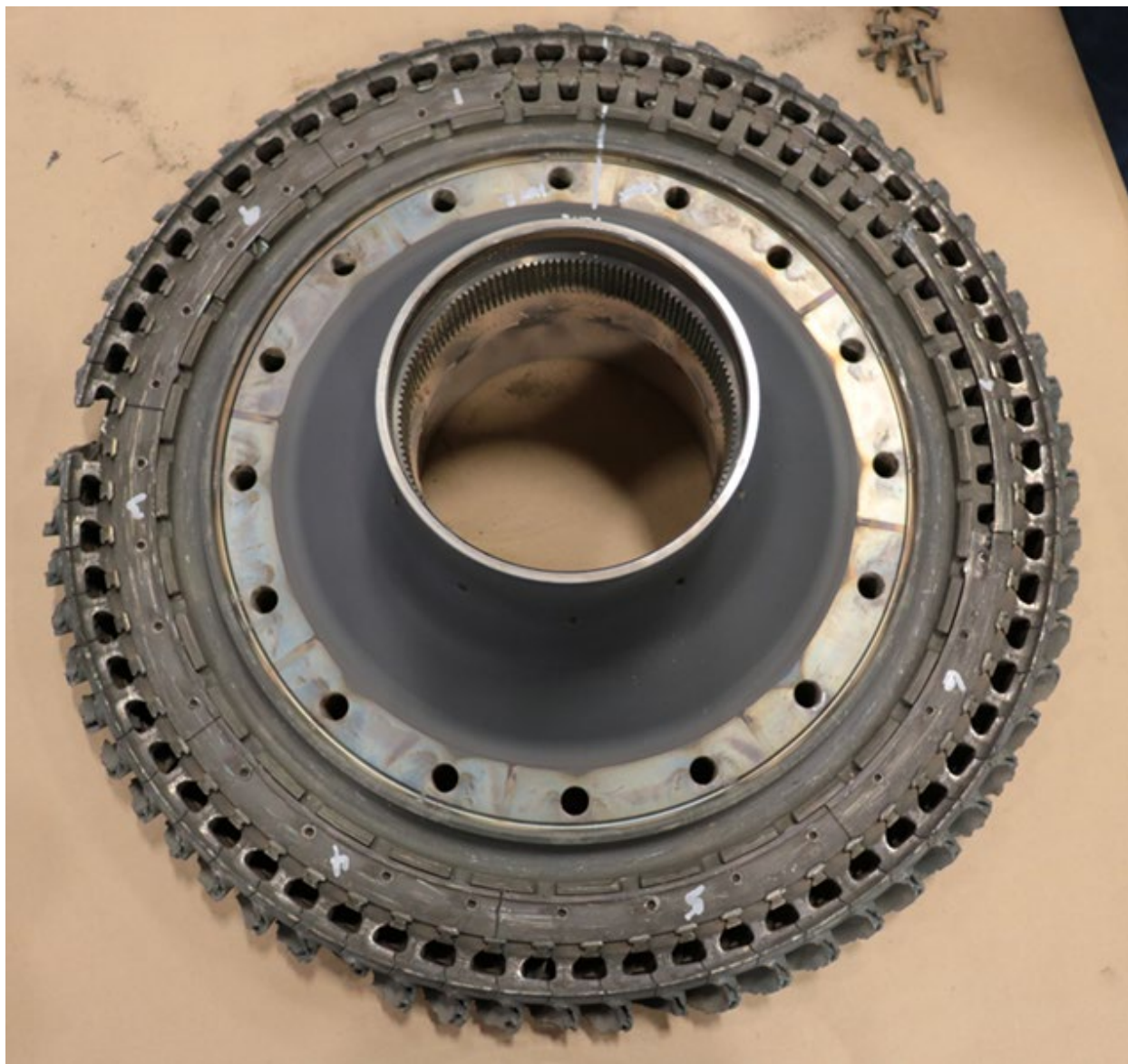


Figure 30. HPT S2 upstream face

The ends of the cover retention rivet plugs were worn and were missing material. Five of the side cover plates were intact, the others were partially or completely liberated. Much of the forward blade platforms were worn away and the remaining material was battered. See Figure 31.

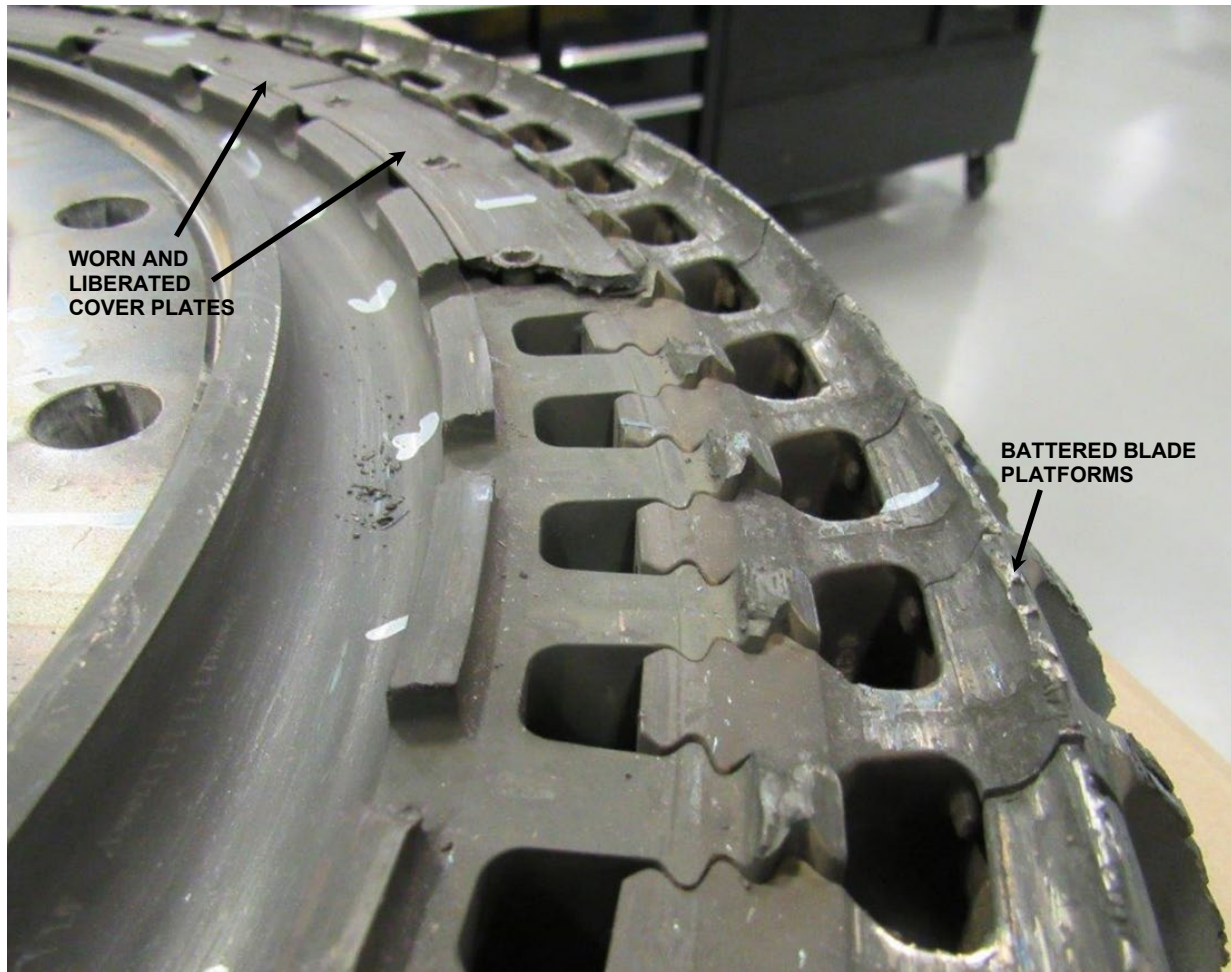


Figure 31. Detail of HPT S2 forward upstream scoring and impact damage

The S2 hub front snap surface (lenticular seal mating surface) was cleaned with isopropyl alcohol. Contact marks were visible on the snap tabs. Most of the marks were unusually light and four were indistinct. There were local areas of missing or displaced material near tab corners.

The HPT S2 vanes were liberated between 3 and 11 o'clock. The S2 vane inner air seal honeycomb material was destroyed and could not be evaluated. See Figure 32.

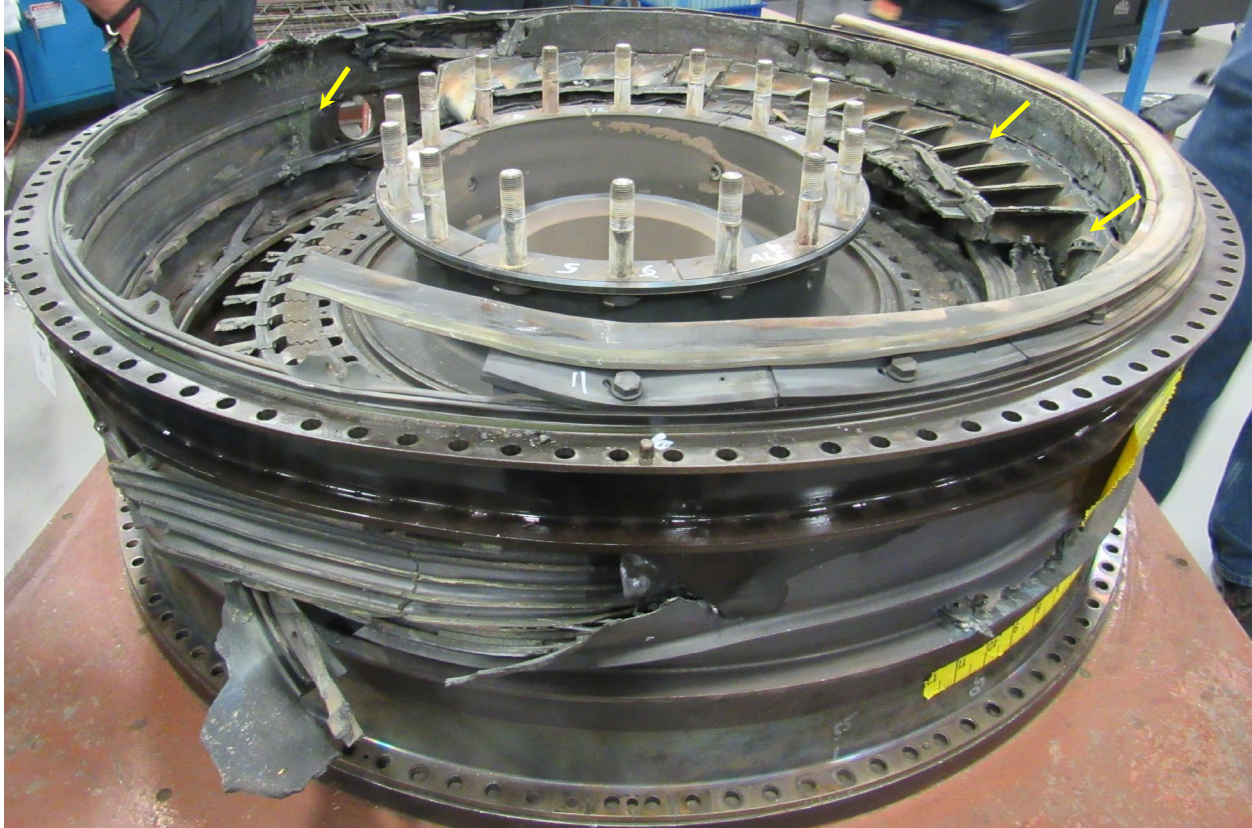


Figure 32. Aft end of HPT with S2 hub removed with destroyed S2 vane segments noted (arrows)

3.4.2 HPT S1

A segment of released lenticular seal was curled around the HPT case inner surface. The lenticular seal brace was exposed. The brace was intact. Its outer surface was circumferentially scored and splattered with metal and the tips of the standoffs on the aft brace edge were marred. The HPT S1 disk downstream side was circumferentially scored from the radial snap outboard. The scoring had consumed the rear platforms of the blades. All the S1 rear side plates were liberated. See Figure 33.

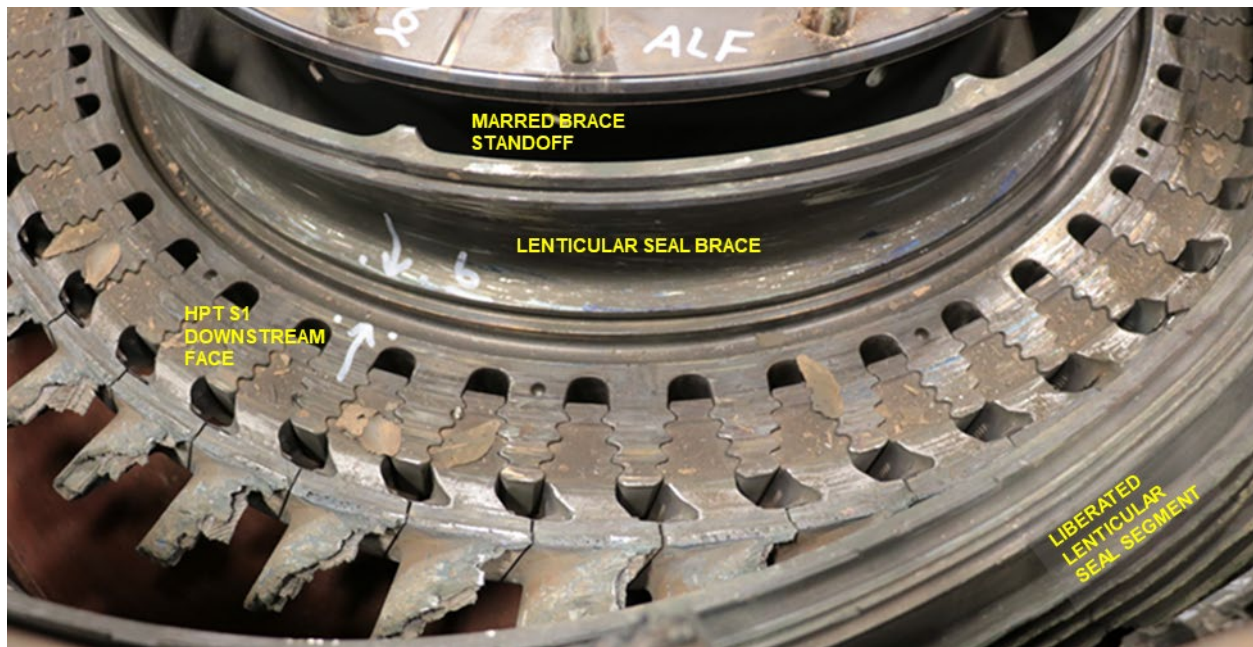


Figure 33. HPT S1 disk downstream face

There were hard deposits on the HPT S1 disk aft snap land where the lenticular seal interfaces with the disk. The surface was not cleaned.

3.4.3 Lenticular seal

Nine lenticular seal fragments, including two larger seal sections and the intact brace, were recovered. A rough reconstruction of the lenticular seal fragments confirmed the 64-inch circumference of an intact seal. See Figures 34 and 35.



Figure 34. Lenticular seal inner brace piece



Figure 35. Eleven recovered lenticular seal fragments

Parts of interest were shipped to Pratt & Whitney Materials and Processes Engineering (MPE) in East Hartford, CT, for evaluation.

4.0 Materials investigation

Pratt & Whitney MPE examined the lenticular seal brace and the two large and nine small seal fragments. Visual and binocular review found significant thermal distress to much of the seal, which was attributed to the event. An axial fracture at the end of one of the larger recovered segments (designated Piece A) was identified as the primary fracture location. The surface included the full seal cross section. The surface was fractured or significantly damaged forward of knife edge 3. The surface from aft of knife edge 3 to the aft seal edge showed discernible fracture features. Knife edges

3, 4 and 5 were fractured outboard of their pedestals and no significant knife edge material remained. See Figure 36. The mating fracture surface on an end of the other large fragment (Piece B) was destroyed. See Figure 37.

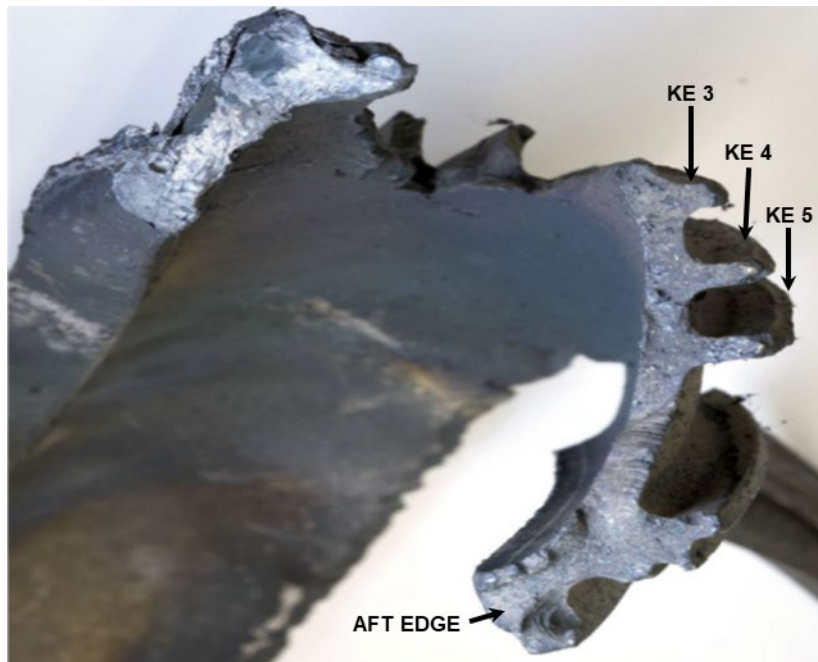


Figure 36. Magnified view of primary fracture on end of Piece A
Photographs courtesy of Pratt & Whitney



Figure 37. Mating surface on Piece B

The Piece A fracture surface was oxidized and covered with deposits and metal splatter, obscuring most signs of directionality. Remnant river lines and beach marks were observed that indicated progression from the knife edge region toward the aft edge. No origin area could be identified. The fracture path in the knife edge region was mostly flat but the topography suggested an initiation location forward of knife edge 3. The crack began to turn circumferentially aft of knife edge 5 while continuing to progress toward the aft edge. Scanning electron microscope (SEM) examination of the fracture surface found no original fracture features.

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

An NTSB materials engineer led the metallurgical investigation and reviewed the findings.

5.0 HPT build investigation

Pratt & Whitney and Delta TechOps performed a detailed review of the 2013 HPT build assembly sequence and methods. Assembly error was eliminated as causal.

6.0 Precursor HPT lenticular seal failures

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

7.0 PW2000 SB 72-754

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

8.0 Corrective actions

On March 15, 2019, PW2000 SB 72-754 (upgrade to the new-PN lenticular seal with the temperature-resistant Al_2O_3 coating) R2 changed the bulletin compliance category from CAT 7 (do when supply of superseded parts is fully used) to CAT 5 (perform at next module exposure).

On August 14, 2019, PW2000 SB 72-754 R3 released new part numbers (PNs) and instructions for rework of the lenticular seal with chromium carbide-coated knife edges to the improved-durability Al_2O_3 knife edge coating (modify PN 1A8209 to PN 1A8209-002 or PN 1A8209-001 to PN 1A8209-003).

Pratt & Whitney developed a technique sheet (NDIP-1217) for on-wing HPT lenticular seal borescope inspection (BSI) in January 2018 and on March 11, 2020, issued CAT 3 PW2000 SB 72-773 requiring BSI of PN 1A8209 or 1A8209-001 lenticular seals every 500 cycles until a part eligible for installation is installed.⁵

Engines configured for unmodulated turbine cooling air (TCA) were identified as a subpopulation with a higher risk of temperature-induced lenticular seal knife edge fatigue.

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

On July 28, 2021, the FAA published Airworthiness Directive (AD) 2021-14-13, effective September 1, 2021, requiring that PN 1A8209 and 1A8209-001 lenticular seals have the chromium carbide coating removed and a fluorescent penetrant inspection performed at every piece part

⁵ A part eligible for installation is defined as a lenticular seal that is not PN 1A8209 or 1A8209-001.

opportunity, as defined by the AD. The lenticular seal must be removed from service and replaced with a part eligible for installation should any crack be found. If a crack is found in a critical area defined by the AD and extends toward the knife edge region, the lenticular seal, the S1 disk and the S2 hub must be removed from service. The AD also requires the replacement of PN 1A8209 and 1A8209-001 with a part eligible for installation at the next shop visit after September 1, 2021.

Carol M Horgan
Powerplants Group Chair