ERA24FA110

AIRWORTHINESS

Group Chair's Factual Report – Attachment 6

GE Presentation Material - CL5584 Annex 13 investigation ERA24FA110 Summary

May 8, 2025

GE Aerospace

CL5584 Annex 13 investigation ERA24FA110

Summary

Originally shared: April 23rd 2025

GE Aerospace

Active Investigation – The information contained in this document is provided in response to a request from the National Transportation Safety Board (NTSB) and pertains to an active investigation. This document and its contents are intended solely for the purposes of the referenced investigation

FDR Event Data Engine Operability Assessment

Summary of detailed Feb 9th FDR analysis

Introduction:
A detailed FDR data analysis was conducted on engines 950105 & 950106 installed in tail CL5584 operated by HOP-A-Jet as part of the active Annex 13 investigation related to the February 9th Challenger 604 event at Naples.

- Engine (105) vs engine (106) comparison for February 9th flight leading to the event
- Engine (105) decel comparison during approach on February 9th (decel @ 2.8K ft/250 kts vs event decel @ 1.8K ft/160 kts); Repeated comparison for sister engine (106)
- Engine event decel/accel vs similar decels/accels from previous 56 flights on engine 105; Repeated comparison for sister engine (106)

Analysis Objective:

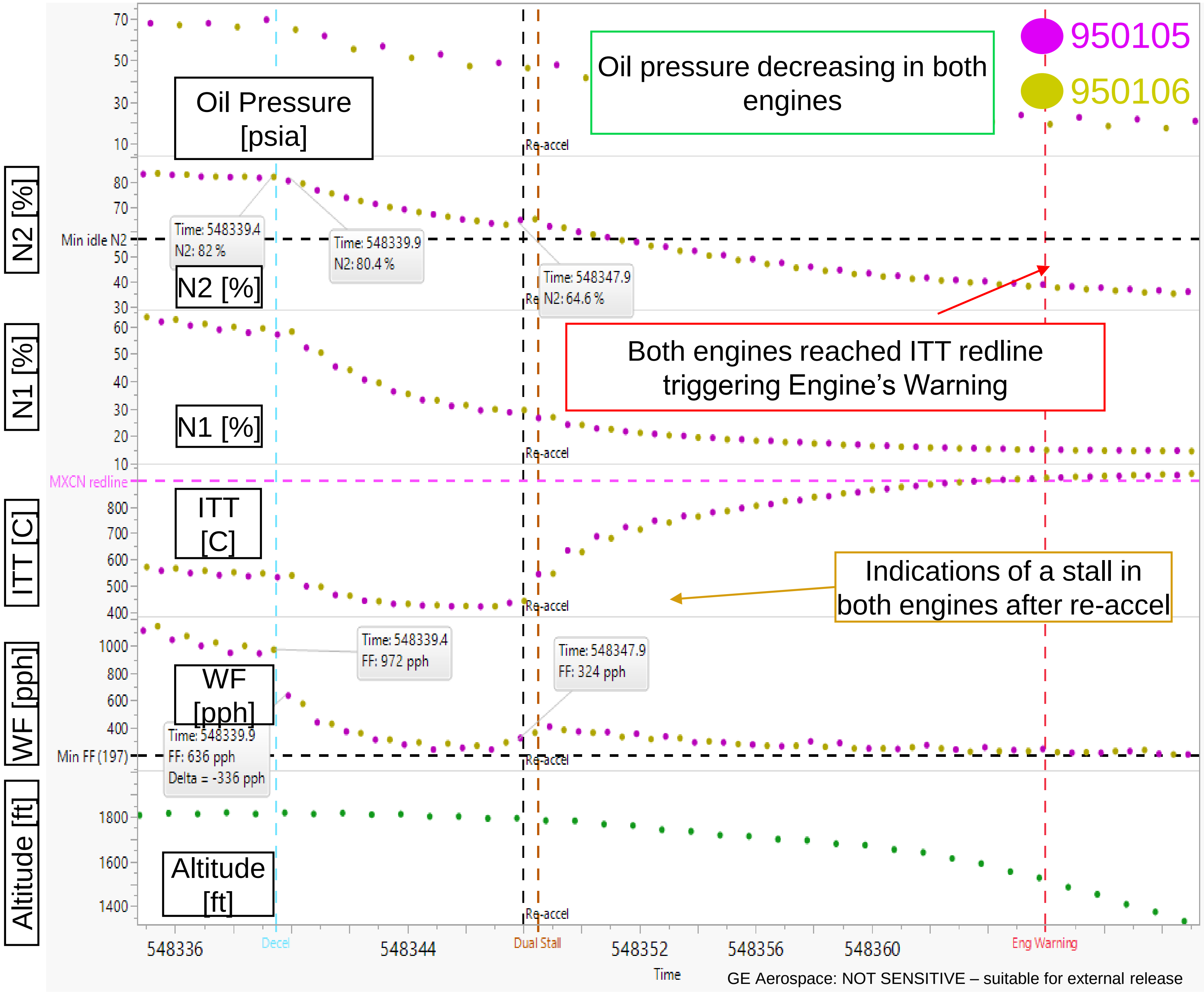
Identify the key elements observed in performance/transient response of engines 950105 & 950106 during February the 9th event.

Conclusions:

- Engine vs engine Comparison
    - ➢ The steady state and transient performance (i.e. accel, decel and stabilization) was remarkably well matched between the two engines
- Engine (105) decel comparison during approach on February 9th
    - ➢ Consistent decel characteristics between the decel at 2.8K ft/250 kts and the event decel at 1.8K ft/160 kts
        - The only notable differences between the decels were confirmed to be attributable to differences in flight condition
    - ➢ Neither decel resulted in an undershoot of idle core speed
    - ➢ Neither decel resulted in a fuel cut or a combustor partial blowout or a combustor flameout
    - ➢ Both decels were followed by an engine accel as indicated by an increase in fuel flow and core rotor speed
    - ➢ Upon the event accel at 1.8K ft/ 160 kts, the engine began to accelerate and then experienced a compressor surge followed by rotating stall
        - As a result, the engine rolled back due to a lack of compressor pumping capacity and the recorded data does not show the engine exiting rotating stall
        - Starter assist required at observed altitude and airspeed/Mach conditions
    - ➢ Analysis of sister engine (106) results in the same conclusions
- Engine event decel/accel vs similar decels/accels from previous 56 flights on engine 105
    - ➢ The event decel & subsequent event accel were subtly different from any other maneuver captured in the 56 previous flights
        - The event decel was quicker over the entire speed range of the decel
        - The event accel was initiated prior to stabilization at idle
        - As a result, the event accel was conducted at a higher residual thermal state in the compressor
        - The event accel, as indicated by a change in core speed, indicated a strong accel response
        - ***While none of these subtle differences are assumed to be the root cause, it does indicate that the event decel/accel was subtly different than anything from the previous 56 flights and these differences would all add pressure onto the compressor stability margin***
    - ➢ Analysis of sister engine (106) results in the same conclusions

While none of the subtle differences noticed are assumed to be the root cause, it does indicate that the event decel/accel was subtly different than anything from the previous 56 flights and these differences would all add pressure onto the compressor stability margin

CL5584 Feb 09 FDR data analysis



GE Aerospace: NOT SENSITIVE – suitable for external release

Conditions during stall/roll sub-idle:

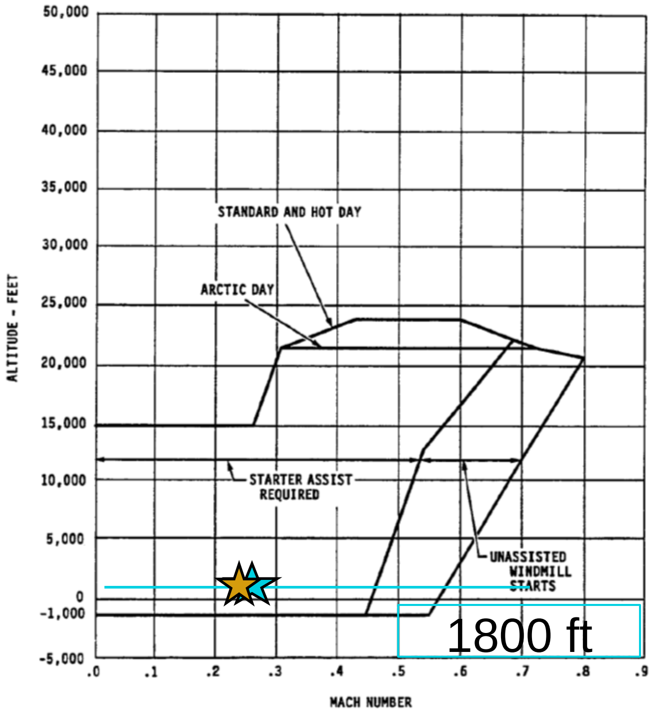
Mach = 0.24

Altitude = 1794 ft

Conditions during decel:

Mach = 0.26

Altitude = 1813 ft



CF34-3 Air Starter Limits

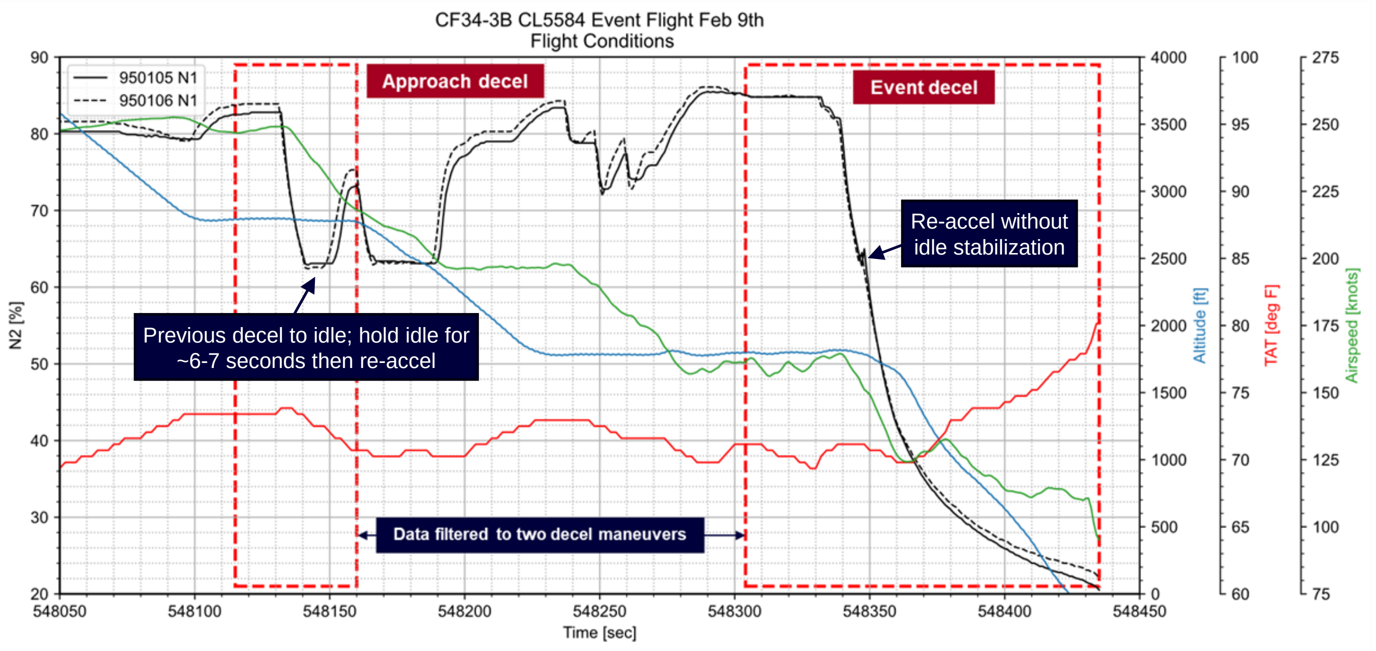
Rolling sub-idle occurred at conditions where starter assist was required

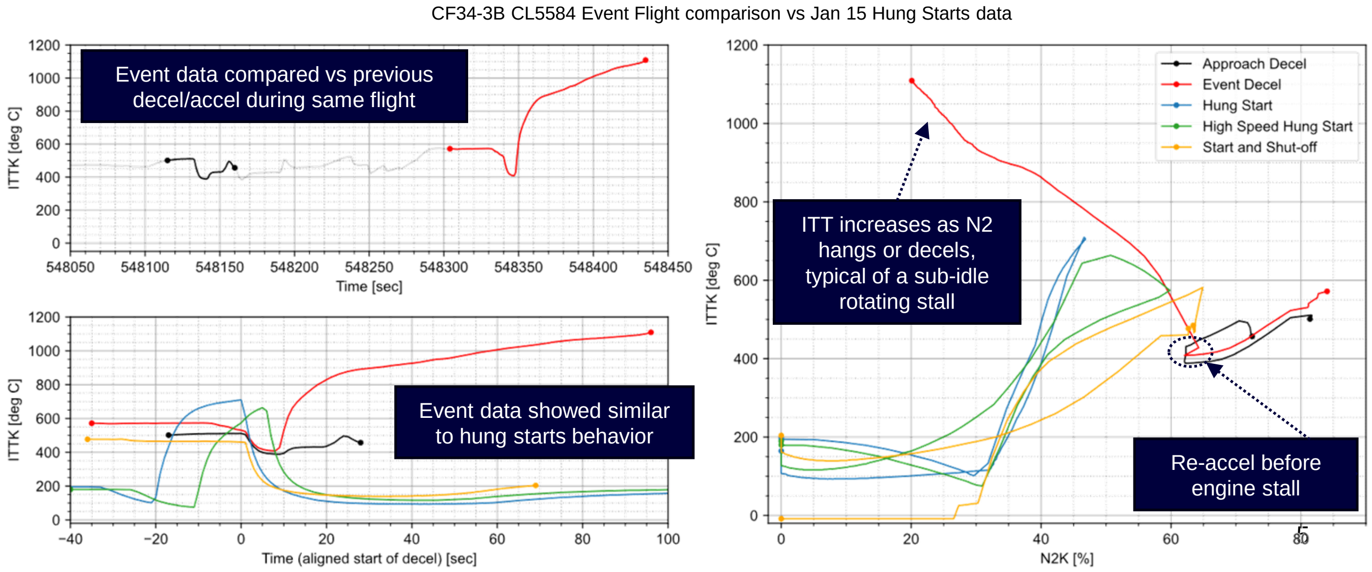
Feb 9th Event Description - GE Aerospace Engine Data Analysis

During approach at 1800 ft/160 knots a decel to idle was commanded in both engines starting at ~84% N2K. Both engines followed the same decel characteristic as previous decels to idle which had occurred at 2800 ft/250 knots down to ~73% N2K; below ~73% N2K a more rapid fan decel is observed, but core speed decel and fuel flow remain similar.

During the event when N2 reaches idle speed, a simultaneous dual engine re-accel is observed followed by a decel and roll sub-idle. The event roll sub-idle characteristic is similar to unsuccessful starts observed during January 15th while troubleshooting starting issues and is consistent with a compressor stall after starter disengagement. Analysis for Feb 9th event data indicates that both engines experienced simultaneously a compressor surge resulting in an unrecoverable rotating stall, with an estimated Ps3 drop of ~20% at surge.

The event data indicates no flameout, fuel cut, or combustor blowout, and both engines followed the characteristic of a compressor surge followed by a rotating stall after the re-accel - similar to the Jan 15th starting issues.





_ ESN 950105 & 950106 Hardware Examination & Corrosion Characterization

ESN 950105 & 950106 HPC VSV System Workscope

- Engine teardown workscope investigating the HPC & VG System completed at GE Aerospace Lynn Plant.
- HPC VSV system investigation included:
  - Measurements of VSV actuator pressures necessary to actuate the system, Maintenance Practice 68, & individual stages IGV-Stg5
  - Vane angle checks (open, closed and total travel) for IGV- Stg5 variable stages
  - Measurements of individual vane drag torques for all variable stages, IGV-Stg5
  - Dimensional inspection of VSV case bushings and HPC case vane bores for IGV-Stg5 variable stages.

ESN 950105 & 950106 HPC VSV System Inspection Results

- *Maintenance Practice 68 (MP68) results showed the pressure to actuate the HPC VSV system on 950105 & 950106 was higher than production limits, but within GE experience of other engines that exhibited hung starts.
- Measured vane angles compared to production rig angles shows stage 5 had 69% & 54% of min production vane total travel range for 950105 & 950106, respectively*.
  - Based on observations, largest stage 5 angle impact was at closed actuator stop resulting in vanes more open at the closed actuator stop.
- Individual vane drag torque measurements show high drag torques vs production limits for stages 4 & 5 on both engines.
  - Highest measurements occurred on stage 5 with worst case vane torque measuring 5.6X and 6X the production limit for 950105 & 950106, respectively.
- Dimensional inspection of VSV bushings prior to removing from the HPC case, confirmed potential bushing ID interference with vane spindle OD for stage 4 & 5 on both engines. Vane percentage per stage show below.
  - 950105: Stage 4 = 18%, Stage 5 = 100%   950106: Stage 4 = 6%, Stage 5 = 100%
- Dimensional inspection of VSV case bores, showed bore ID smaller than drawing min limit for 100% of vanes on stage 5 with worst case measuring .016u/min for 950105 & 950106 due to presence of corrosion/oxidation.

Higher VSV system pressures required to actuate system & reduced Stg5 total travel is due to presence of corrosion/oxidation in HPC case vane bores.

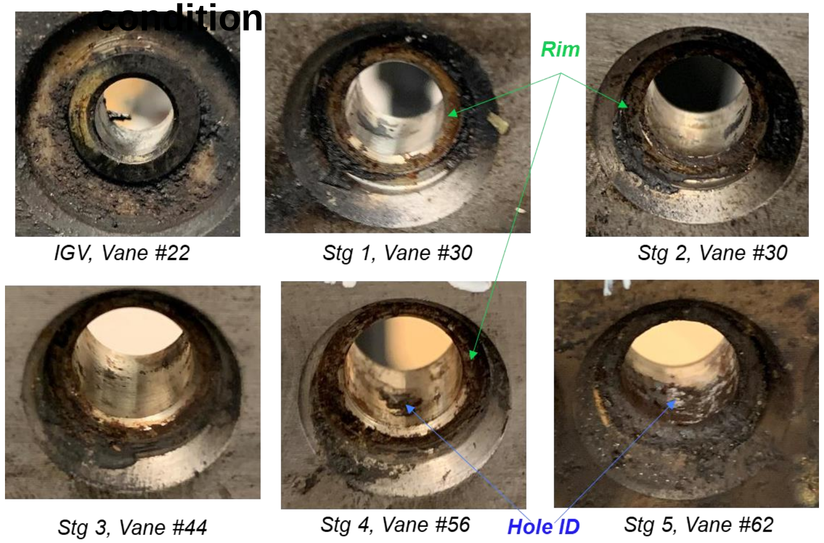
***VG functional test calls to gradually apply pressurized air to fully actuate the VG system. Maximum pressure allowed is 100 psi that is lower than actual fuel pressure at operation conditions ranging from 250 psi to 400 psi**

Executive Summary

- As part of an Annex 13 investigation, hardware from ESN 950105 and ESN 950106 was analyzed at the GE Lynn lab. The results indicated that corrosion in the HPC case vane boreholes was consistent with crevice corrosion caused by Cl and S, traditionally associated on hardware exposed to a saline environment. Pitting was observed along the HPC case, with the worst corrosion in the stage 5 bore hole due to additional oxidation because of higher operating temperatures.
- Also, debris from various areas of the HPC case and bushings was analyzed, revealing corroded steel products and elements typical of saline environments (Cl, S, Na, Ca, K, Mg). Fluorine and Titanium were also found; Fluorine likely came from fire extinguishers used during event, while the source of Titanium is unknown. Neither Fluorine (except in gaseous or highly concentrated forms) nor Titanium are corrosive to Stainless Steels.
- Additionally, compressor rotor spools from event engines were analyzed for missing abradable coating that was not due to rubbing, revealing Cl and S presence in the affected areas, also associated to a saline environment. These findings align with prior experience with similar coating delamination in CF34-3 compressor spools due to bond coat corrosion.
- Finally, the chemical composition of debris from event engines was compared with other analyses of corroded HPC cases from same and different operators. The results showed the same chemical characteristics, including corroded steel with Cl, S, Na, Ca, K, and Mg.

HPC cases as received condition

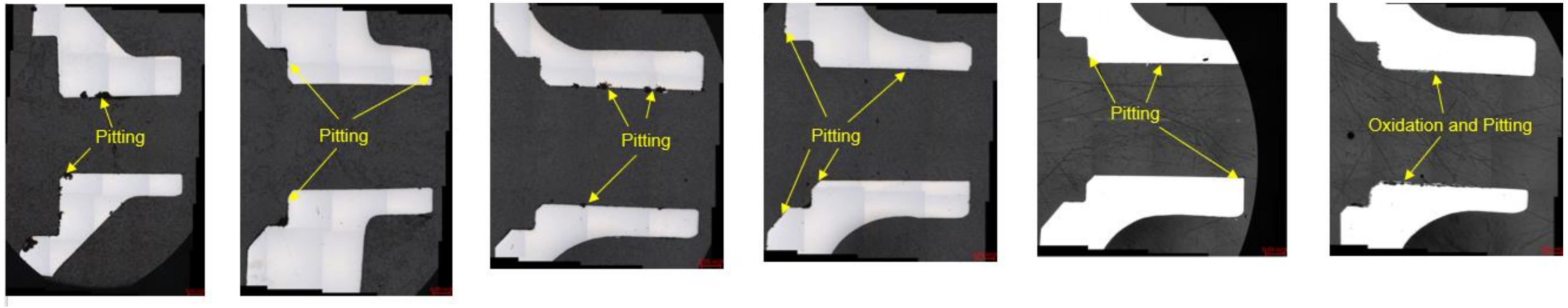
HPC case bore holes surface condition



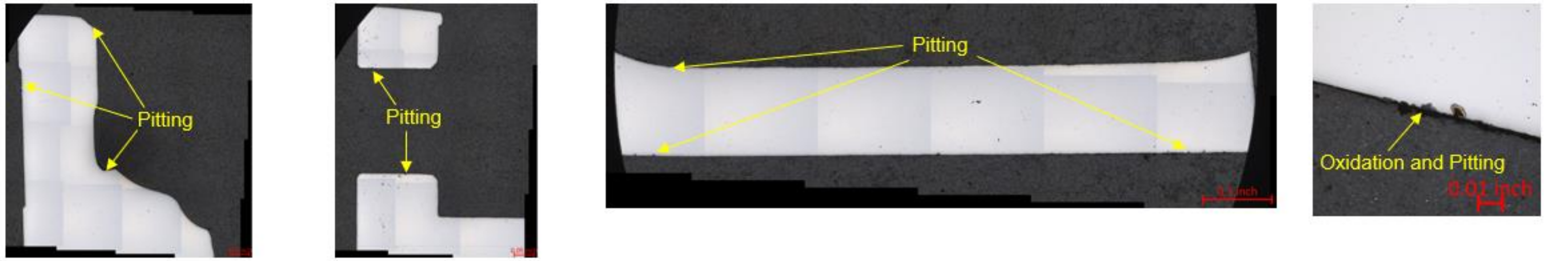
- All bore hole stages show evidence of corrosion at rim, where bushing is located.
- Majority of Stg 5 bore holes show higher amount of corrosion at rim and ID locations

HPC VG bore holes cross sections

IGV | STG1 | STG2 | STG3 | STG4 | STG5



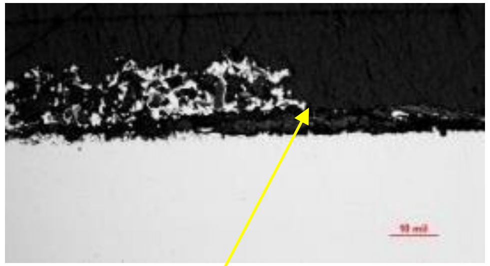
Left flange | Right flange | Rub land area #2 | HPC Aft Eng Fishmouth

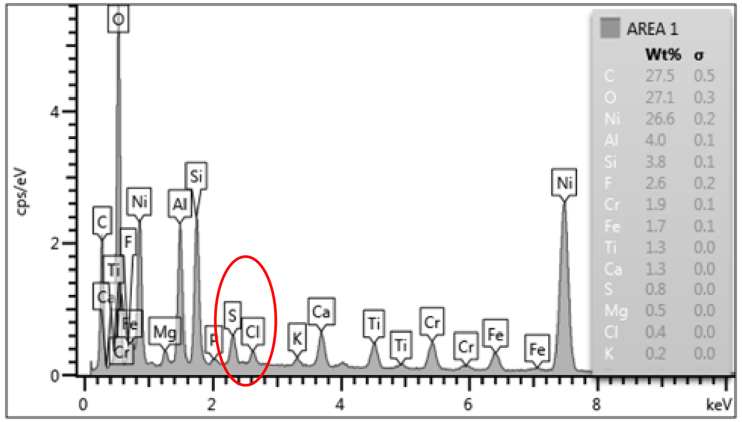


Consistent pitting corrosion identified in both HPC cases. Stg 5 shows additionally an oxide layer as compared to prior stages; oxide layer is also observed on Aft End Fishmouth cavity section to a lesser degree. Thicker oxide layer in stage 5 can be attributed to operation temperature >500F and Cr depletion due to corrosion mechanism (passivation loss).

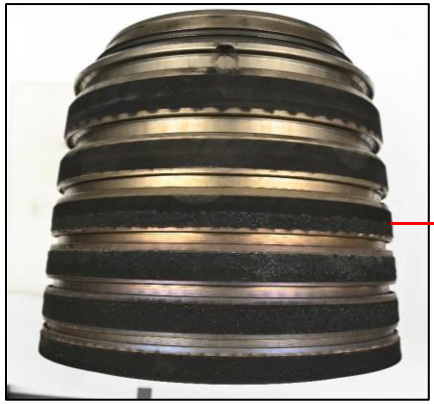
HPC Spools Evaluation

HPC Spool Stg 5 – ESN 950105

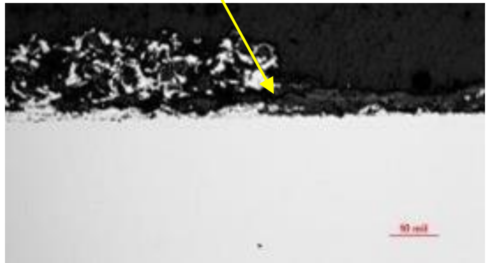


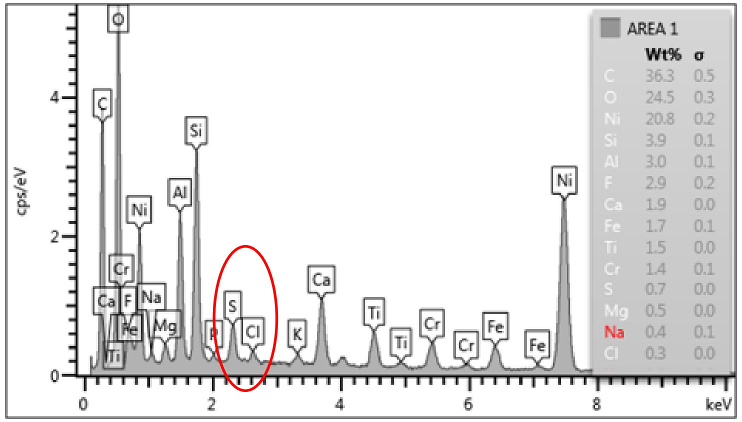


Delaminated coating due to oxidation/corrosion of bond coat



HPC Spool Stg 5 – ESN 950106





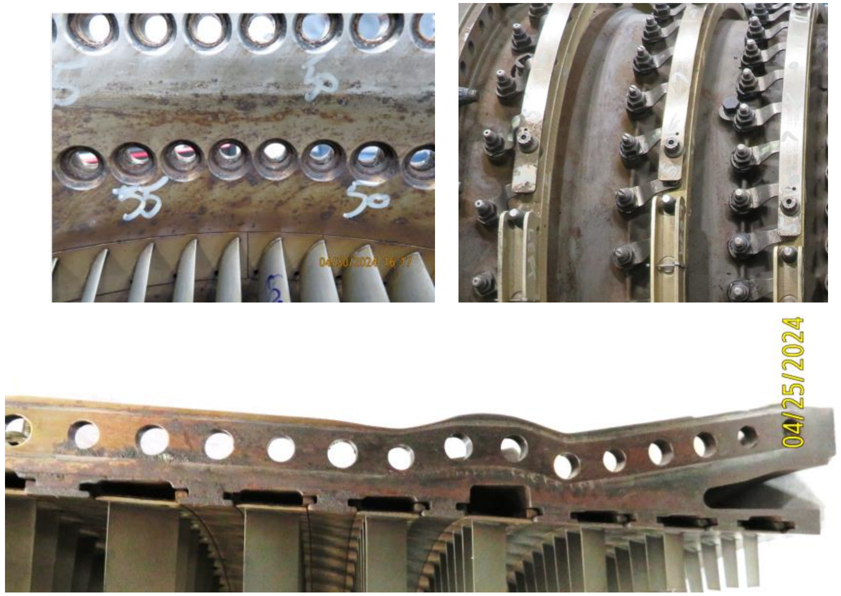
Delamination of Ni-Cr-Al bentonite coating attributed to corrosion of bond coat due to Cl and S presence as identified in EDS, along with Nickel oxide formation between the bond and topcoat. Cl and S presence along with other elements such as Na, Mg and K are generally associated to engines exposed to saline environment. Fluorine traces identified may come from fire extinguishing agents used during event.

Event Engines Comparison vs Other Engines With Observed Corrosion

Event Engine

Non-event HPC case

Non-event HPC case



Comparison among different HPC cases presenting corrosion. Typically pitting is found along all HPC case being more predominant in later stages (corrosion + oxidation associated). Reports from debris gathered from other non-event engines showed Cl and S presence along with Na, Ca, K and Mg elements. These elements are generally associated to engines exposed to saline environment.

HPC Components Corrosion and Oxidation Conclusions

- 2 different types of corrosion observed on HPC compressor case: Crevice corrosion (bores ID and mid flanges) and pitting corrosion (inner HPC case surface)
- Crevice and pitting corrosion are both related to chlorine presence, as identified in EDS analyses of corroded areas. The key difference is that crevice corrosion involves geometry (solution entrapment), leading to localized acidic conditions due to chloride or sulfur, making it more aggressive
- HPC bore ID characteristics are consistent with crevice corrosion due to geometry and presence of chlorine in debris. Crevice corrosion also occurs in mid flanges, which presented also surface pitting
- Cl presence and elements such as Na, Mg and K are linked to engines exposed to saline environment.
- Fluorine, likely from fire extinguishers and Titanium were also found; neither of these elements is corrosive to Stainless Steels (except for Fluorine in gaseous or highly concentrated forms)
- Stg 5 undergoes a mix of corrosion and oxidation. Crevice corrosion can breakdown the M152 steel Cr protective oxide layer along with further dissolution of Cr ions, leaving surface susceptible to oxidation and further corrosion (cyclic process)
- Once crevice corrosion is activated, it can be accelerated due to galvanic effect with bushing made of graphite reinforced polyimide; formed pits will act as anode, while the remaining metal surface and bushing in contact with the bulk electrolyte acts as a cathode

Hop-A Jet Fleet FDR comparative analysis

Summary of confirmed corrosion vs confirmed NO corrosion FDR data analysis

Introduction:

GE Engine Operability team performed a FDR Data comparative analysis from the HOP-A JET fleet. FDR analysis focused on comparisons of the event engines 950105 & 950106 with a sample comprised of other two ESNs that experienced hung starts and presented corrosion, in addition to two ESN with no corrosion findings or hung start reports.

Tail or ID	Eng 1 (LHS)	Eng 2 (RHS)	Observations	Status	Total # flights analyzed
CL5584	950105	950106	Corrosion confirmed	Received	56
Tail1	Eng1	Eng2	Corrosion confirmed	Received	66
Tail2	Eng1	Eng2	Pass MP68, no hung starts reported	Received	80 used

Analysis Objective:

Quantify the differences in key engine performance/transient response metrics on engines with confirmed HPC case corrosion (as observed at engine examination at GE Lynn facilities). Analysis focused on HOP-A JET fleet to reduce variables between operators.

Conclusions:

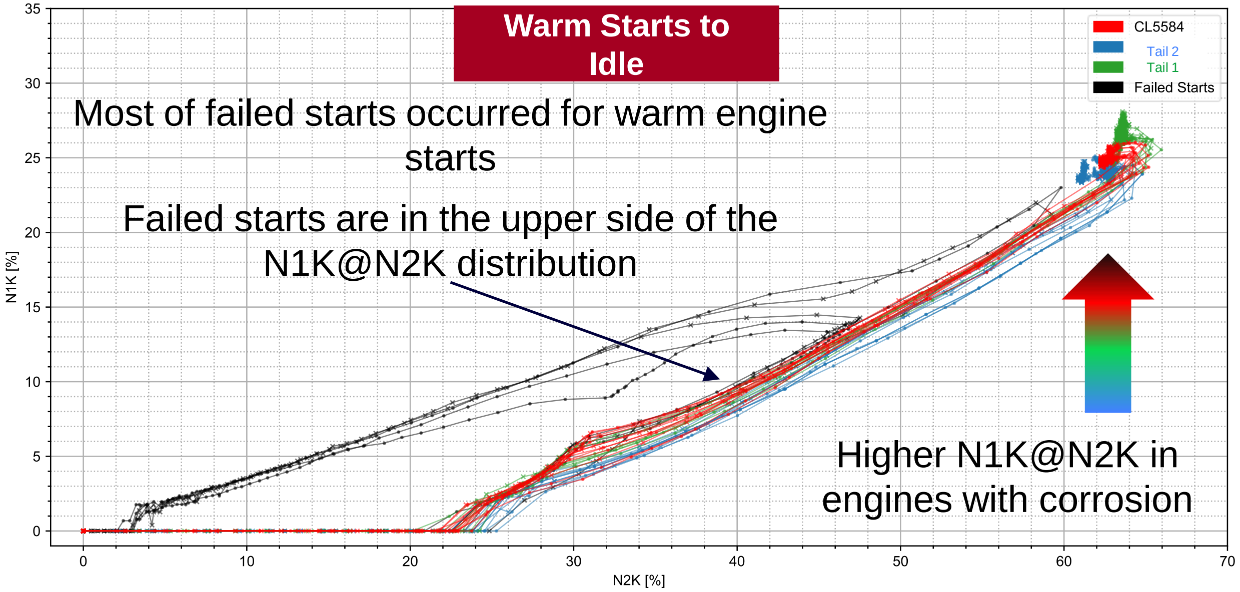
- FDR data includes all sources of variation, not only corrosion; other factors may contribute to the observed differences including main fuel control variable stator vane schedule variation and variable stator vane feedback cable adjustments
- Engines with confirmed HPC corrosion tend to have a higher fan speed at the same core speed during all start to idle operations
- Engines with confirmed HPC corrosion tend to have a higher fan speed at the same core speed when approaching idle during a decel
- Based on steady-state cycle model derivatives at idle, the effect in fan speed vs. core speed observed is translated into an equivalent effect of a more open variable stator gang in engines with confirmed HPC corrosion
- A more open variable stator vane off-schedule condition will have a negative impact to compressor stability during startup and above idle; the effect is stronger sub-idle than above idle based on CF34-3B fleet experience
- Combination of open VG angle, and other factors such as throttle transient, engine thermal state, engine deterioration, and control tolerance variation can lead to a compressor instability

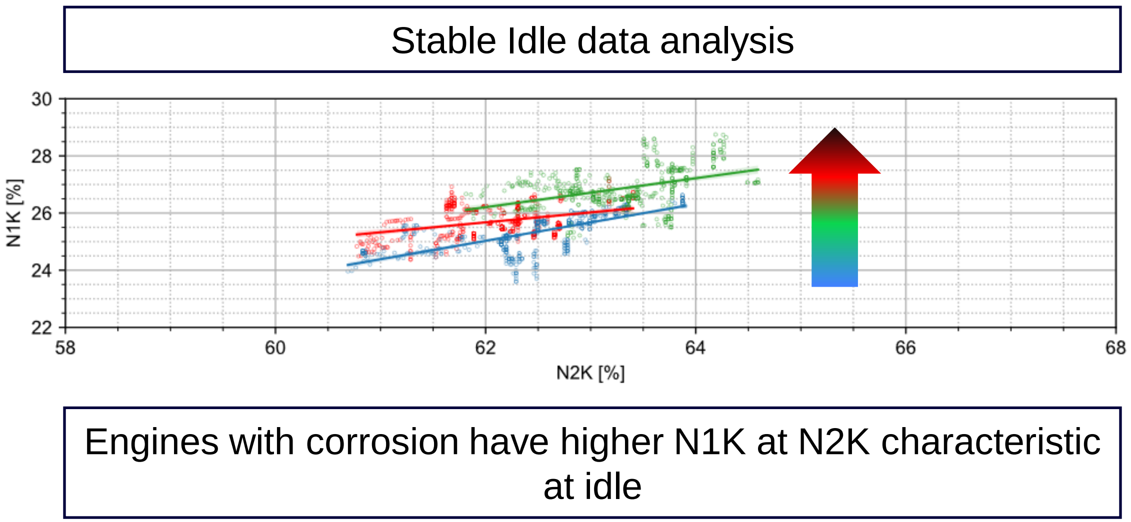
Evaluation of Corrosion Effects During Start and Idle

Startup to idle data are split between cold starts (first start of the day) and warm starts (ITT > 100 °C, Left Hand Side Plot)

Data was also compared using stable idle shaft speeds (Right Hand Side plot)

Tail or ID	Eng 1 (LHS)	Eng 2 (RHS)	Observations
CL5584	950105	950106	Corrosion confirmed
Tail1	Eng1	Eng2	Corrosion confirmed
Tail2	Eng1	Eng2	Pass MP68, no hung starts reported





Trends show higher fan speed at same core speed for engines with corrosion vs engines without corrosion during startup and Idle, no effect observed at high power operation

Consistent with expected behavior if VG gang is more open than nominal, below table represents expected effect from the performance cycle model

Steady-state cycle model derivative at Ground Idle ISA / SLS No bleed				
	VG (degree)	N1 [%]	ITT [°C]	WF [pph]
1 ° Open	-1.00	0.69	-2.86	10.07

Higher fan speed at core speed during starts for engines with corrosion consistent with more open VGs

MFC Test data analysis

Summary of MFC test results at Woodward

Test Objective:

Simulate the deceleration characteristic observed during event under Annex 13 investigation to gather information to support / refute contribution of MFC as part of root cause investigation.

Units tested:

1. WYG85935 (from ESN 950105 LHS in tail CL5584)
2. WYGA5167 (from ESN 950106 RHS in tail CL5584)
3. Unit from non-event engine

Accomplishments:

6 runs simulating chop to idle for 3 units at constant compressor discharge pressure (CDP) since it is not possible to vary this parameter in the test bench.

3 runs simulating Power Lever Angle (PLA) from idle to shutoff and then back to idle for 3 units (at high CDP pressure)

3 runs simulating PLA from min Fuel Flow to shutoff and then back to min Fuel Flow for 3 units at low and constant CDP and constant N2 ~34%

Conclusions:

1. A rapid throttle movement from idle to shutoff then back to idle will likely be captured in FDR (1 scan/sec)
2. Chop to idle test showed similar deceleration characteristics among the 3 units tested but different than the FDR data, this is mainly driven by the significant differences in test conditions. It was not possible to replicate the event condition in Woodward test bench.
3. Based on the test conducted, the 3 units showed very similar behavior, it is unlikely the MFCs to be a significant contributor for the event

All MFCs tested behaves similarly, this is refuting evidence for the MFCs as main contributors of the event
A rapid throttle movement to shutoff and back to idle is likely captured in 1 Hz

– Leading Indicator SB 72-0345 One-time VG Functional Check

Leading Indicator SB 72-0345

Objective

- To gain an understanding of how prevalent the HPC corrosion impacting the VG system condition is across the CF34-3 BJ fleet by executing MP68 on engines that had experienced a hung start within 24 months previous SB publication (5/14/24)

Subject Population

34 ESN estimated

Compliance

60 flight cycles from publication date of the SB. If an aircraft has two subjected engines, 1st engine within 10 flight cycles and 30 flight cycles for the other engine from the issue date of the SB.

Outcome

- 8 engines failed MP68 further confirmed with HPC corrosion from 4 different operators worldwide – (50% of impacted population belong to one Operator)
- 26 engines have performed the VG Functional Check (MP68) without findings from 15 different operators
- P68 “VG Functional Check” is an effective procedure to identify engines with potential corrosion in the HPC/VG system.

HPC corrosion mitigation plan

Proposed Interim/Containment Plan

- FIM-07 Hung or Slow start troubleshooting procedure has been updated to identify engines with corrosion impacting VG function, preventing excessive corrosion on field engines and calling to conduct VG functional check before replacing any LRU

- Cat 2 SB 72-0347 calling for one-time inspection of the whole CF34-3 BJ Fleet to perform a local HPC Case S5 BSI and to conduct VG functional check
  - Inspection priority set as function of engine utilization (lower and higher than 250 hr/year)
  - Heat Soak restart testing to be performed every 3 months until engine is VG checked and/or Borescope inspected

- Based on SB 72-0345 results shortfall expected is low

- SB 72-0347 publication expected by May 2025

Cat 2 SB for one-time inspection of the whole CF34-3 BJ Fleet to confirm VG condition

HPC Corrosion Mitigation and Control Plan

Completed Tasks:

- GE has been reinforcing maintenance recommendations to mitigate HPC corrosion in different CL600 forums (CL600 Advisory, CL600 Maintenance & Operations, CL600 Industry Steering Committee)

In progress tasks:

- GE to introduce 48 month periodic inspection of VG functional check to SEI-780 Chapter 05 – Publication date expected by 2026 Q1
- GE SB 71-0000 “CONSOLIDATED ON-WING INSPECTION RECOMMENDATIONS AND SERVICING TASKS LIST” is being revisited to update the Sea Salt Environment program currently intended for Special Mission Operators. The revised version of this SB will show effectivity on the conditions that will target engines to be subject to this recommendations. The tasks recommended to mitigate corrosion are Fan/Compressor Water Wash, inspection of the VG hardware and lubrication of the VG bushings. Publication date expected by May 2025.
- GE has requested the CL600 Industry Steering committee to evaluate to introduce MP-68 Variable Geometry Functional Check as a periodic item to the Challenger 6XX MRB Report, with a 48-month interval, with a start target date of 2026
- GE has requested the CL600 Industry Steering committee to introduce the water-wash optional task in the MRB

– CF34-3 HPC corrosion experience from Special Mission Operators

Special Mission Operators Experience

Problem/Background

- On 2018 A CL604 Special Mission Operator reported hung start events on #2 engine TSN/CSN: 2,055/1,230
- Operator Provides over-the-sea flying services, mainly for search and rescue, air ambulance, firefighting, and law enforcement agencies' operations
- Successful starts the first time of the day; unable to start the engine on second and subsequent starts
- Extensive troubleshooting recommendations provided
- Issue worsen: Not able to start at any attempt and extended to #1 engine
- Additional aircraft from the same fleet exhibited similar operational behavior
- Engine removed and shipped to MRO shop for incoming testing
- Investigation team found excessive pressure to actuate the VG system

LH engine	Pressure/PSI	Status
1st test	110	Start to Move
	190	Fully open
	40	Start to Move
	230	Fully closed
2nd test	10	Start to move
	170	Fully open
	30	Start to move
	230	Fully closed
3rd test	15	Start to Move
	150	fully open
	20	Start to Move
	220	Fully closed

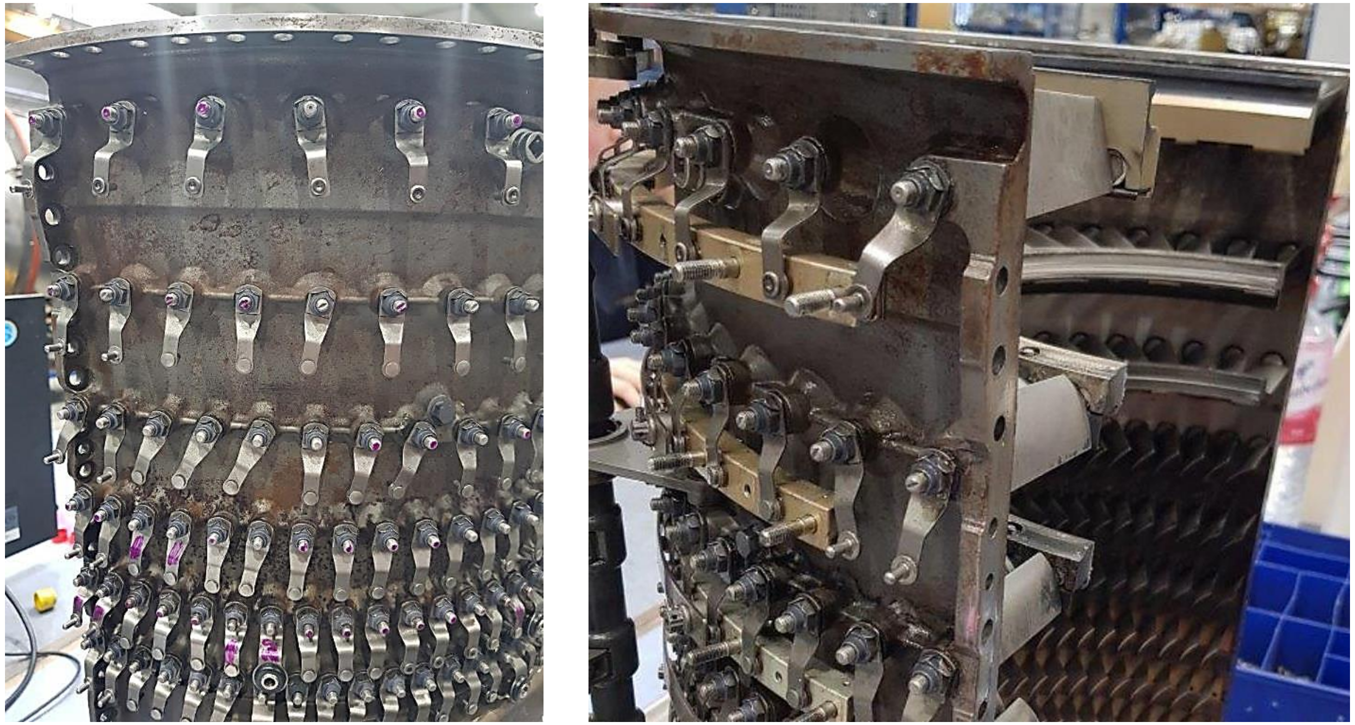
RH engine	Pressure/PSI	Status
1st test	20	Start to Move
	100	Fully open
	20	Start to Move
	130	Fully closed
2nd test	20	Start to move
	100	Fully open
	20	Start to move
	130	Fully closed

VG actuating test pressures

Investigation Conclusions

MRO Findings

- During incoming inspection it was noticed that the VG system had an unusual spring loaded-like response
- Moving the VG Actuator Shaft required significant additional force
- Additional disassembly showed corrosion in the upper & lower HPC cases, bores and bushings
- Several stators were stuck



HPC case with corrosion

HPC case Stage 5

HPC case S5 Borehole

HPC case S5 VG spindle bushings

Investigation Conclusions

It was confirmed corrosion/contamination in the HPC case bore holes due to a combination of the following contributing factors which led to an increased resistance to actuate the VG system of the engine:

1. Operators overall mission profile

2. Continued exposure to excessive salt air environment

3. Contamination and corrosion of the vane/case interface at a piece part level

4. Water-wash scheduling frequency and execution possible contributing factor and to be reviewed for effectiveness

These findings are aligned with experience from other GE programs used in sea salt environment such as CFM56 P8, CT7 and CF6.

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