



ATTACHMENT 1

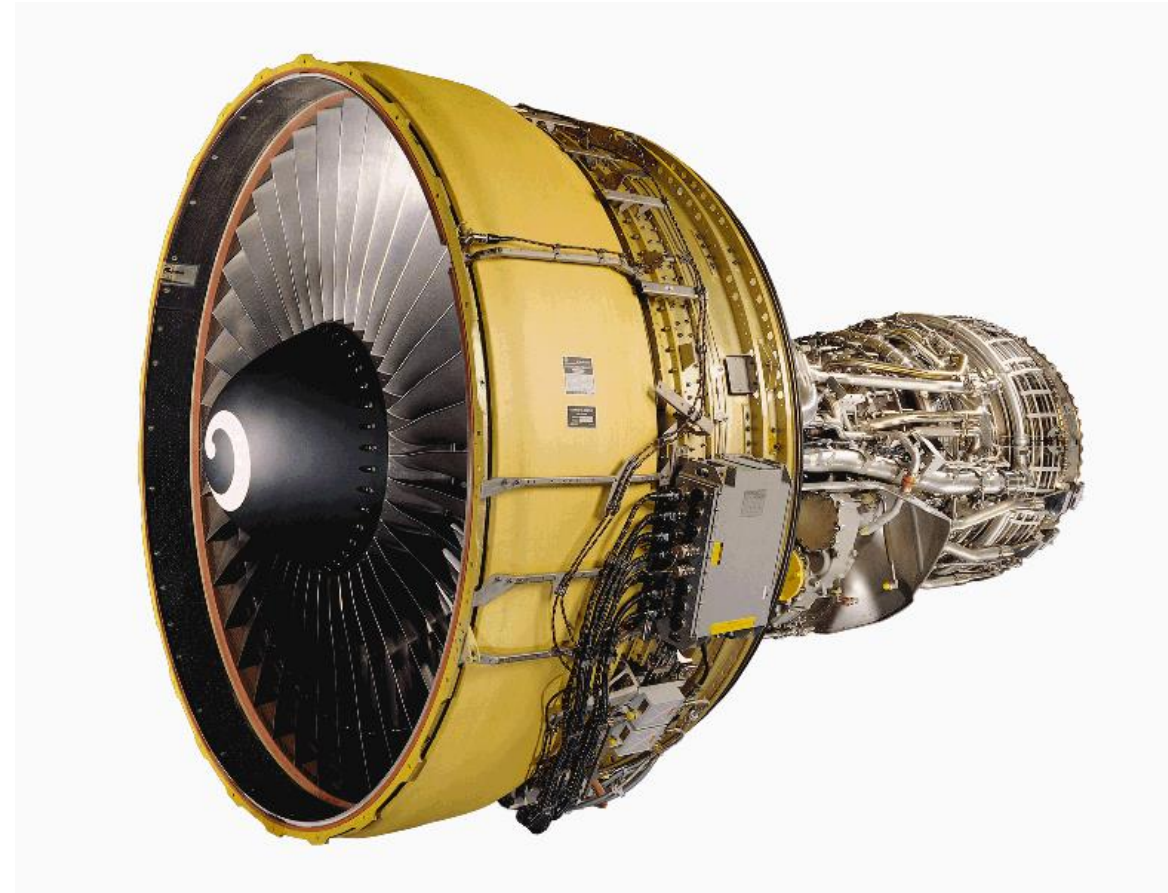
POWERPLANT GROUP CHAIRMAN'S FACTUAL REPORT

ENG21LA013

**GE's MAS Air Cargo ESN 695440 Failure Analysis Findings & Root
Cause Summary Presentation**

MAS Air Cargo ESN 695440 Failure Analysis Findings & Root Cause Summary

4/1/2021



MAS Air Cargo ESN695440 Event - Introduction

This report includes the following:

- Event Background
- Hardware Overview
- Pre-Engine Teardown Investigation
- Flight Data Analysis
- LPT Teardown Hardware Overview
- Metallurgical Evaluation
- Unbalance Calculation
- Event Failure Scenario
- Summary



MAS Air Cargo ESN695440 Event – Background

Event Summary

A CF6-80C2 engine operated by MAS Air Cargo (leased asset) experienced an in-flight shut-down during climb with an associated fire of number 2 engine, ESN 695-440, on departure from Las Angeles, CA to Mexico City, Mexico. When at 12,000 ft the crew declared an emergency and by that time the fire went out. The aircraft was then diverted to Ontario, CA due to weather and had an uneventful landing 65 min later. Based on DFDR data from the event the engine operated in a high unbalanced condition (>5 IAC) for approximately 4 min (with the fire occurring near the end of the high imbalance), then continued windmilling for at least 40 minutes near 2.5 IAC (until the N2 signal was lost).

Aircraft : 767-300 freighter

Tail: N363CM



Engine – GE CF6-80C2

- Engine Serial Number : 695440
- Installation Date : December 1, 2020
- TSN / CSN : 54,187 / 20,656
- TSLSV / CSLSV : 1,649 / 669

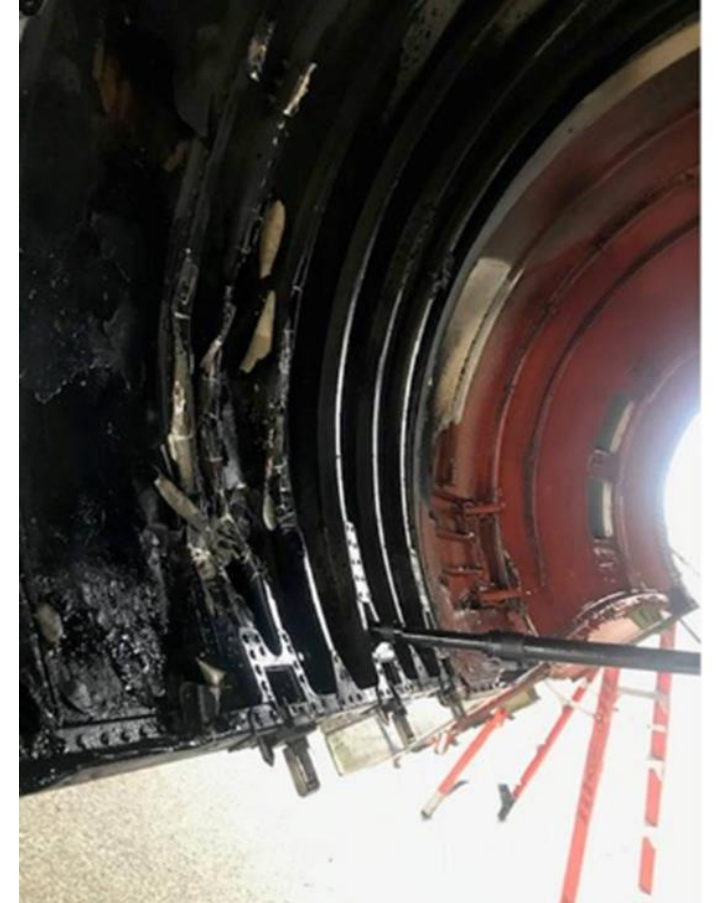


MAS Air Cargo ESN695440 Event – Hardware Overview-Ontario, CA



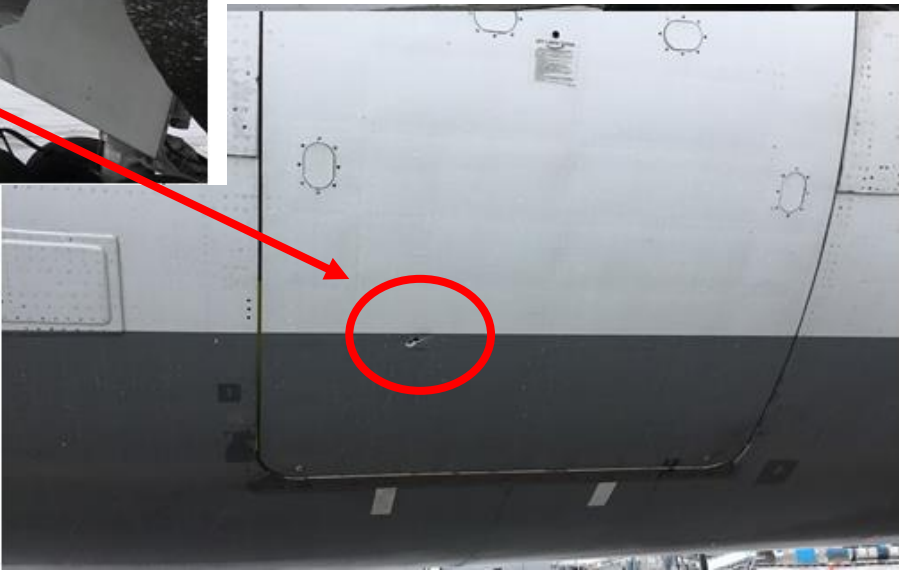
Engine Condition: Exhaust Nozzle missing material, TRF strut cracking, ABG Transverse link separated ,Oil tube broken , Evidence of heat distress on various tubes from the 9 -6 o'clock position (ALF).

MAS Air Cargo ESN695440 Event – Hardware Overview-Ontario, CA



Distress observed on engine and Cowl doors from engine fire

MAS Air Cargo ESN695440 Event – Hardware Overview-Ontario, CA



Damage observed on Exhaust Nozzle with AC
distress observed on Aileron Flaps and Cargo door



MAS Air Cargo ESN695440 Event – Pre-Engine Teardown

NTSB Investigation: Engine sent to GE Evendale Development Assy for engine teardown

Initial Investigative Screening:

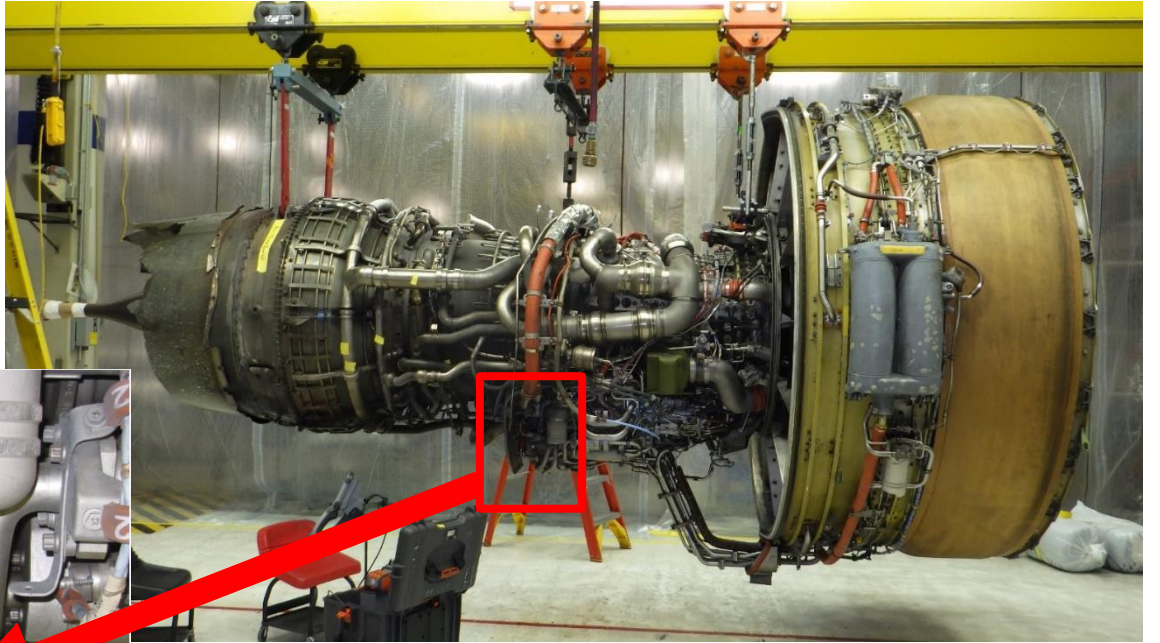
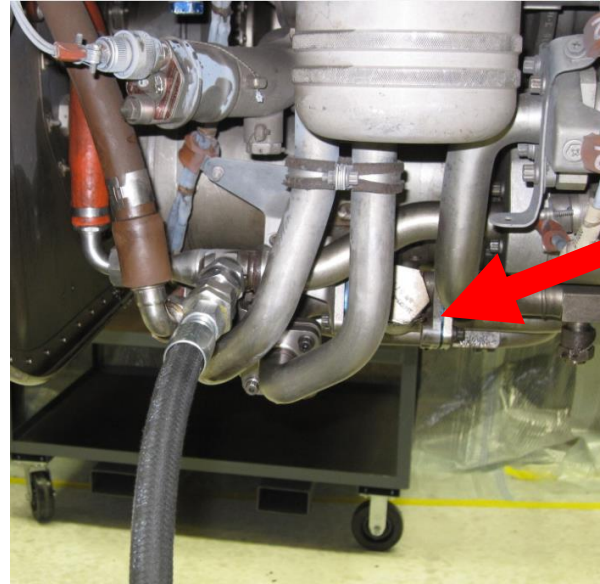
- Fuel System pressure/leak check performed
- Full Engine Borescope Inspection
- Review of DFDR data



MAS Air Cargo ESN695440 Event – Fuel Leak Check

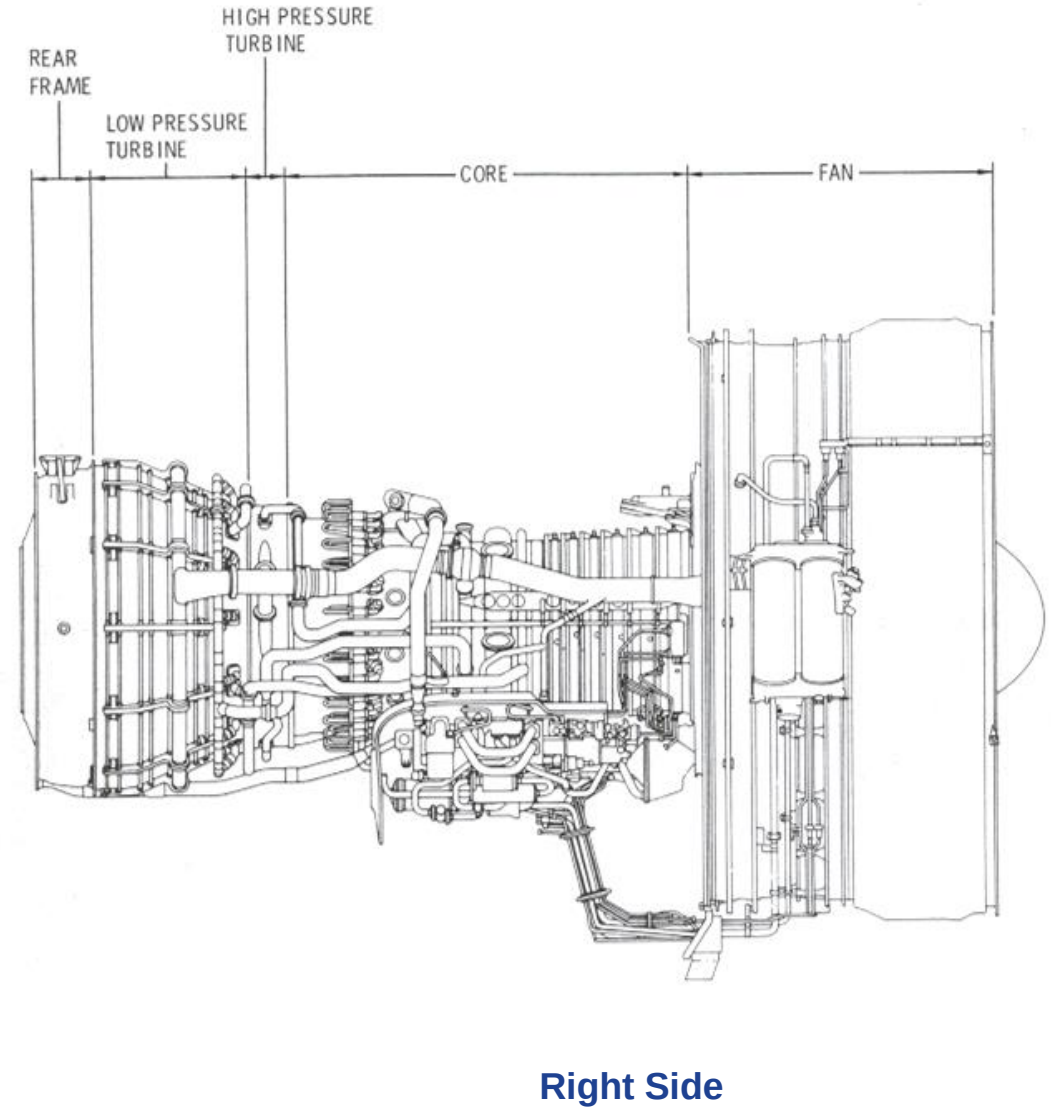
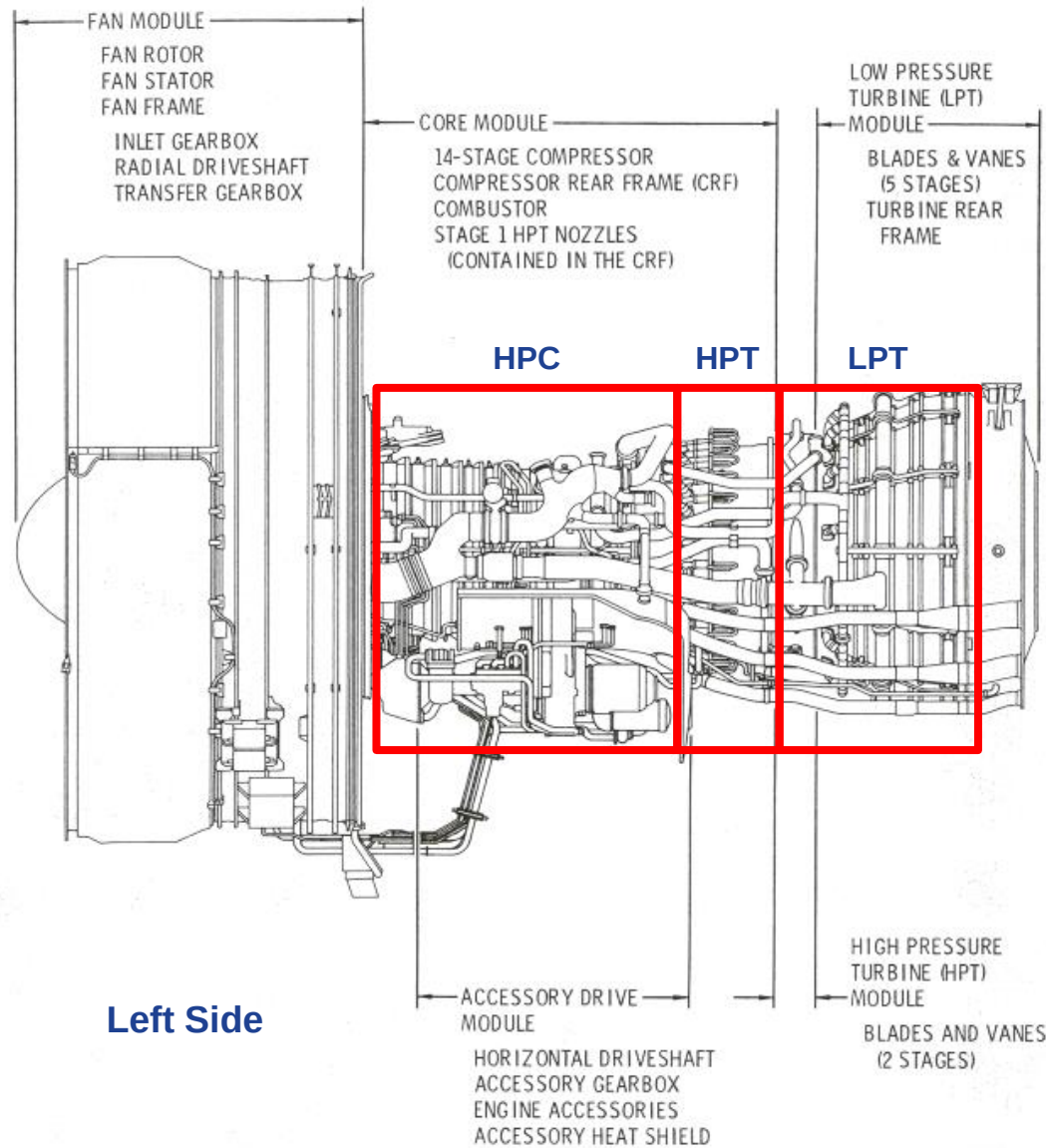
Nitrogen Fuel System pressure/leak check performed.

. (Fuel Nozzles pigtails were not tested)



No fuel leaks identified

MAS Air Cargo ESN695440 Event– BSI – HPC, HPT and LPT



MAS Air Cargo ESN695440 Event – HPC BSI

- No distress observed on HPC Blades or Vanes
- No missing airfoils observed.
- No signs of impact damage.
- Core rotation was noted as normal.



HPC Stage 1 Airfoil



HPC Stage 5 Airfoil and Vanes



HPC Stage 7 Airfoil



HPC Stage 10 Airfoil



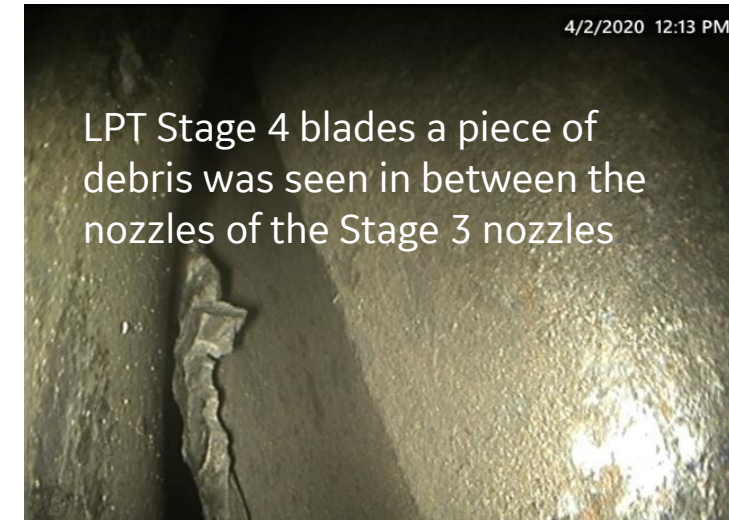
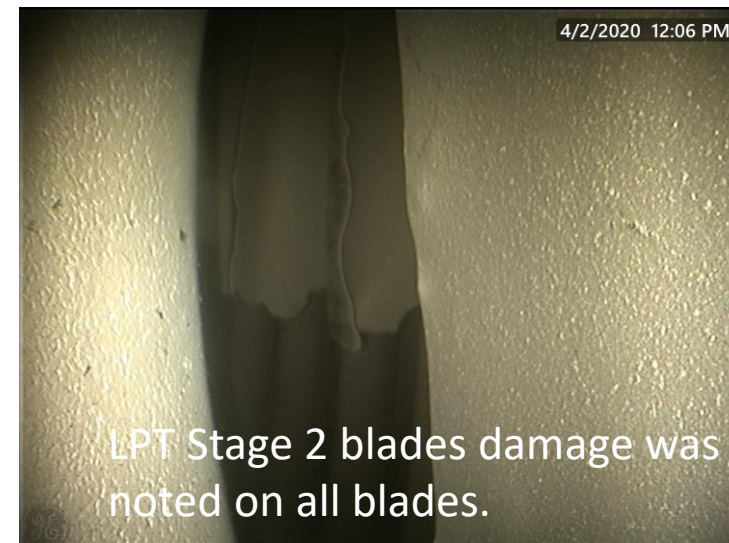
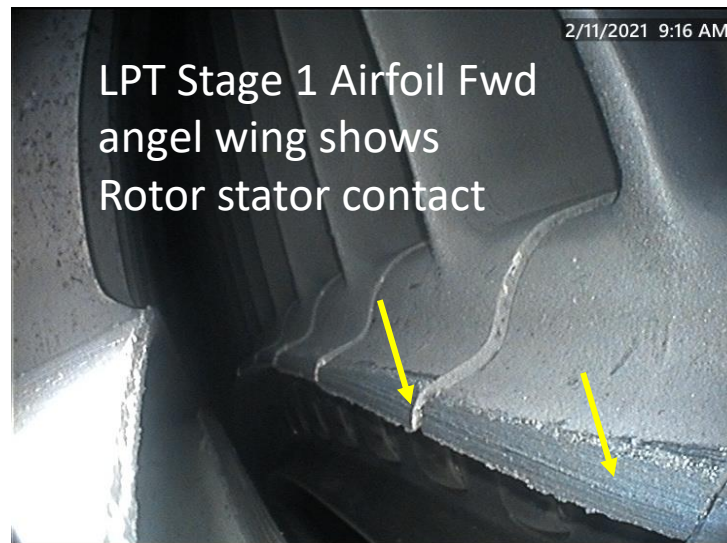
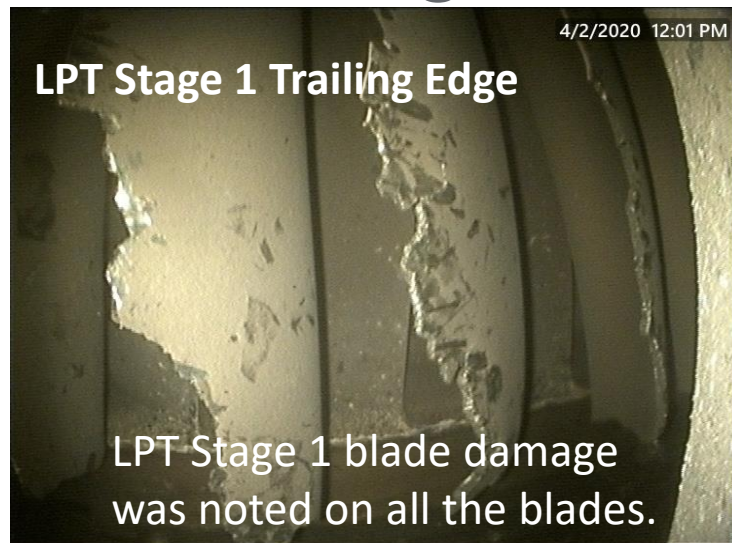
HPC Stage 14 Airfoil

MAS Air Cargo ESN695440 Event – HPT BSI

- HPT Stage 1 blades, mid core burnout was noted on various blades.
- No missing airfoils observed.
- No signs of impact



MAS Air Cargo ESN695440 Event – LPT BSI



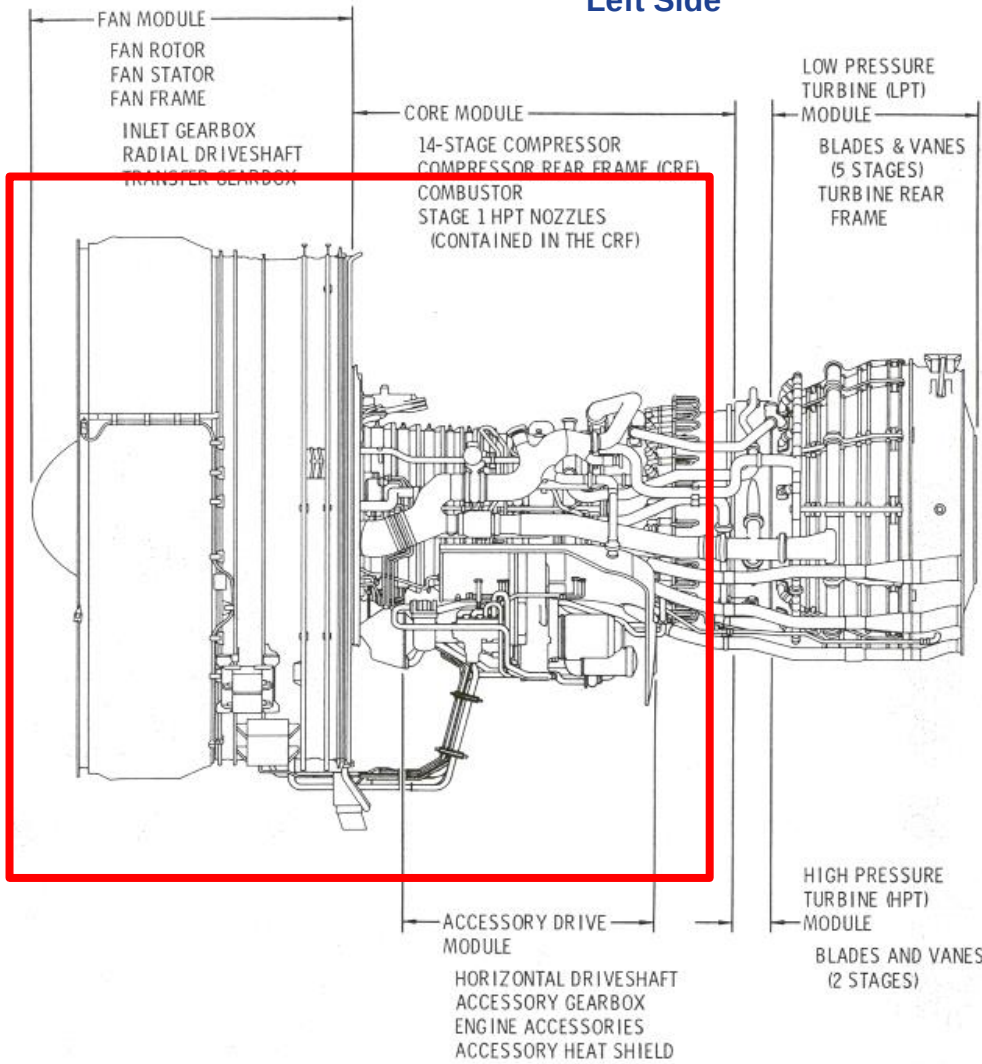
Severe distress observed on all LPT stages



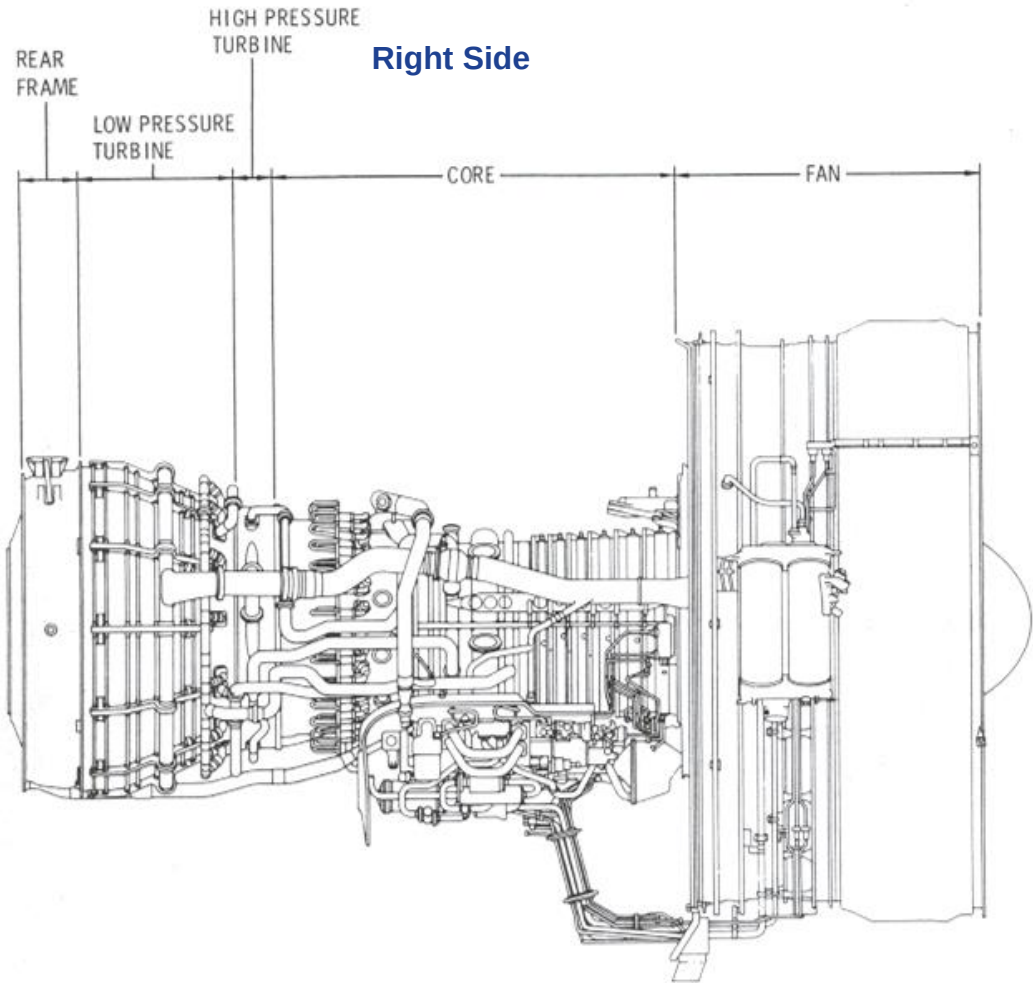
Engine Overview – External Views

Design Features

Left Side

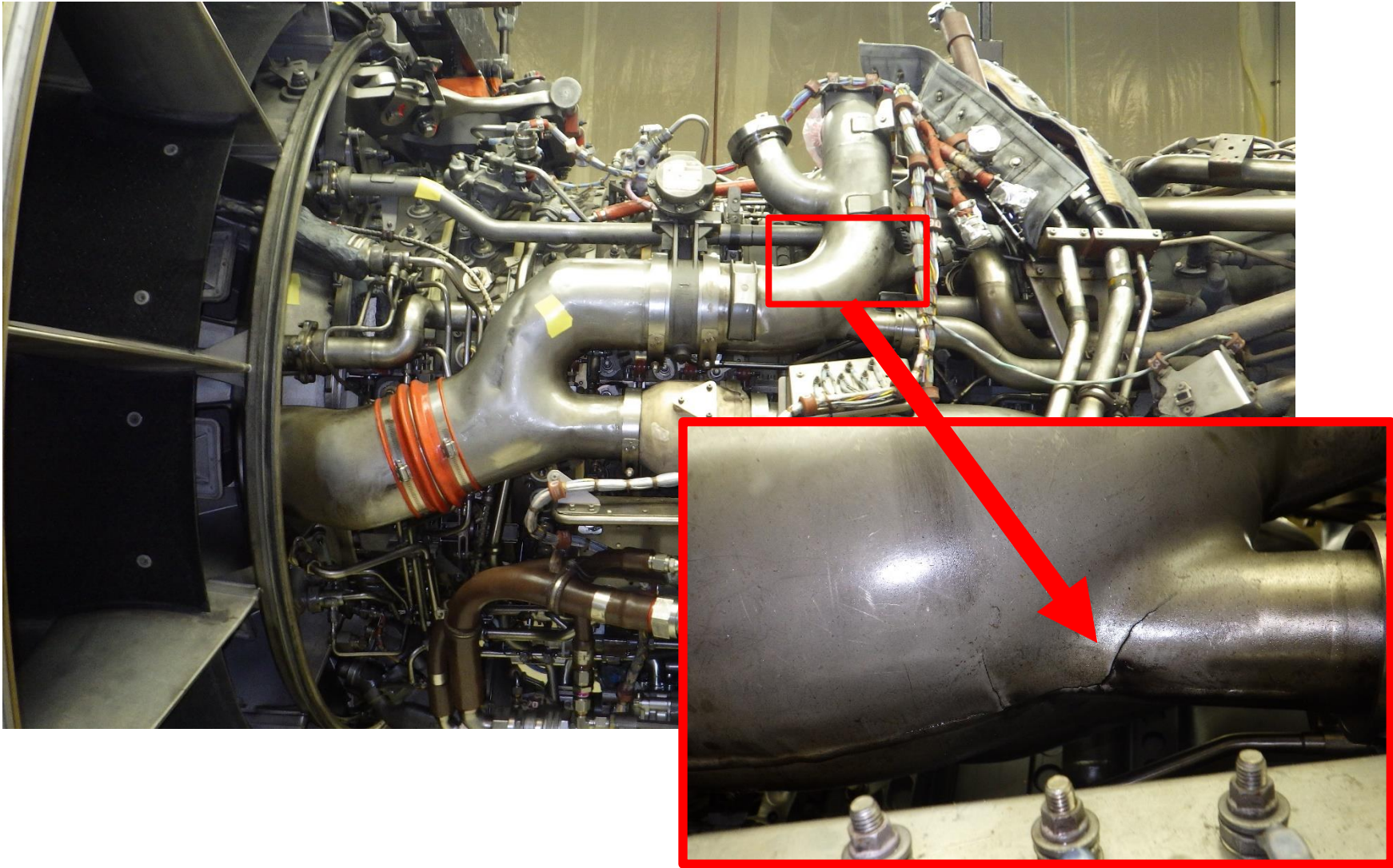


Right Side

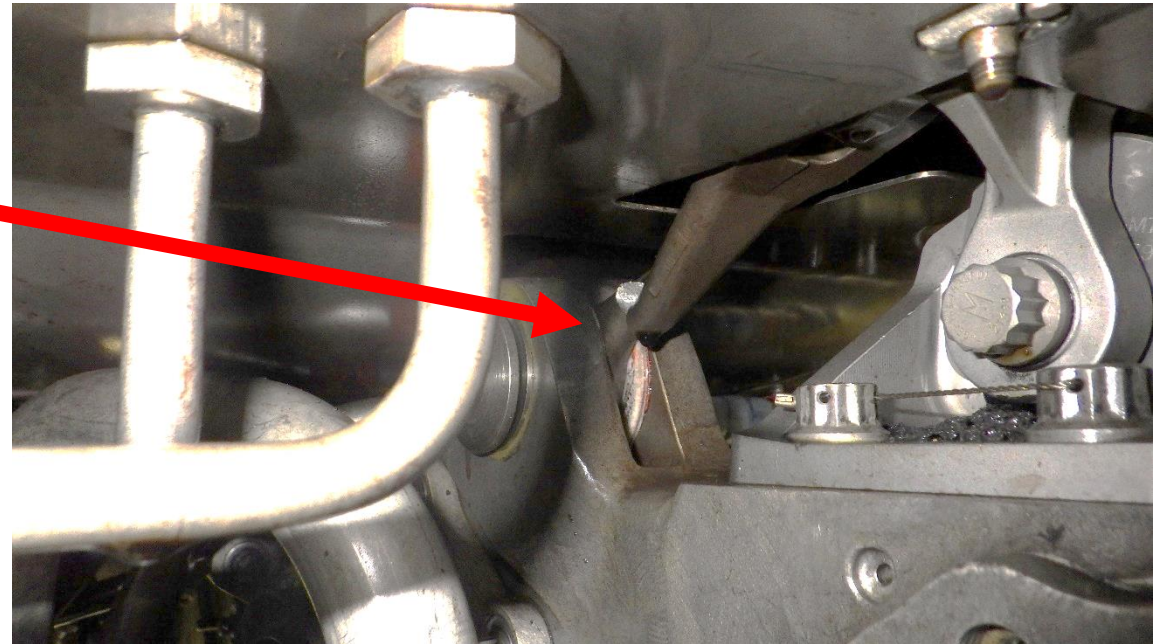
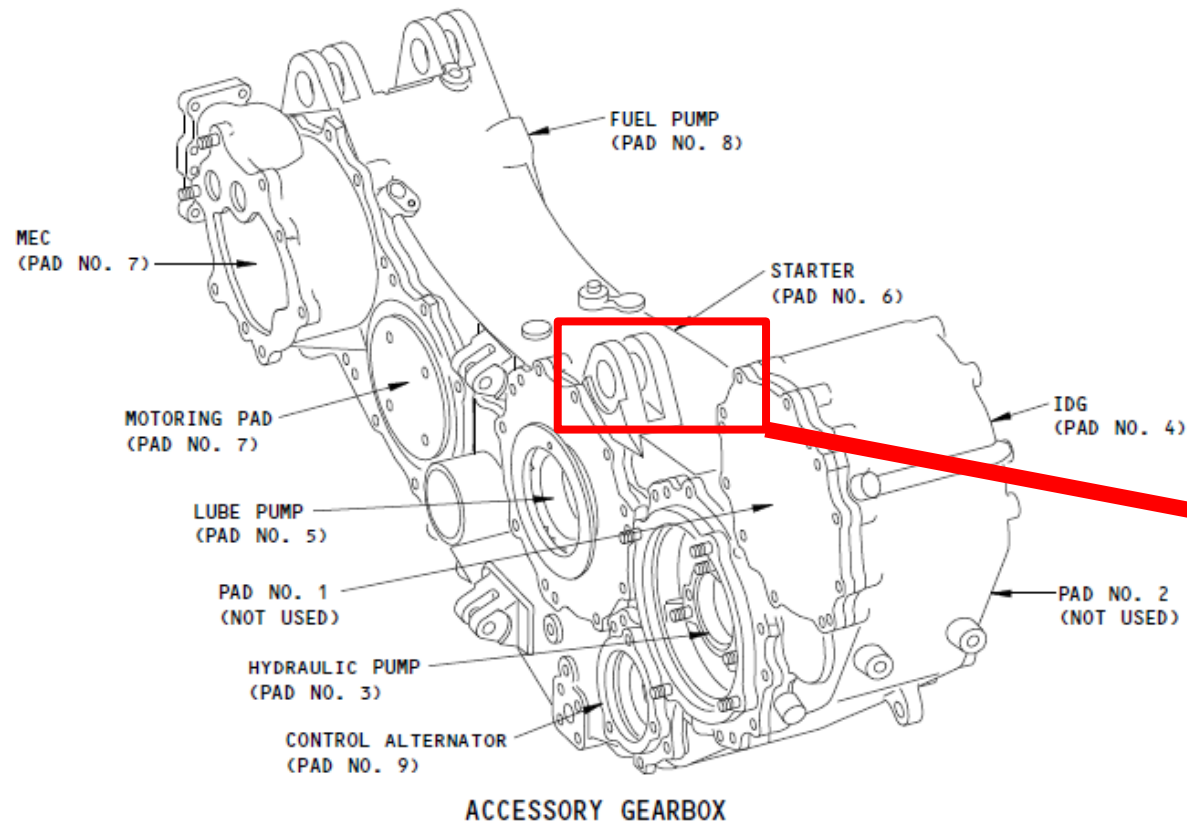


MAS Air Cargo ESN695440 Event – Engine Externals

Crack can be seen on the compartment cooling manifold around the 9 o'clock position (ALF)



MAS Air Cargo ESN695440 Event – Engine Externals



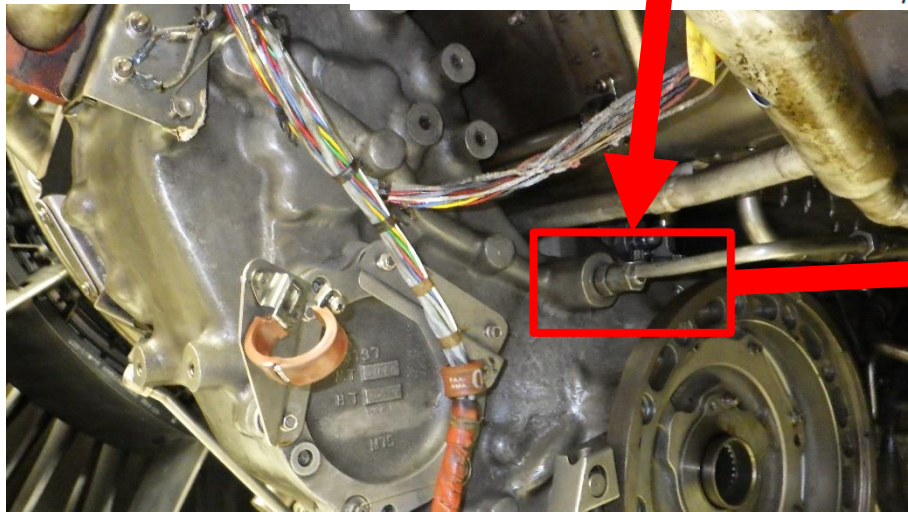
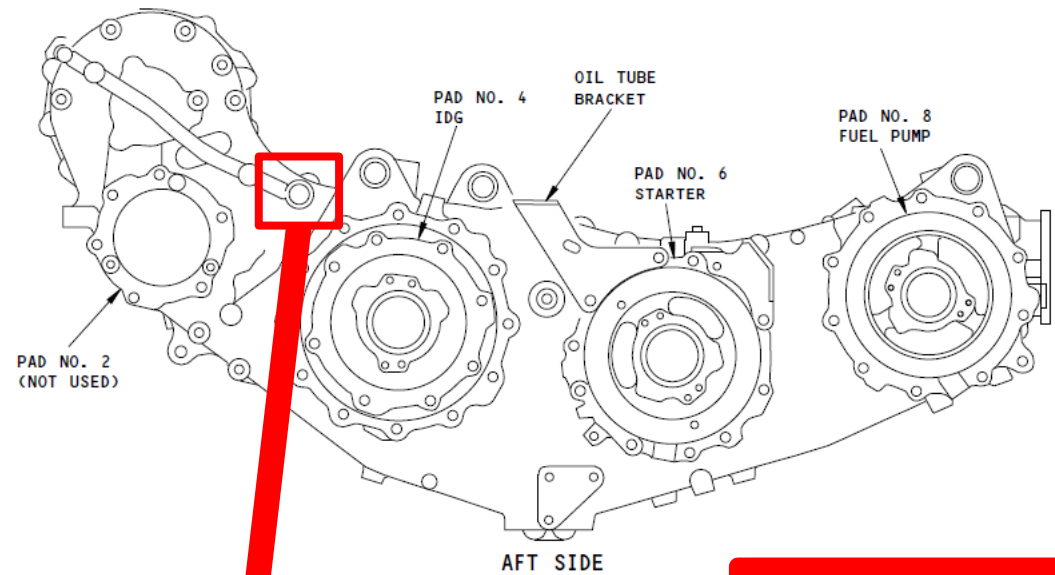
ABG Transverse link separated at the 7 o'clock position toward the center of the AGB.

- Unusual finding, link not previously reported broken



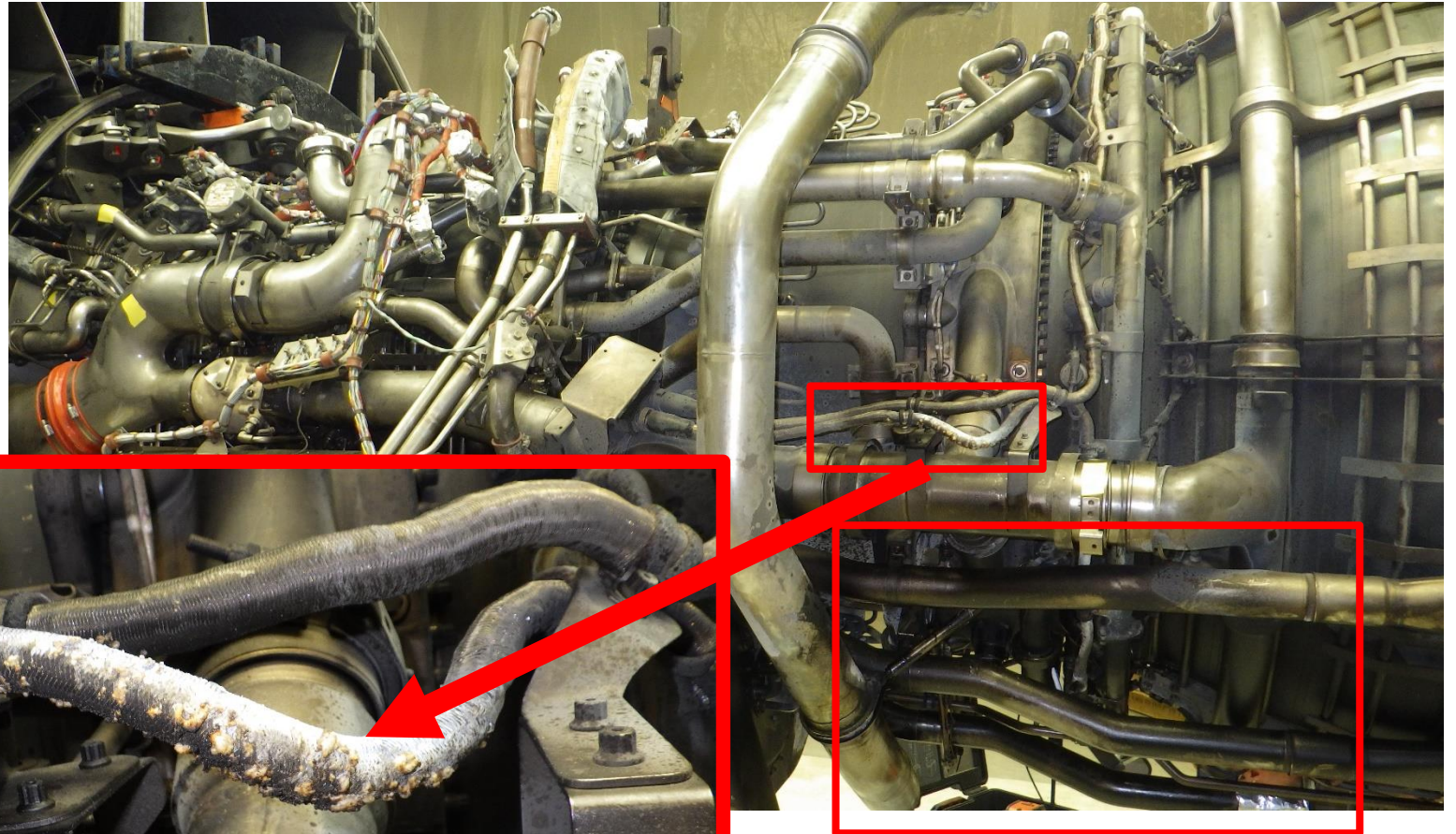
MAS Air Cargo ESN695440 Event – Engine Externals

Oil tube separated on the AGB at the 7 o'clock position (ALF).



MAS Air Cargo ESN695440 Event – Engine Externals

Evidence of heat distress can be seen on one Evidence of heat distress can be seen on various tubes and wiring harnesses at the 9 o'clock position (ALF)



Engine 695440 – Pre-Engine Teardown Summary

- No Fuel Leaks identified
- Fan/Rotor spun freely during BSI inspections
- HPC BSI shows no impact damage or missing airfoils.
- Several HPT Stage 1 Blades have mid cord burn thru, no missing airfoils or signs of impact damage.
- LPT has distress aft of the LPT Stage 1 Nozzles.
- LPT Stage 1 airfoil angel wing shows indications of rotor shift
- Stages 4 and 5 missing airfoil segments >50% with material observed between nozzle segments
- 2 missing LPT S5 Airfoils segments
- Broken AGB Link, Crack on cooling manifold, and broken Oil tube observed



LPT Stages 1-5 showed missing airfoils and nozzle distress



Broken Oil Tube on AGB

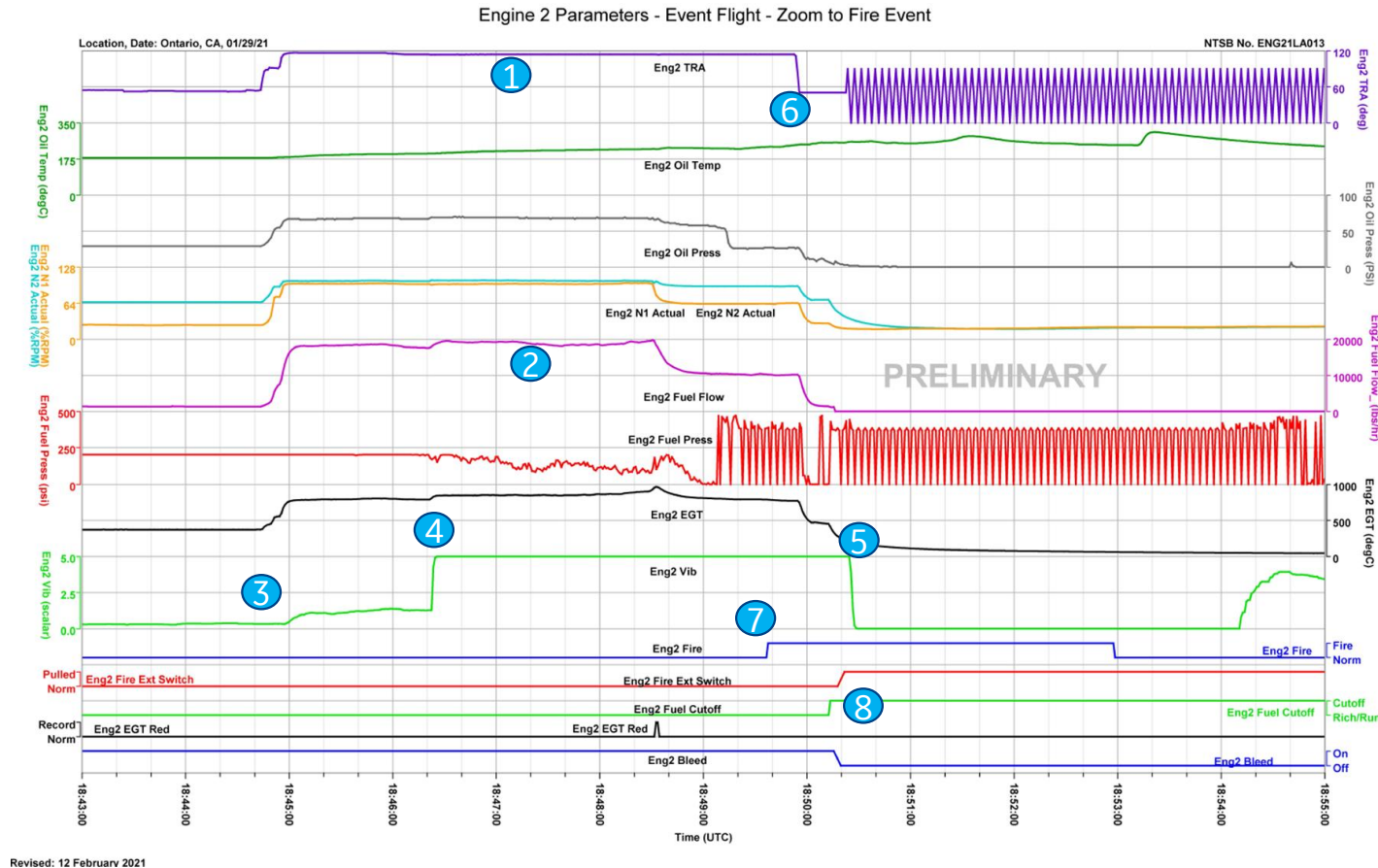
Observed hardware conditions prior to engine teardown focused investigation on the LPT module

Flight Data Analysis



MAS Air Cargo ESN695440 Event – DFDR Data Observations

1. TRA stable throughout event
2. No fuel flow changes prior to the event. Fuel Flow begins to fluctuate after event begins
3. Event engine within vibration experience prior to event
4. At time 18:46:20 step change in vibration from 1.3-5.0 CU maxing out indicator at 5.0 CU
5. Elevated vibrations continued for approx. 4 mins
6. Engine shut down initiated at 18:50
7. 3:30 minutes into event fire indication activated
8. Fuel cutoff and fire bottle pulled 40 second after indication.



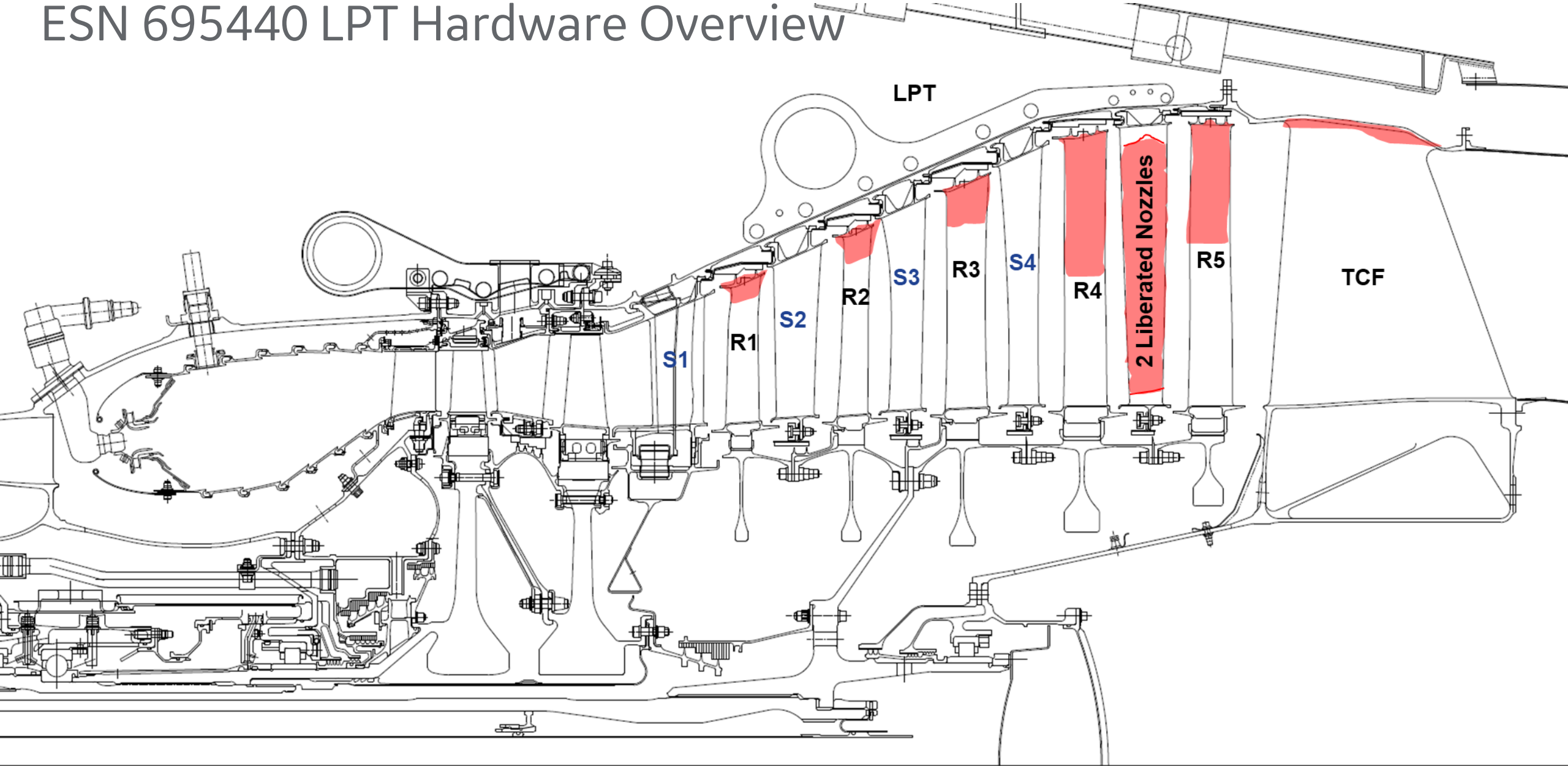
MAS Air Cargo ESN695440 Event –Teardown Investigation

Severe airfoil distress observed during BSI of LPT focused NTSB investigation on LPT disassembly

- LPT full disassembly
- Metallurgical failure analysis
- LPT vibratory study in post event condition



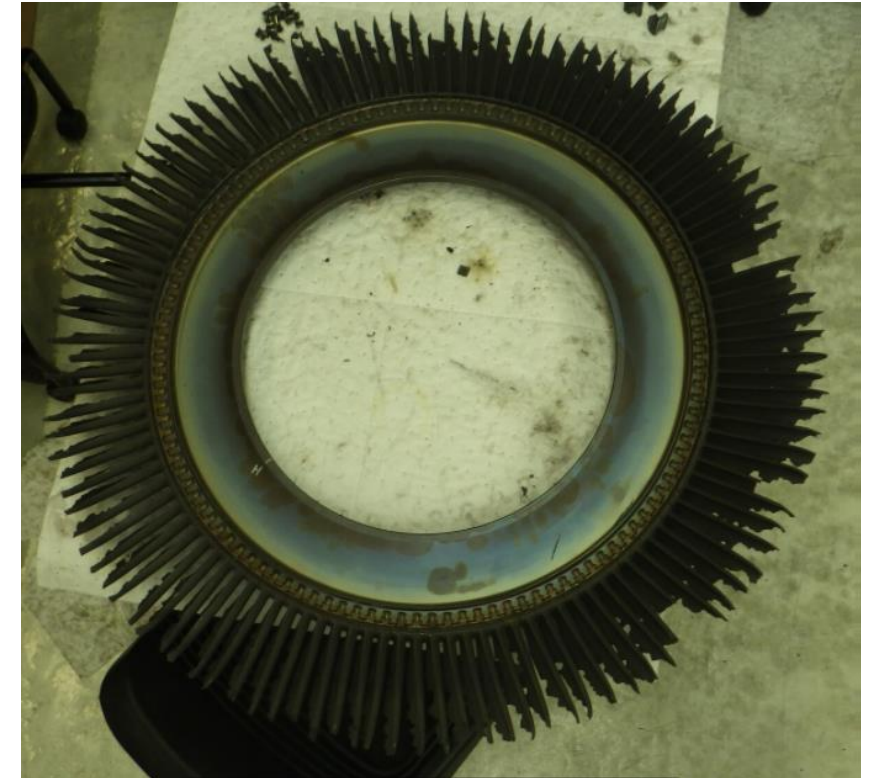
ESN 695440 LPT Hardware Overview



MAS Air Cargo ESN695440 Event – LPT Disk Stage 1



LPT Stage 1 Nozzles (Aft)



LPT Stage 1 Blades (Fwd)

MAS Air Cargo ESN695440 Event – LPT Disk Stage 2



LPT Stage 2 Nozzles (Aft)



LPT Stage 2 Blades (Fwd)

MAS Air Cargo ESN695440 Event – LPT Disk Stage 3

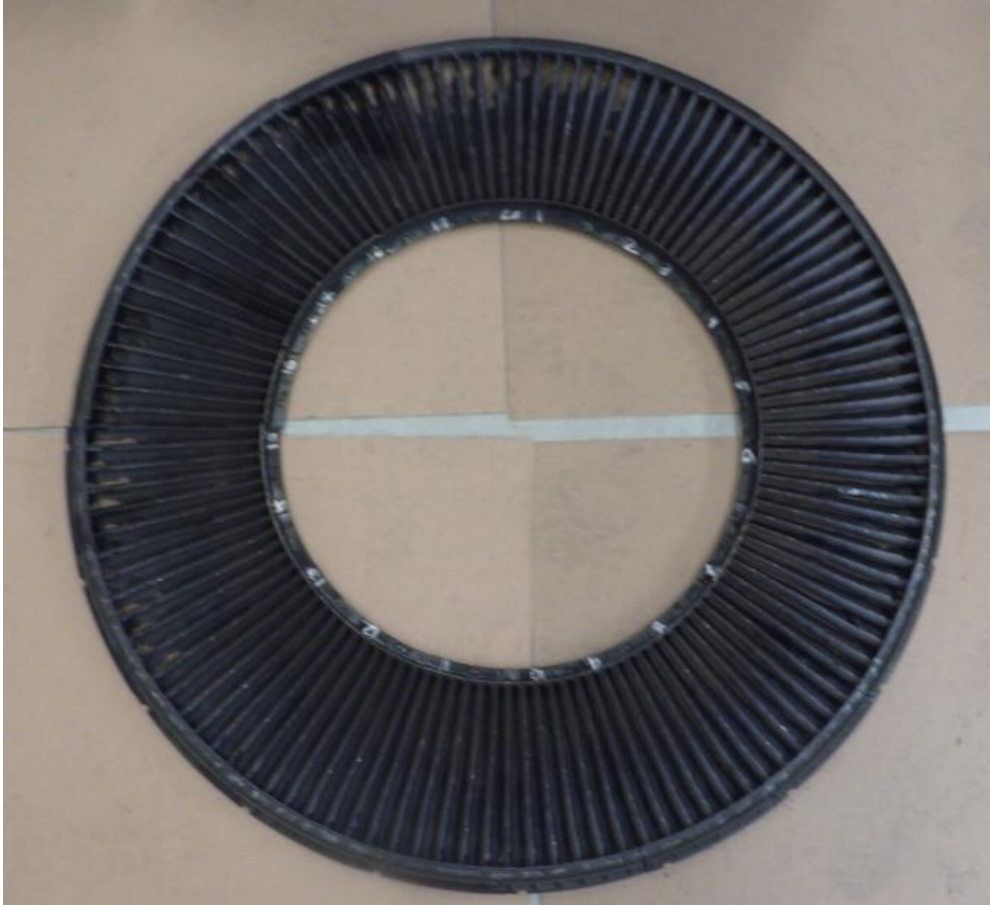


LPT Stage 3 Nozzles (Aft)



LPT Stage 3 Blades (Fwd)

MAS Air Cargo ESN695440 Event – LPT Disk Stage 4



LPT Stage 4 Nozzles (Fwd)



LPT Stage 4 Blades (Fwd)

MAS Air Cargo ESN695440 Event – LPT Disk Stage 5



LPT Stage 5 Nozzles (Aft)



LPT Stage 5 Blades (Fwd)

MAS Air Cargo ESN695440 - LPT Hardware Condition



All LPT blades had features consistent with overstress.

Metallurgical Investigation



MAS Air Cargo ESN695440 - LPT Stage 5 Nozzle

Overall view of stage 5 nozzle segment 3 with 2 missing airfoils.

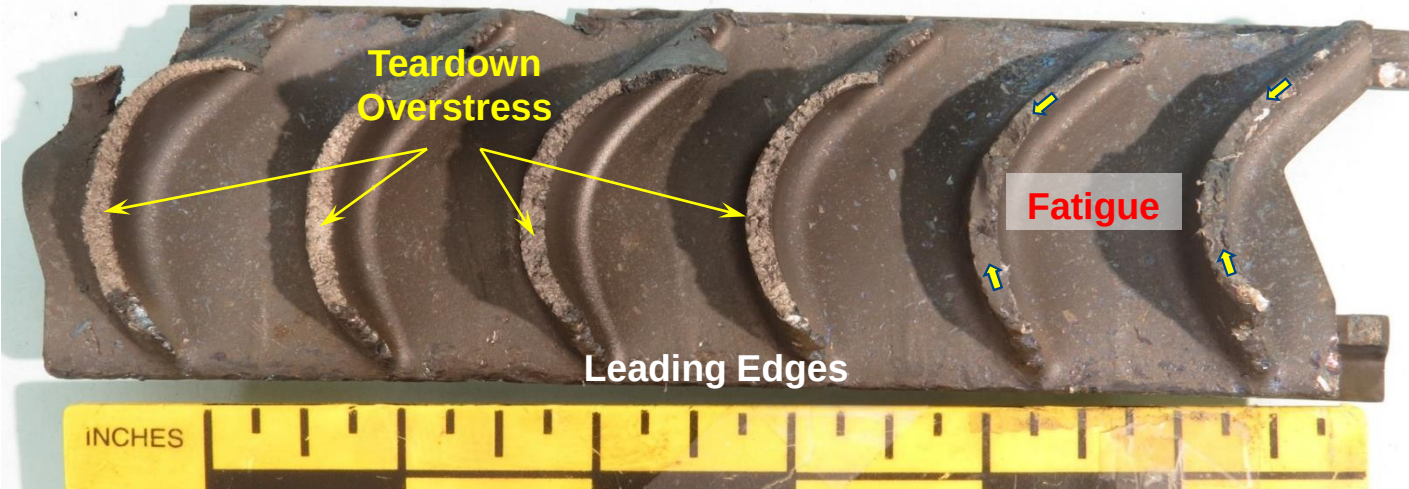
All 4 fracture surfaces had regions with fatigue with the outboard 2 fractures extending in toward /airfoils near the outer band radius.

On the inboard end one fracture extended at the airfoil base near the high-C (airfoil 6) and one extended from the airfoil leading and training edge areas.

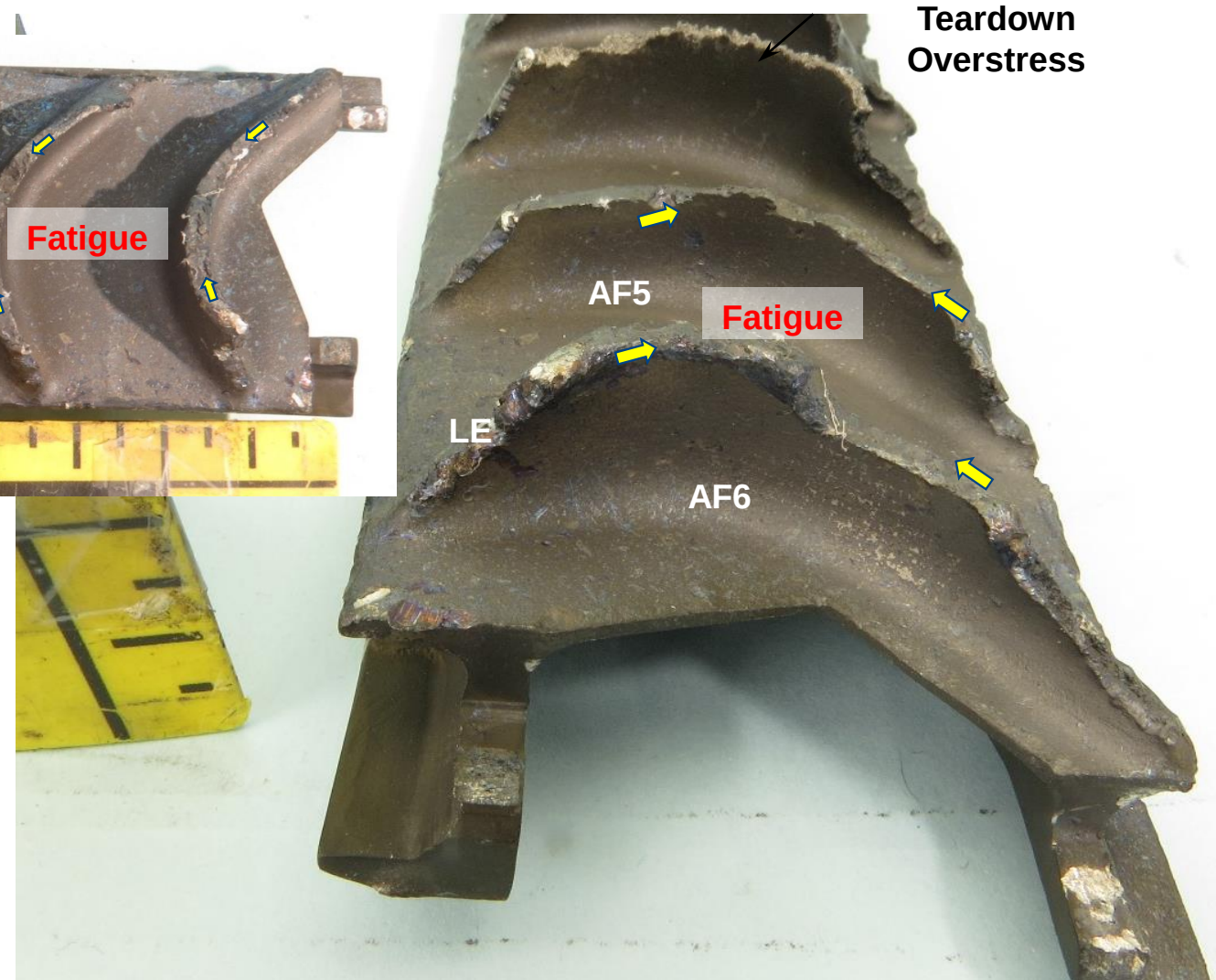


MAS Air Cargo ESN695440 - LPT Stage 5 Nozzle

Segment 3- Outer Band



Overall view of the outboard fractures showing that airfoils 5 and 6 had cracking extending in the airfoils near the tip extending from both the leading and trailing edges (that were damaged by post-fracture impacts).



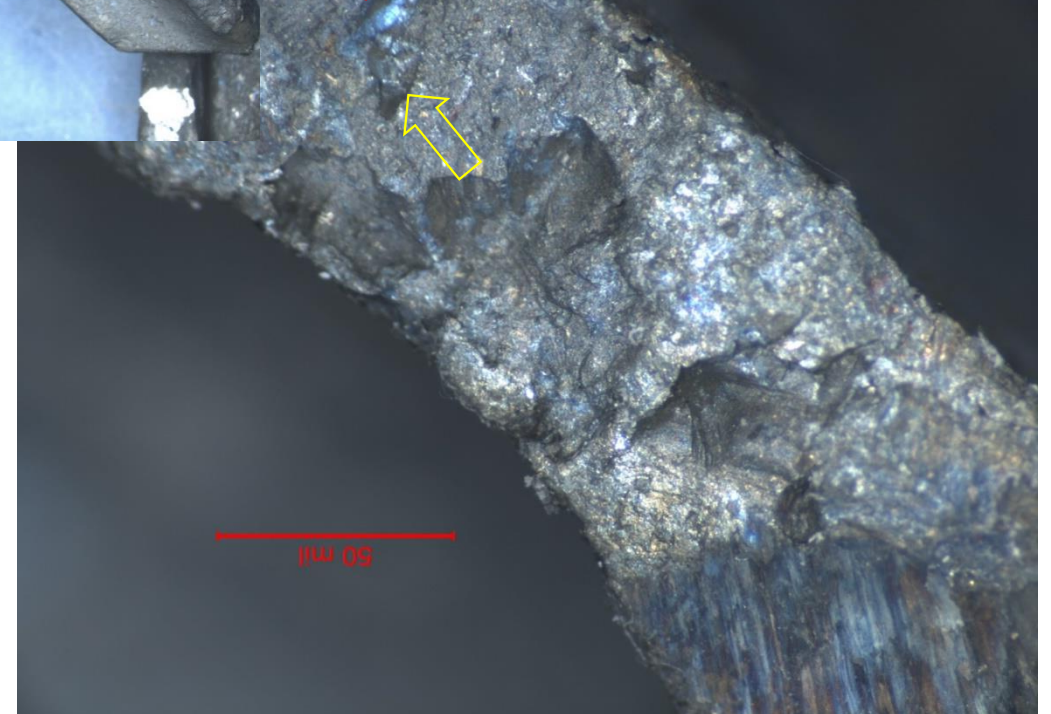
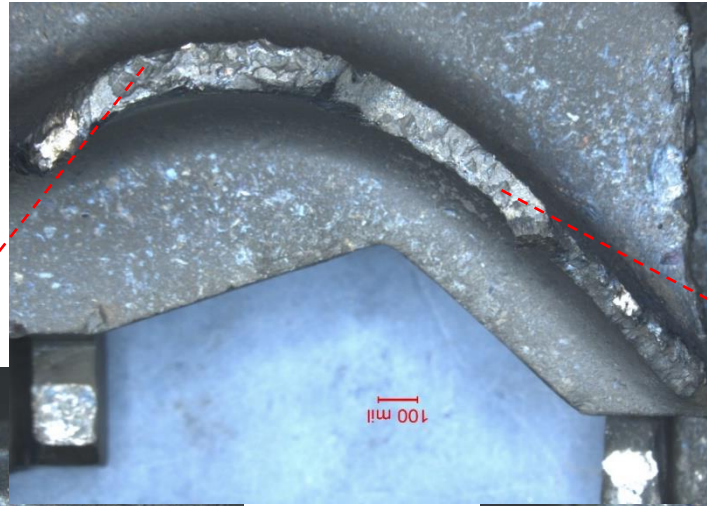
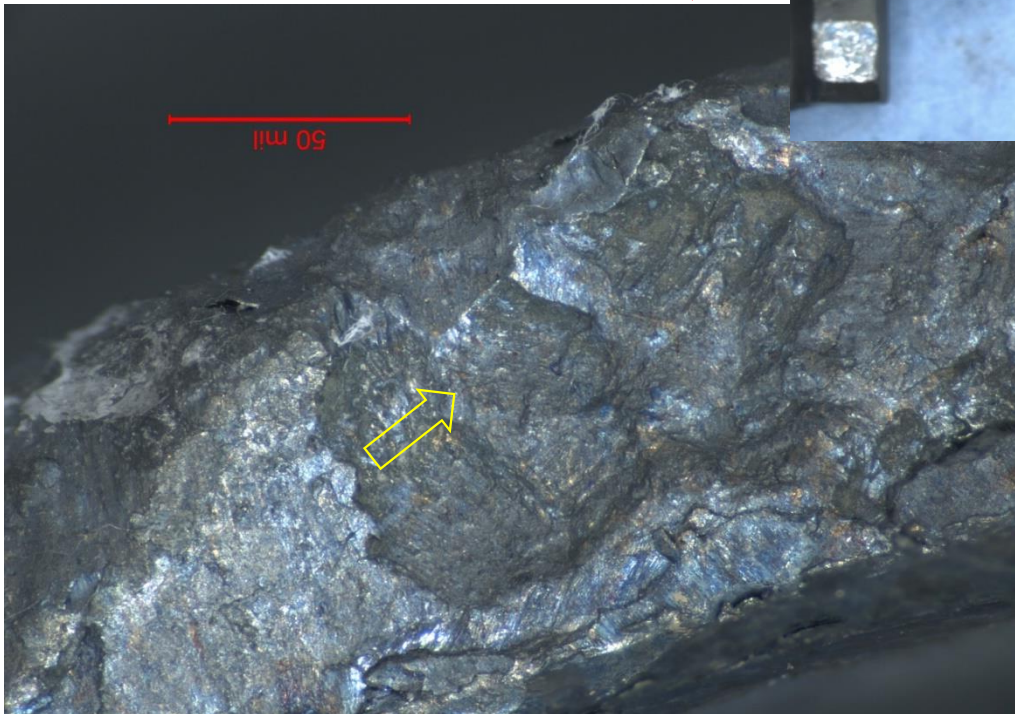
MAS Air Cargo ESN695440 - LPT Stage 5 Nozzle

Segment 3- Outer Band

AF6

LE

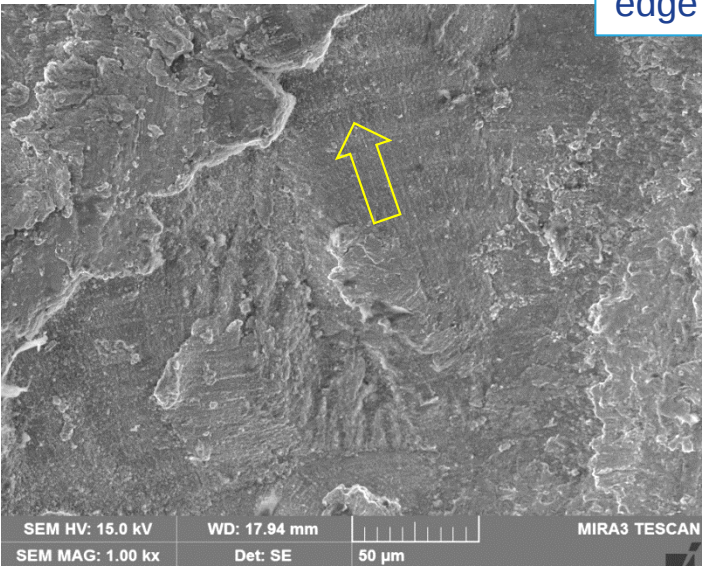
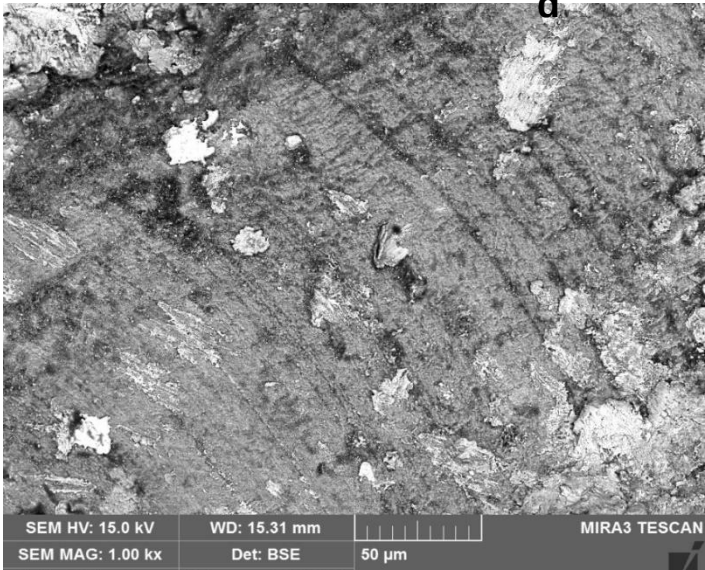
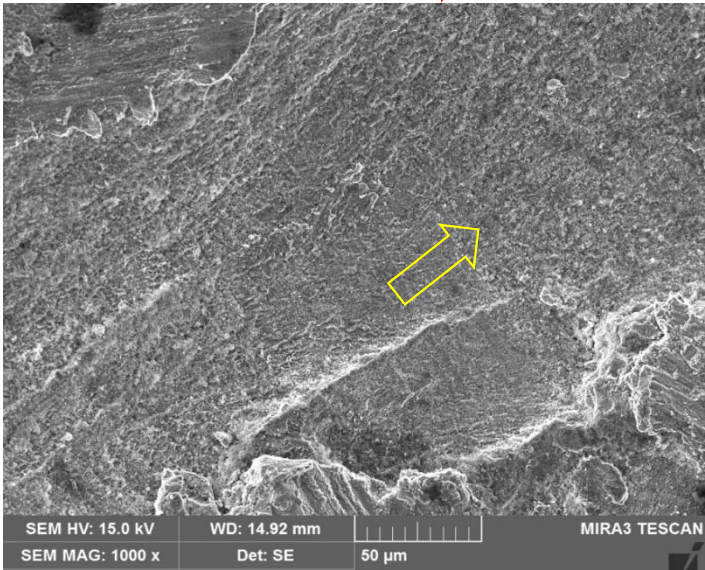
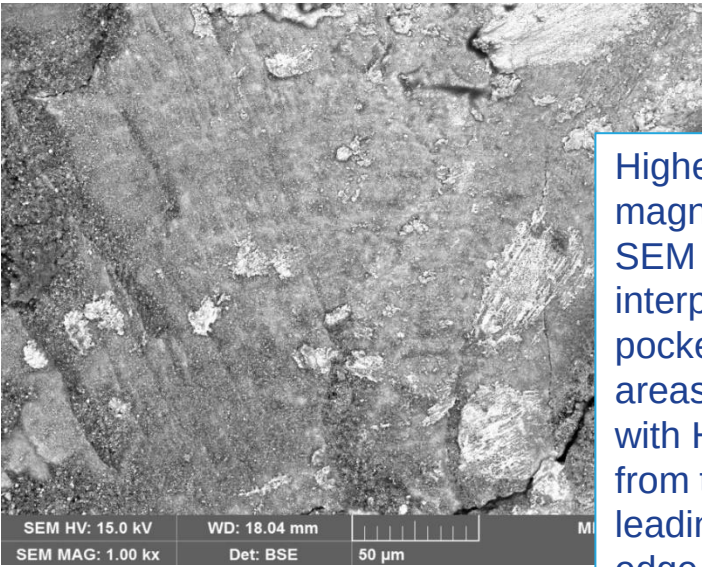
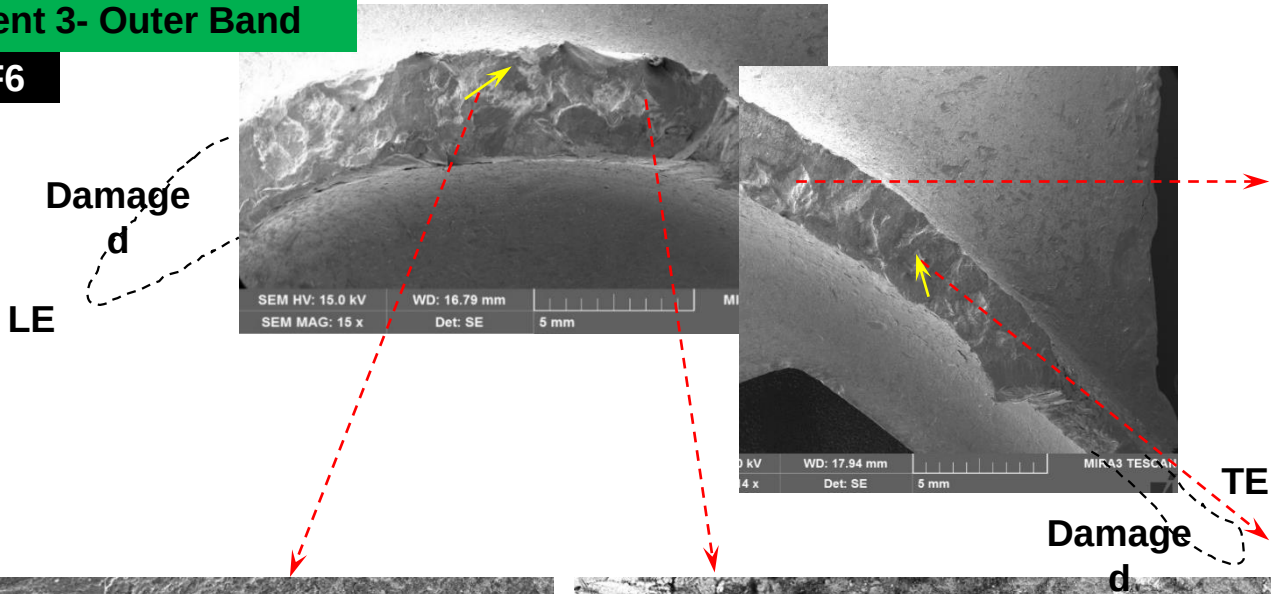
Optical views of the outboard fracture of airfoil 6 showing features consistent with fatigue growth extending from both the leading and trailing edge areas (also see next page). The majority of the fracture, however, was damaged by post-fracture impacts.



MAS Air Cargo ESN695440 - LPT Stage 5 Nozzle

Segment 3- Outer Band

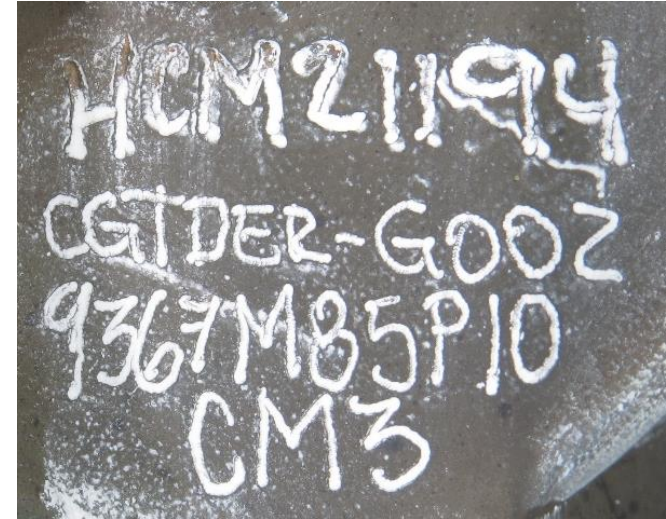
AF6



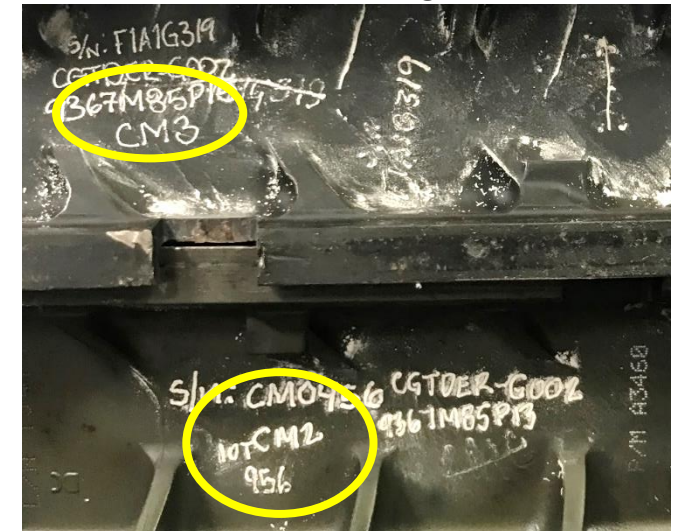
MAS Air Cargo ESN695440 - LPT Stage 5 Nozzle

Repair Codes

- The LPT5 vanes were last subjected to a full heavy maintenance in 2014.
- Repair documents show vanes were repaired per DAL Repair 01; Chromalloy DER Repair 93-CLA-002-17.
- Chromalloy confirmed the CGTDER-G002 marking does indicate the DER repair 93-CLA-002-17
- LPT Stage 5 Nozzles repaired outside CF6-80C2 ENGINE MANUAL GEK92451 procedures.

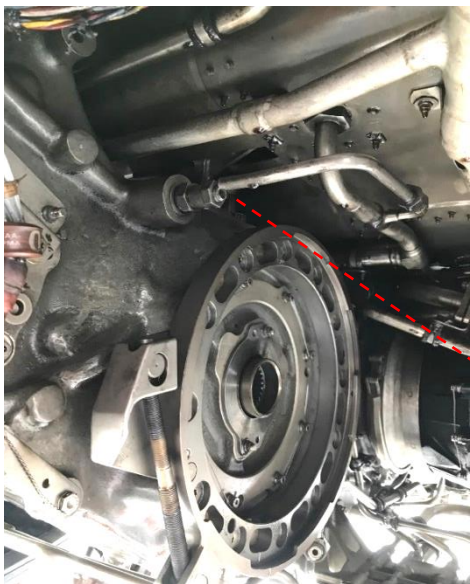


Nozzle segment 3



Nozzles 2 and 4

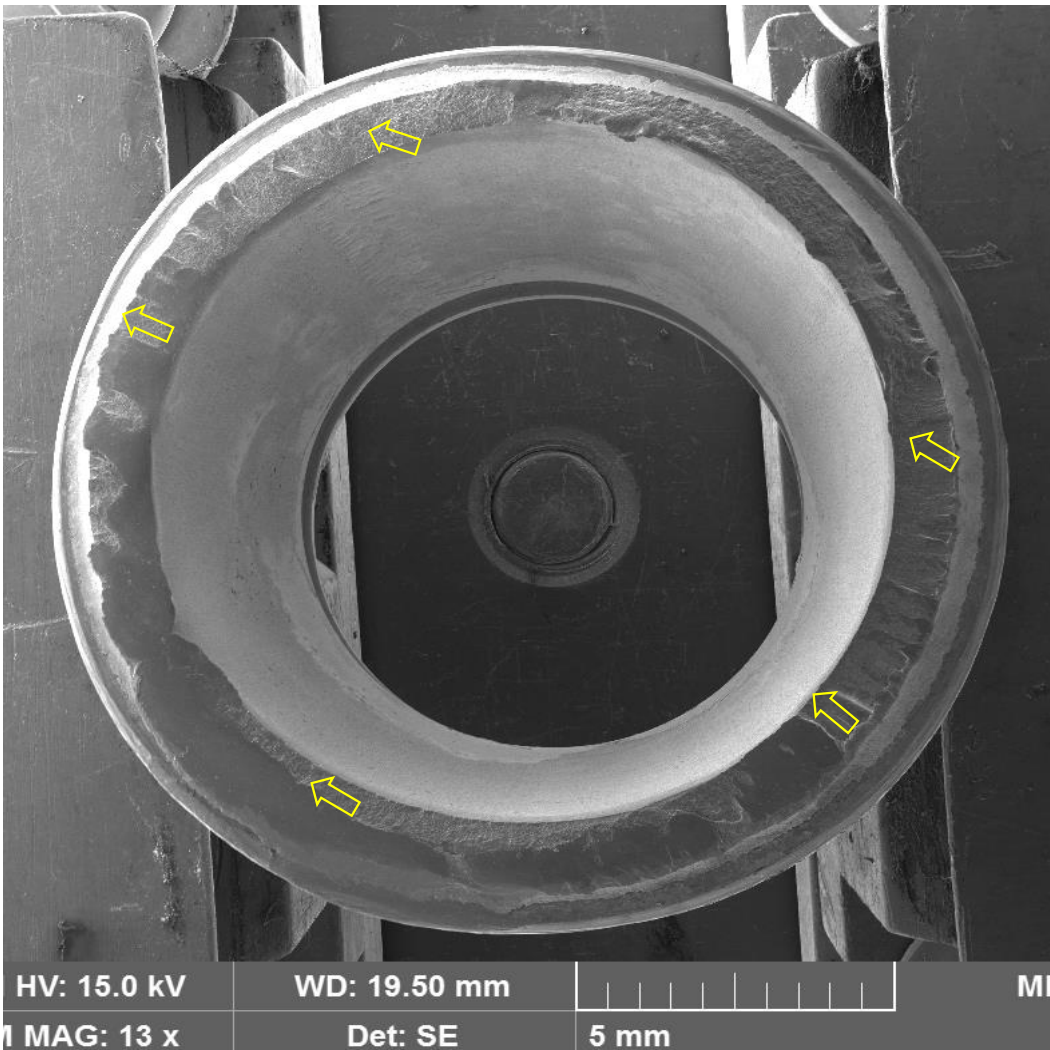
MAS Air Cargo ESN695440 – Oil Tube



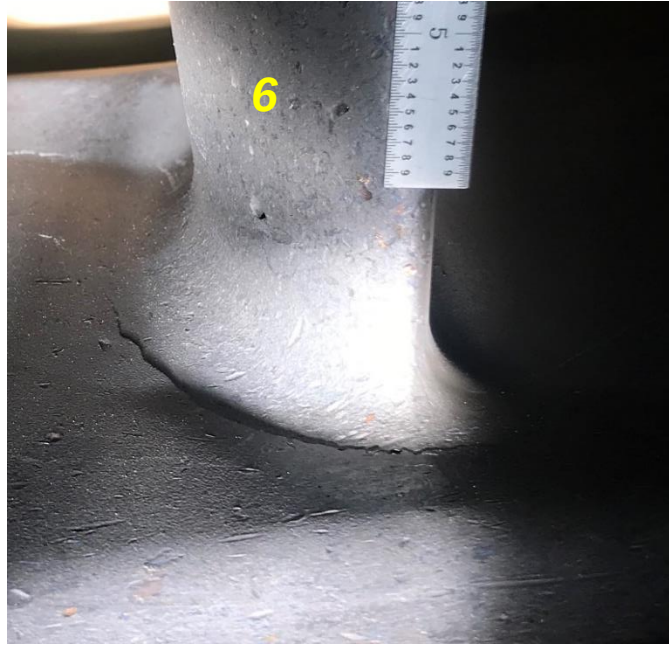
ALF at angle



Fractured oil tube showing plastic deformation and a planar fracture consistent with fatigue/cyclic tensile.



MAS Air Cargo ESN695440 – TRF struts



Cracking around the TRF struts showing bulk deformation and rough fracture features consistent with overstress.

MAS Air Cargo ESN695440 Event – Unbalance Calculation

Purpose:

Calculate level of unbalance of the LPT rotor during event.

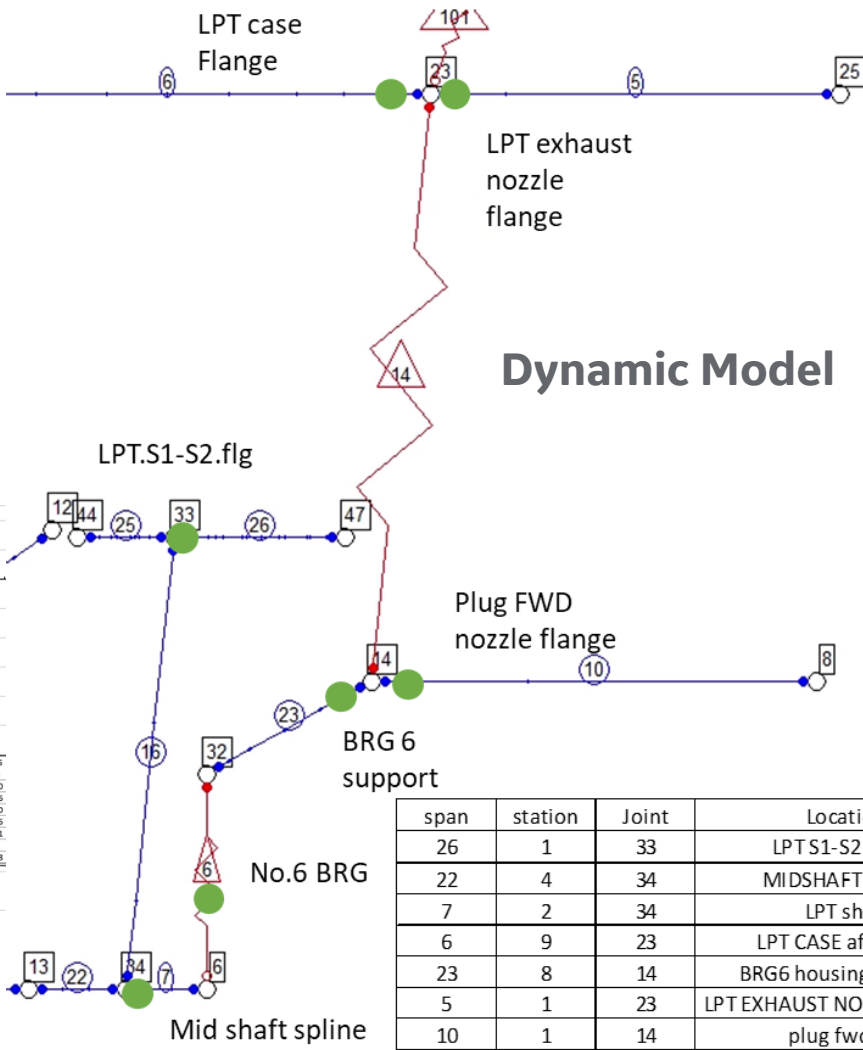
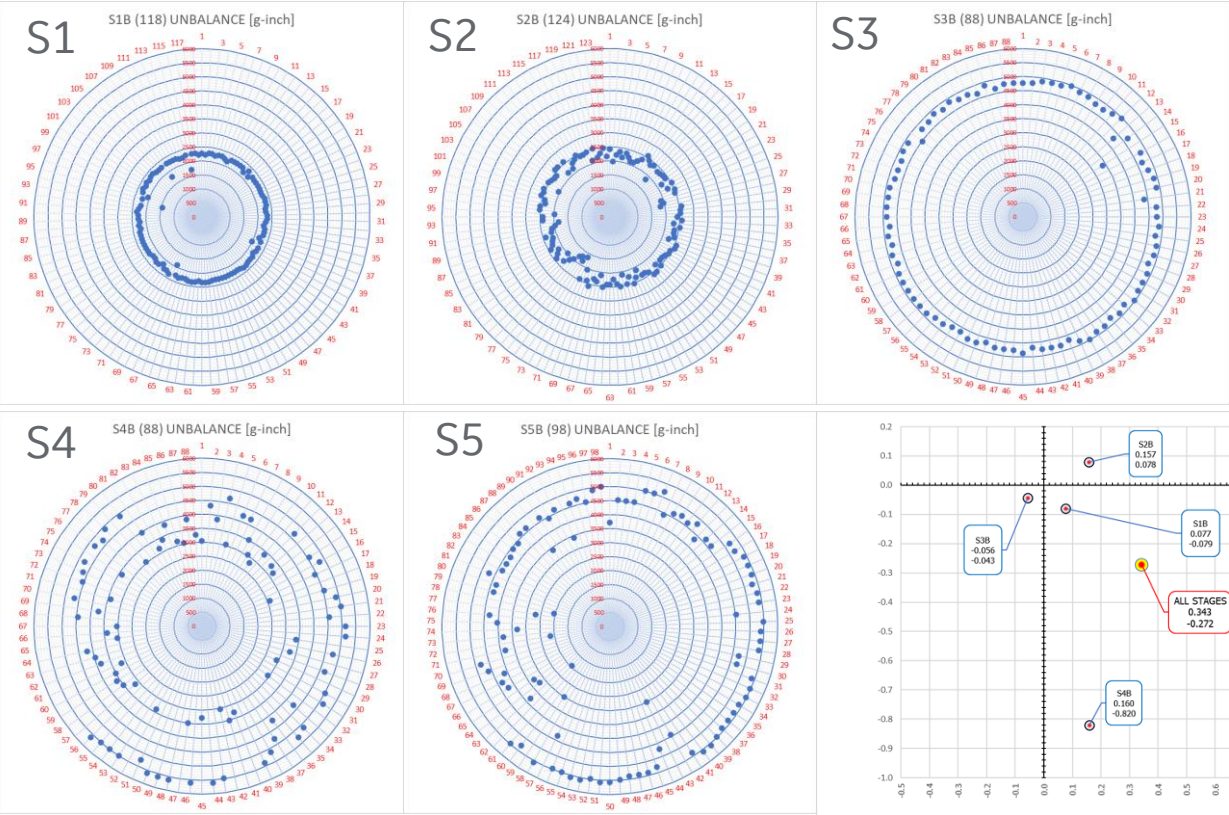
Assumptions:

- Calculation does not take into hardware debris collected /captured in LPT rotor.
- Unbalance calculation is for as-is-rotor post event only. Peak unbalance during event cannot be calculated.
- LPT airfoil lengths measured as-is for input into unbalance calculation.

Results are compared to known unbalance loads. Fan Blade Out (FBO) and LPT Blade Out (BO) loads for reference only.



CF6-80C LPT Unbalance calculation



Radial plots show worst damage and unbalance present in LPT Stages 4 & 5



MAS Air Cargo ESN695440 Event – Unbalance Calculation Results

Loads comparison FBO/ LPT high unbalance / LPT BO / blade liberation unbalance

Results:

Event LPT unbalanced is approximately equal to a Fan blade out event and ~60% of LPT blade out.

**72 CU or 49 CU
depending on AVM scale**

LPT Stage	Deflection/Amplitude at 3,750RPM, Event LPT as Disassembled (mils)
LPT Stg. 1	578
LPT Stg. 2	581
LPT Stg. 3	603
LPT Stg. 4	646
LPT Stg. 5	683

Damaged rotor amplitudes for each stage >0.500.
Normal running clearances (0.080-0.120)

- LPT unbalance loads are comparable to Fan and LPT blade out loads
- Unbalance is sufficient to result in heavy rubs/damage from rotor stator contact



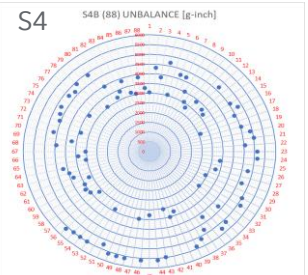
MAS Air Cargo ESN695440 Event – Most Likely Failure Sequence



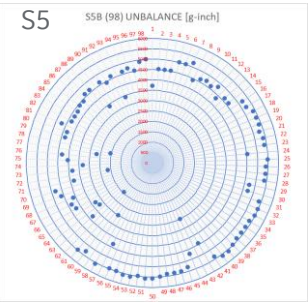
1. LPT S5N liberated 2 airfoils.



2. Failure leads to secondary damage to LPT S4&5

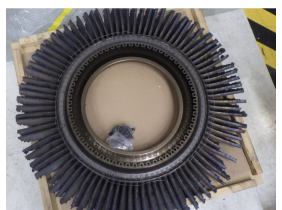
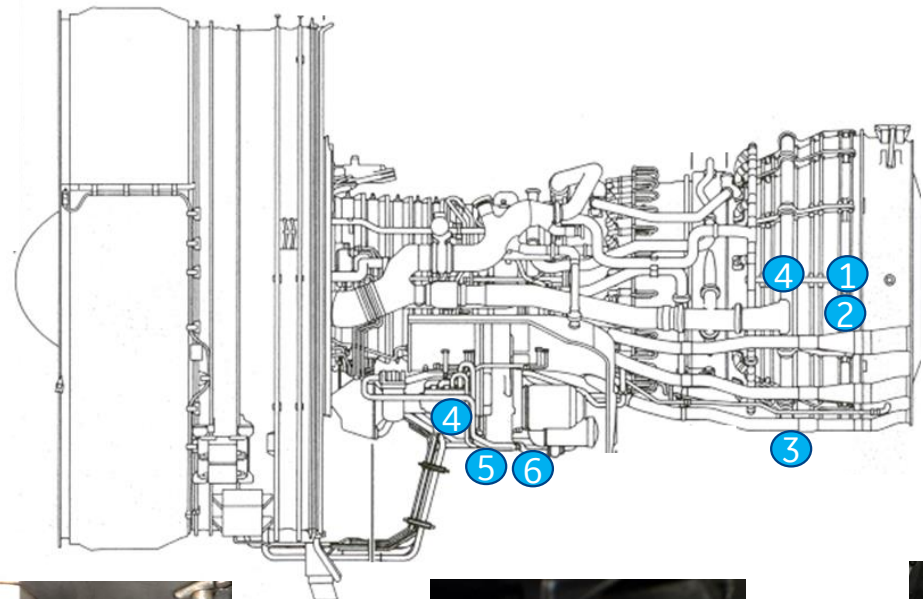


3. Rotor imbalance, 50+ CU



LPT S5N initiated failure led to secondary damage to LPT S4. Ultimately leading to 50.0+ CU rotor imbalance.

Secondary damage includes LPT Fwd. Stages, exhaust nozzle, TRF cracking, broken ABG Transverse link and broken oil line resulting in engine oil fire.



4a. LPT S1,2,3 Severe rubs, airfoil cracking at midspan



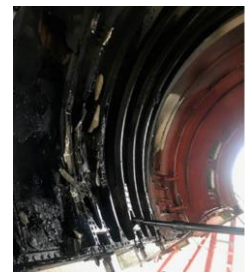
4b. Exhaust nozzle, TRF cracking



4c. Broken ABG link



5. Broken Oil Line

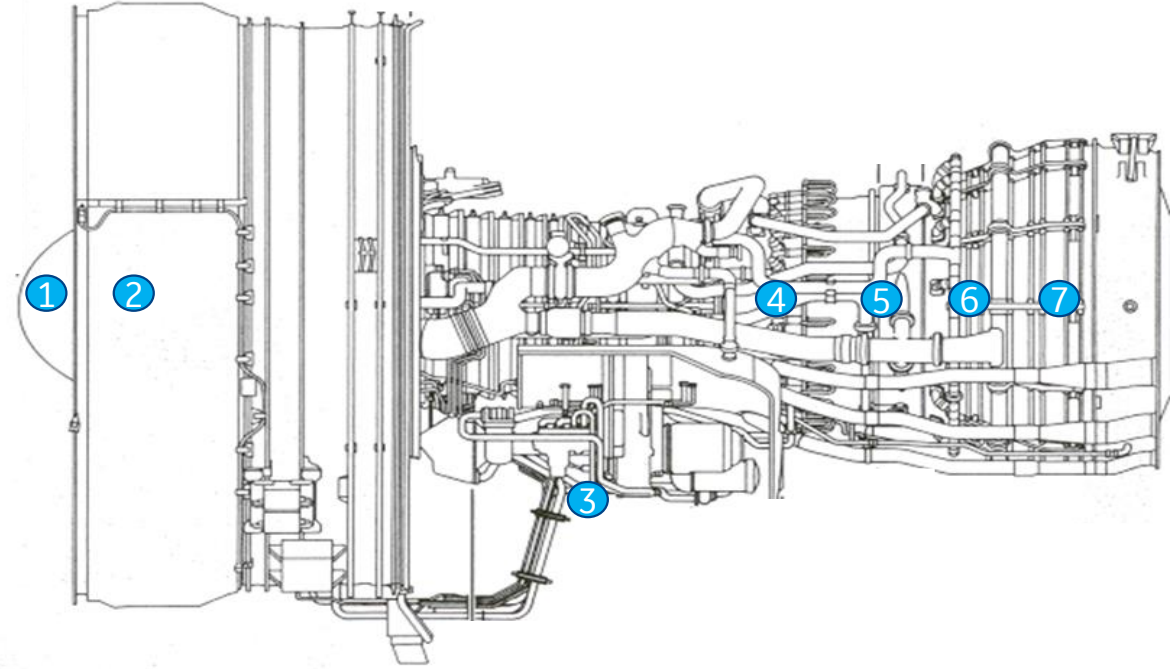


6. Oil Fire



MAS Air Cargo ESN695440 Event – Alternate Failures Evaluated

1. **Shaft separation** – Fan rotated freely, No issues during BSI inspection
2. **Bearing Failure** - Fan rotated freely, No issues during BSI inspection
3. **Fuel Leak** – Fuel Leak check passed
4. **Combustor** – BSI of combustor showed no signs of distress or Hot streaks
5. **Missing HPT Airfoils** – BSI showed some HPT S1 blade distress but confirmed no missing airfoils or failures which could contribute to high vibration
6. **LPT Stage 1-3 Airfoil separation** – No blades with under platform separation or missing airfoils observed during teardown
7. **LPT Disk separation** – Disk were intact during disassembly.



MAS Air Cargo ESN695440 Event – Summary

- No missing airfoils observed during BSI forward of LPT S1 Nozzles observed
- Distress hardware concentrated in LPT module and TRF
- Vibration and imbalance from LPT S5 Nozzle airfoil liberation resulted in up to +50 CU of vibration for ~4 mins.
- LPT S5 Nozzles with confirmed DER repairs shows fatigue
- Engine Controls and Fire suppression system worked as expected
- No uncontained hardware



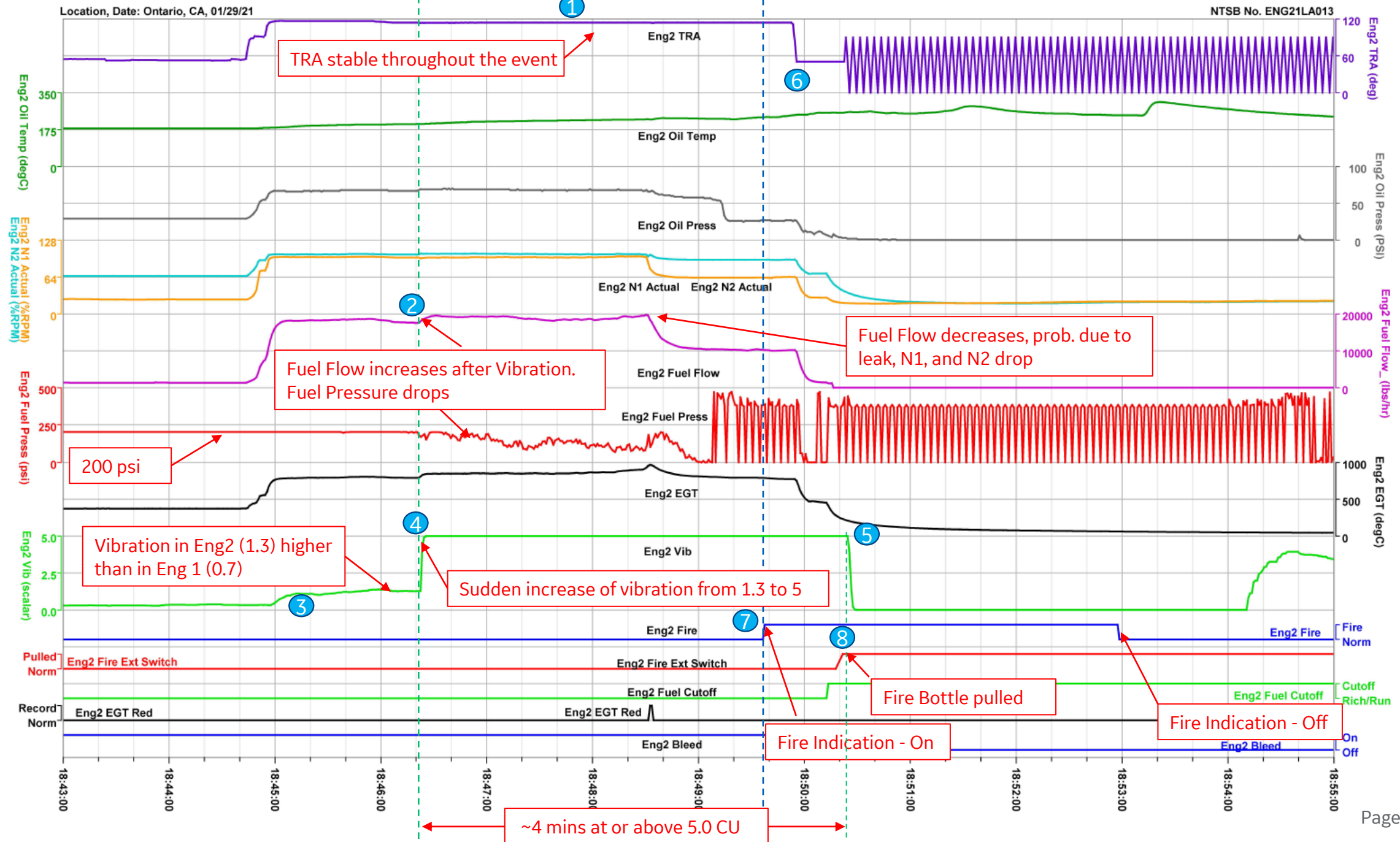
Most Likely Root Cause

LPT S5N initiated failure led to secondary damage to LPT S4. Ultimately leading to 50.0+ vibe units rotor imbalance. Secondary damage includes LPT Fwd. Stages, exhaust nozzle, TRF cracking, broken ABG Transverse link and broken oil line resulting in engine oil fire.



Appendix





Loads comparison FBO/ LPT high unbalance / LPT BO / blade liberation unbalance

			Historic Loads				LPT BO/ 1.5 FBO	LPT S1-S5 liberation		S1-S5 LPT /FBO	S1-S5 LPT /LPT BO
			1.5 BO 462,600gr-in		LPT-S5 BO 83,260gr-in						
Location	Type	unit	Speed	Amplitude	Speed	Amplitude	RATIO	Speed	Amplitude	RATIO	RATIO
CRF-FF (28,4)	DEFL	MIL DA	2,750	1,817	2,700	269	0.15	2,700	158	0.09	0.59
LPT.S1-S2.flg	SHEAR	LB PK	2,750	113,931	3,750	186,475	1.6	3,750	109,047	1.0	0.6
Mid.shaft.spline	SHEAR	LB PK	3,750	46,114	3,750	47,863	1.0	3,750	30,814	0.7	0.6
LPT.shaft.aft.spline	SHEAR	LB PK	2,750	181,901	3,750	289,803	1.6	3,750	180,642	1.0	0.6
LPT.case.aft.flg	SHEAR	LB PK	2,800	252,826	3,750	247,736	1.0	3,750	154,692	0.6	0.6
NO. 6 BRG	SHEAR	LB PK	2,750	187,235	3,750	295,691	1.6	3,750	184,336	1.0	0.6
NO. 6 BRG support	SHEAR	LB PK	2,750	198,907	3,750	300,878	1.5	3,750	187,578	0.9	0.6
Nozzle.fwd.flg	SHEAR	LB PK	2,750	70,661	3,750	37,342	0.5	3,750	23,128	0.3	0.6
plug.fwd.flg	SHEAR	LB PK	2,750	114,665	3,750	53,318	0.5	3,750	32,997	0.3	0.6
LPT.S1-S2.flg	MOM	IN-LB PK	3,750	862,671	3,750	1,323,920	1.5	3,750	787,844	0.9	0.6
Mid.shaft.spline	MOM	IN-LB PK	3,750	267,867	3,750	230,684	0.9	3,750	118,537	0.4	0.5
LPT.shaft.aft.spline	MOM	IN-LB PK	2,750	1,021,900	3,750	1,626,320	1.6	3,750	1,013,690	1.0	0.6
LPT.case.aft.flg	MOM	IN-LB PK	3,750	3,910,500	3,750	7,160,080	1.8	3,750	4,455,380	1.1	0.6
NO. 6 BRG	MOM	IN-LB PK	2,900	0	3,750	0	0.9	3,700	0	0.4	N/A
NO. 6 BRG support	MOM	IN-LB PK	2,750	2,236,810	3,750	3,498,150	1.6	3,750	2,180,770	1.0	0.6
Nozzle.fwd.flg	MOM	IN-LB PK	2,750	2,098,720	3,750	1,118,790	0.5	3,750	692,838	0.3	0.6
plug.fwd.flg	MOM	IN-LB PK	2,750	2,182,290	3,750	1,536,270	0.7	3,750	952,765	0.4	0.6
CC LPT STG-1	DEFL	MIL PK	2,800	1,160	3,750	898	0.8	3,750	578	0.5	0.6
CC LPT STG-2	DEFL	MIL PK	2,800	929	3,750	912	1.0	3,750	581	0.6	0.6
CC LPT STG-3	DEFL	MIL PK	2,800	704	3,750	967	1.4	3,750	603	0.9	0.6
CC LPT STG-4	DEFL	MIL PK	3,750	545	3,750	1,076	2.0	3,750	646	1.2	0.6
CC LPT STG-5	DEFL	MIL PK	3,750	498	3,750	1,171	2.4	3,750	683	1.4	0.6

72 CU or 49 CU
according AVM scale

Damaged rotor
amplitudes for each stage
~>0.500. Normal running
clearances ~(0.080-0.120)

- LPT unbalance loads are comparable to Fan and LPT blade out loads
- Unbalance is sufficient to result in heavy rubs/damage from rotor stator contact



