Leading Edge Protective Coating Against Fluid and Particulate Erosion for Turbofan Blades

(Public Only)

Presented to: FAA Office of Environment and Energy

By: Delta TechOps (DTO)

GKN Aerospace (GKN)

MDS Coating (MDS)

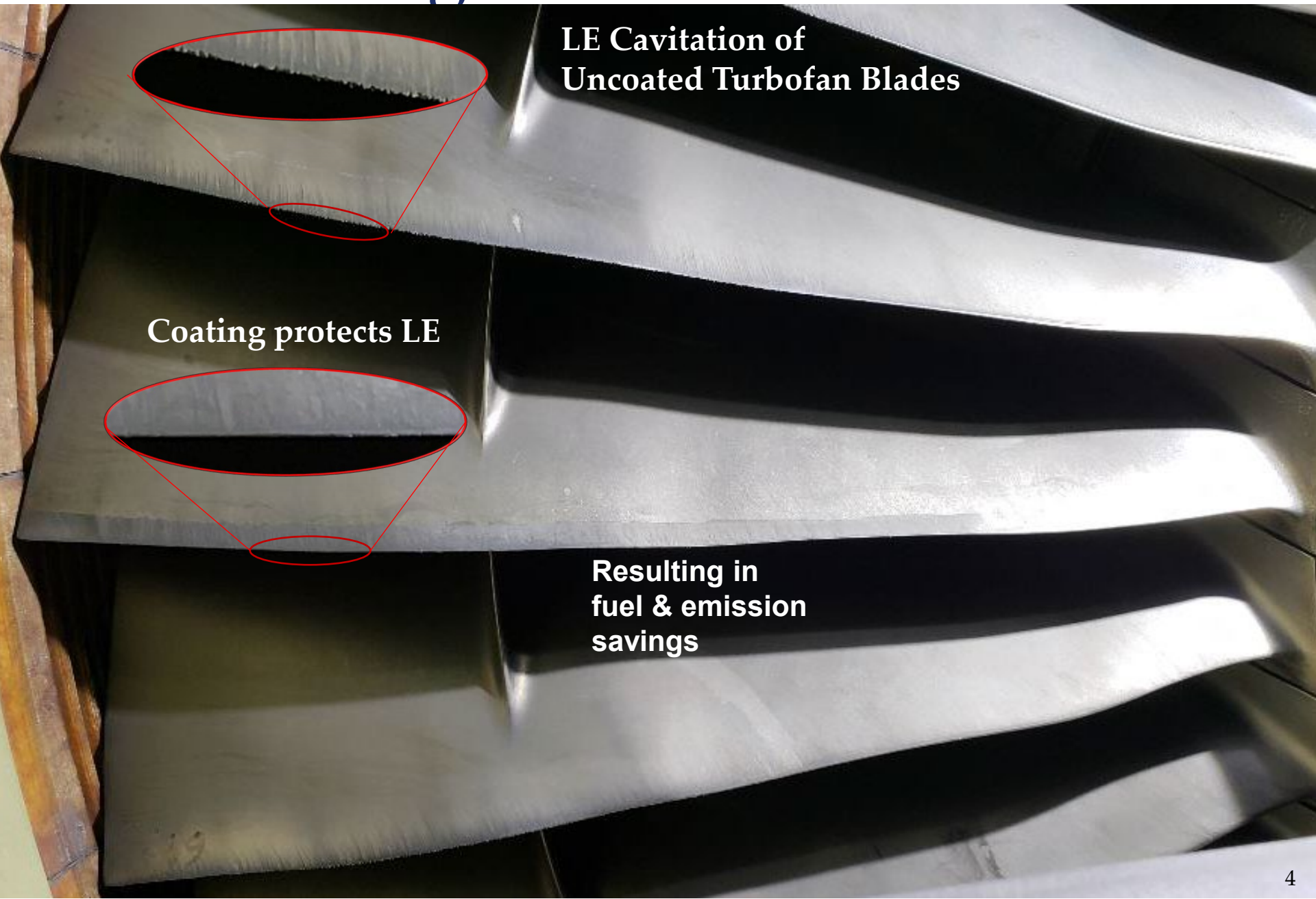
America's Phenix, Inc. (AP)

Date: 16 November 2022

The Problem – LE Cavitation

Due to water ingestion on take-off

CLEEN II Flight Demo



Project Overview

Objective - Demonstrate MRL & TRL 8-9 the application of a LE protective coating for all Turbofan Blade configurations:

High AR Blades

LE Ti Strips

Hollow Fan Blades

LE Repair and Low AR Blades

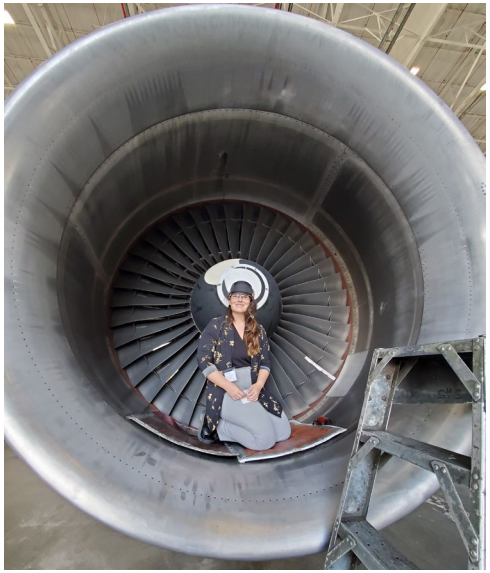
Schedule (Overview)

- **Phase I – Data Gathering (throughout CLEEN III program)**
  - Blade Condition Analysis on inducted and on-wing engines and TF blades at GKN
  - Engine Tests: V2500,
  - CFD Analysis: CFM56, CF34, CF6 or PW4000, Geared Turbofan
- **Phase II – Coating Optimization Tests – COMPETED MARCH, 2023**
  - Conduct tests at AFRL Supersonic Rain Erosion (SuRE) Rig
- **Phase III – Flight Certification (PW2000 by 1Q, CY23)**
  - Certification & Test Plan
  - Metallographic Analysis
  - **Fatigue testing**
  - Mechanical Testing & Frequency Analysis
  - Impact Tests
  - Instructions for Continued Airworthiness (ICA) analysis
- **Phase IV – Flight Demo at TRL8-9 – Fully Coated 1st stage TF sets**
  - PW2000 on B757: supply by 2Q, CY23 and install by 3Q, CY23
  - Other engine types to follow

Phase I – Data Collection

- Measured & photographed LE condition of various engines at DTO in Oct 2021 & Oct 2022
- Measured on-wing or on inducted blades for following engines:
  - PW2000
  - PW4000
  - CF34
  - CFM56
  - BR715
  - PW1100
  - Trent 1000
  - Trent XWB
- V2500 engine test @ United, 1Q / CY23
- V2500 measurements at IAD or DEN, 1Q / CY23

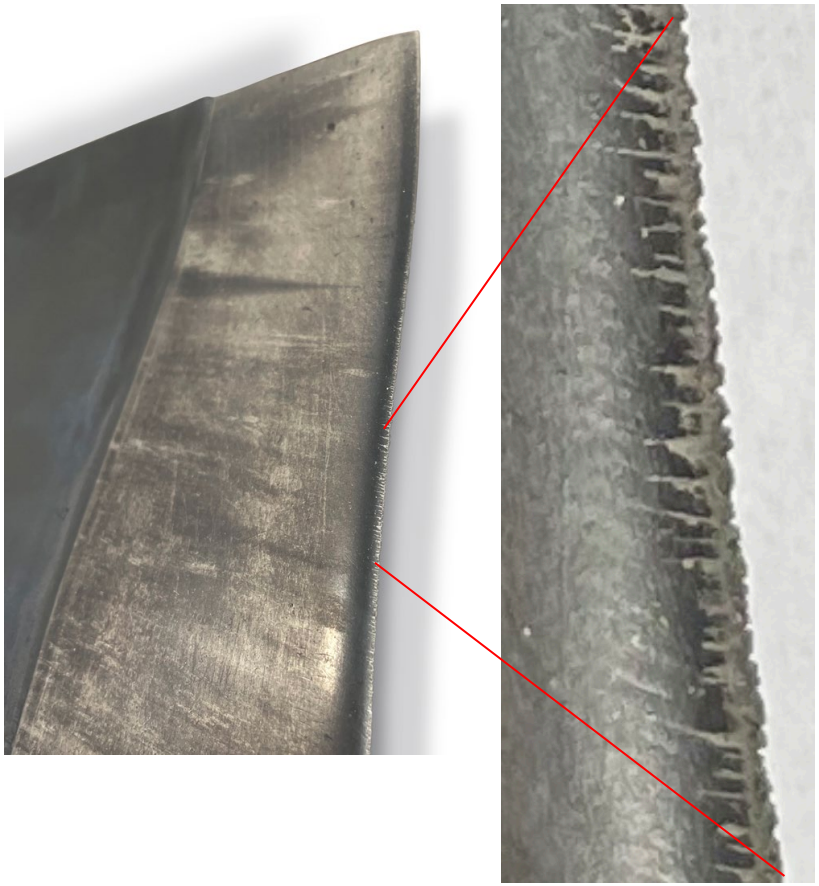
On-wing Repliset @ DTO



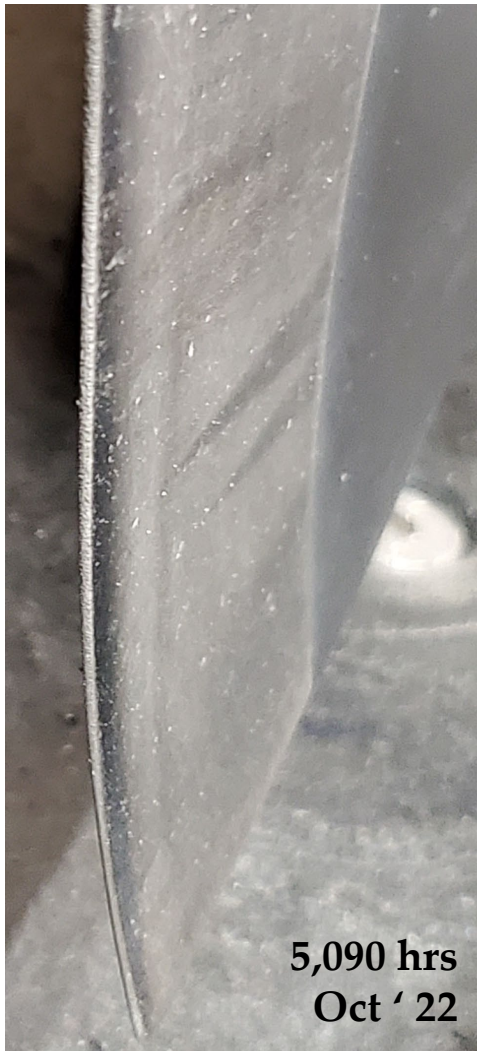
Measuring @ DTO

Phase I – Data Collection

PW1100, In-Shop at DTO



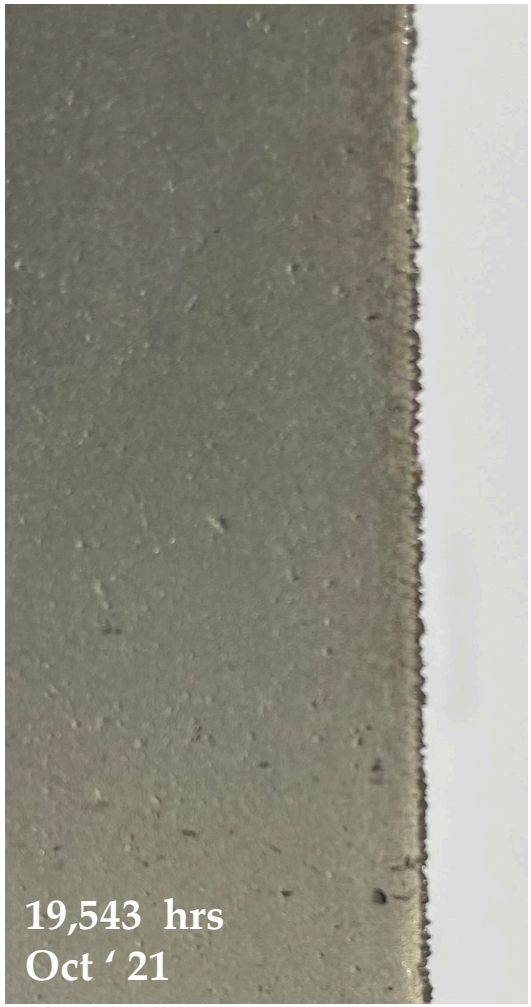
4,269 hrs
Oct ‘21



5,090 hrs
Oct ‘ 22

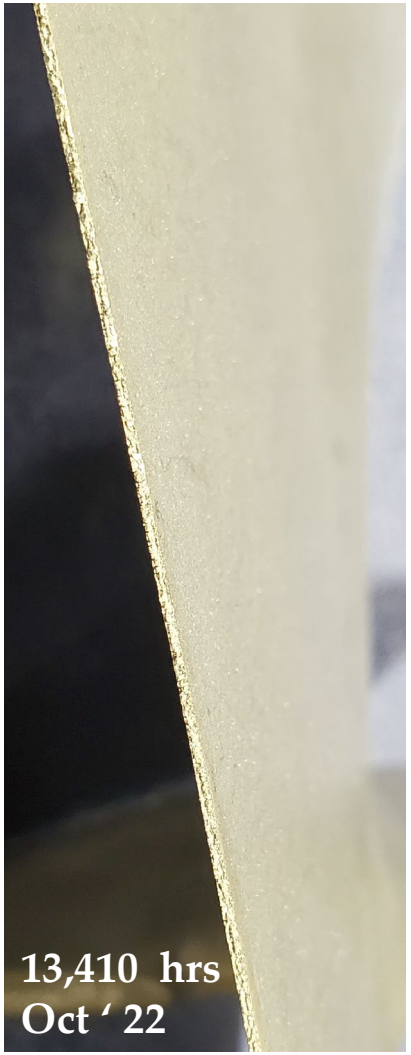
Phase I – Data Collection

CF34, Regional Jets @ DTO



Phase I – Data Collection

PW2000, B757 @ DTO



Phase I – Data Collection

CFM56s, On-wing @ DTO

Phase I – Data Collection

P-8 CFM56-7B, 1st stage TF Blades

A/C 559: 1,635.1 hrs
Eng S/N 362251

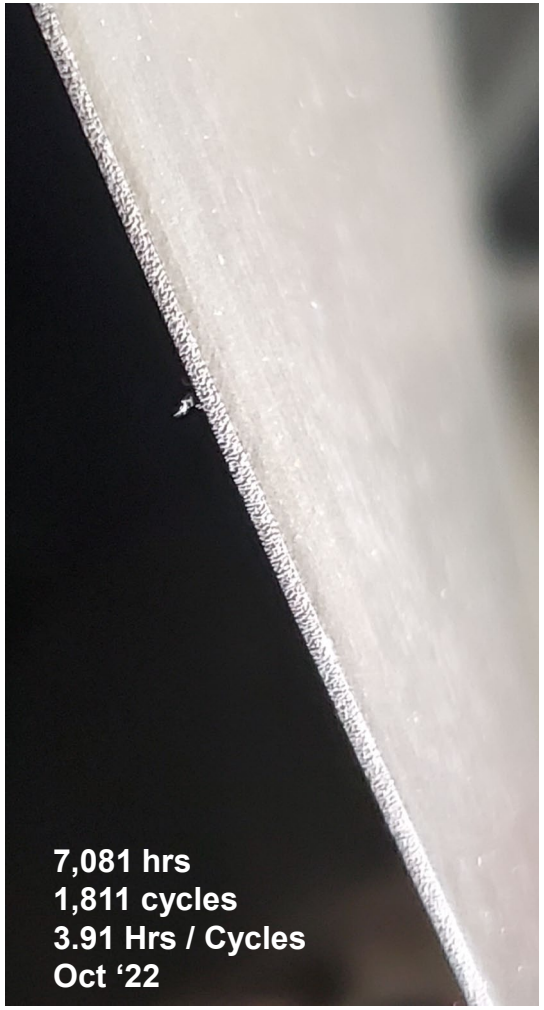
A/C 326: 3,521.9 hrs
Eng S/N 362181

A/C 764: 4,895.4 hrs
Eng S/N 362159

A/C 429: 8,184.1 hrs
Eng S/N 362372

Phase I – Data Collection

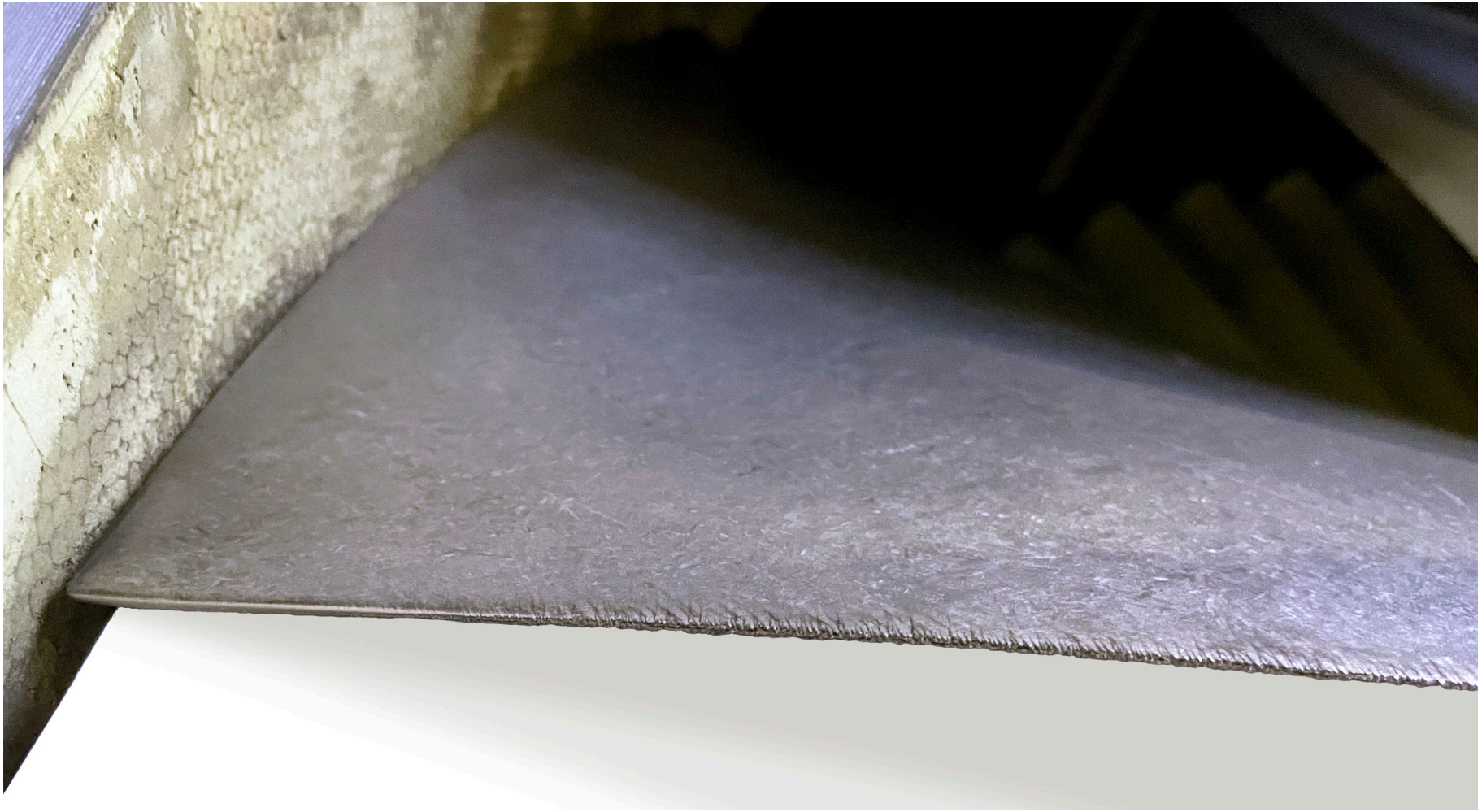
PW4000 @ DTO



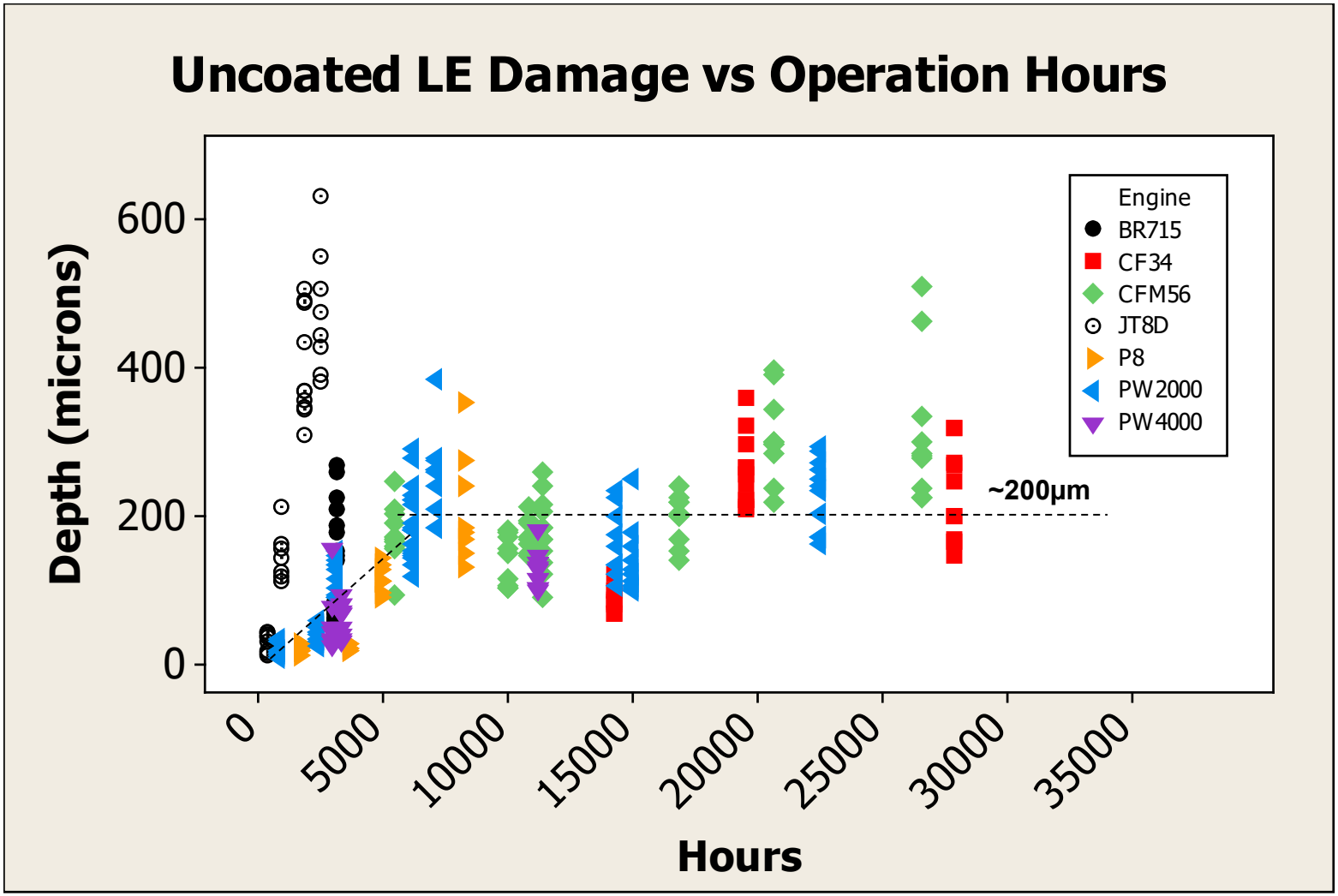
Phase I – Data Collection

Phase I – Data Collection

V2500, A320 On-Wing at United Tech Ops



Phase I – Data Collection



Phase I – Data Collection

	Location & Dates									
Engine	**PW2000**									
Location	In-Shop DTO	On-wing DTO	On-wing DTO	On-wing DTO	On-wing DTO	On-wing DTO	On-Wing DTO	On-wing DTO	On-wing DTO	In-shop DTO
Date	10-21-21	10-20-22	10-20-22	10-21-21	10-20-22	10-20-22				24-Oct-22
TF SN or AC #	728863	716516	716398	726621	?	726664	?	668	673	K28844
TSO (hrs)	22494.5	6146.76	6146.76	7060.04	760	14956.9	14,300	6,997	3,094	13,411
Cycles	4362	2391	2391	2952	332	5610				3,809
Hrs / Cycles	5.16	2.57	2.57	2.39	2.29	2.67				3.52
Avg Depth (µm)	232.000	190	190	262	19.5	139.5	168	119	41	
Engine	**CF34**									
Location	In-Shop DTO	In-Shop DTO	In-Shop DTO							
Date	10-20-21	10-20-21	25-Oct-22							
TF SN or AC #			194802							
TSO (hrs)	19,543	14,247	27933.37							
Cycles	15,864	10,887	20070							
Hrs / Cycles	1.23	1.31	1.39							
Avg Depth (µm)										
Engine	**CFM56-5**									
Location	On-Wing DTO	On-Wing DTO	On-wing DTO	On-wing DTO	InShop DTO	On-wing DTO	On-Wing DTO			
Date		10-21-21	SG	SG	Oct 25 2022	25-Oct-22	25-Oct-22			
TF SN or AC #			SG	SG	535516	733318	733288			
TSO (hrs)					8785.12	1593.17	390.48			
Cycles					3921	7776	264			
Hrs / Cycles			10,000	20,611	2	0.20	1			
Avg Depth (µm)			141	306						
Engine	**PW4000**									
Location	In-Shop DTO	On-Wing DTO	On-Wing DTO	In-Shop DTO	In-Shop DTO	On-Wing DTO	On-Wing DTO	On-wing		
Date	10-21-21	10-22-21	10-22-21	25-Oct-22	25-Oct-22	25-Oct-22	25-Oct-22	25-Oct-22		
TF SN or AC #	724372	733605	733565	729222	729223	724147	733558	735		
TSO (hrs)	3,291.13	2,952.43	11,209.63	17,290.28	7,080.82	24,309.48	15,049.00	13		
Cycles	530	510	1556	3600	1811	3367	2088	183		
Hrs / Cycles	6.21	5.79	7.20	4.80	3.91	7.22	7.21	7.0		
Avg Depth (µm)	62	58	127							
Engine	**PW1100**									
Location	In-Shop DTO	In-Shop	In-Shop							
Date	10-21-21	25-Oct-22	25-Oct-22							
TF SN or AC #		771207	771886							
TSO (hrs)	4269.39	5090.25	6489.75							
Cycles	2669	3524	4113							
Hrs / Cycles	1.60	1.44	1.58							
Avg Depth (µm)										
Engine	**V2500**									
Location	In-Shop UTO	On-Wing UTO								
Date	01-19-22	1-19-22								
TF SN or AC #										
TSO (hrs)										
Cycles										
Hrs / Cycles										
Engine	**BR715**									
Location	In-Shop DTO	In-Shop DTO	In-Shop DTO							
Date	10-20-21	24-Oct-22	24-Oct-22							
TF SN or AC #		13111	13363							
TSO (hrs)	2973	3856	3081							
Cycles	1334.15	3223	2767							
Hrs / Cycles	2.23	1.20	1.11							
Avg Depth (µm)										
Engine	**F117**									
Location	In-Shop United TO	In-Shop UTO	In-Shop UTO	In-Shop UTO						
Date	01-19-22	01-19-22	01-19-22	01-19-22						
TF SN or AC #	171003	170638	170676	171167						
TSO (hrs)	2,863	4,844	5,141	8,439						
Cycles										
Hrs / Cycles										
Engine	**CFM56-7**									
Location	In-Shop DTO	On-Wing DTO	On-wing DTO	On-wing DTO						
Date	25-Oct-22	25-Oct-22	25-Oct-22	25-Oct-22						
TF SN or AC #	962782	658191	874896	888630						
TSO (hrs)	26632	1229.22	26521	16827						
Cycles	12897	577	10183	6862						
Hrs / Cycles	2.06	2.13	2.60	2						
Avg Depth (µm)										

Data Collection continues …

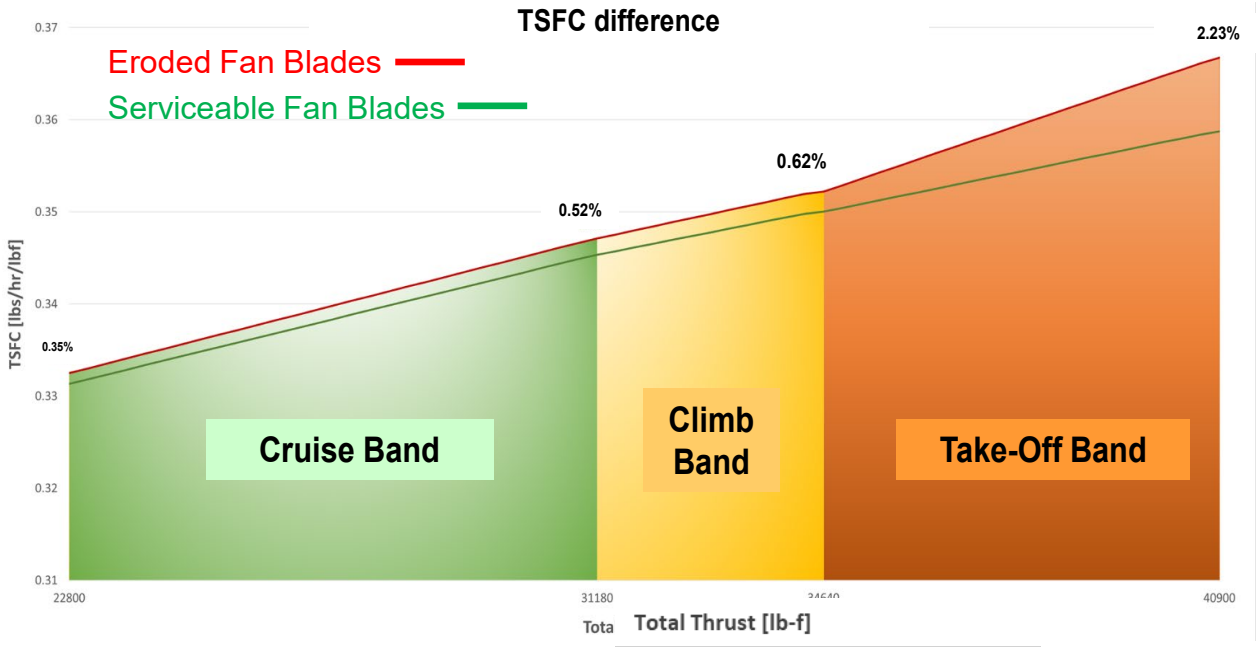
- Over 50 engines either photographed and / or measured
- Includes CFM56 & F117 military engines

Engine				
Location	In-Shop DTO	On-Wing DTO	On-wing DTO	On-wing DTO
Date	25-Oct-22	25-Oct-22	25-Oct-22	25-Oct-22
TF SN or AC #	962782	658191	874896	888630
TSO (hrs)	26632	1229.22	26521	16827
Cycles	12897	577	10183	6862
Hrs / Cycles	2.06	2.13	2.60	2
Avg Depth (µm)				

Phase I – Data Collection

Fuel Consumption Impact

- Isolated fuel consumption differences between eroded and serviceable fan blades on same inducted engine
- Delta completed tests on JT8D and PW2000 engines
- Quote received from United Air Lines conduct test on V2500
  - Scheduled for 1Q, CY23



Phase I Data Collection

Fuel Consumption Impact

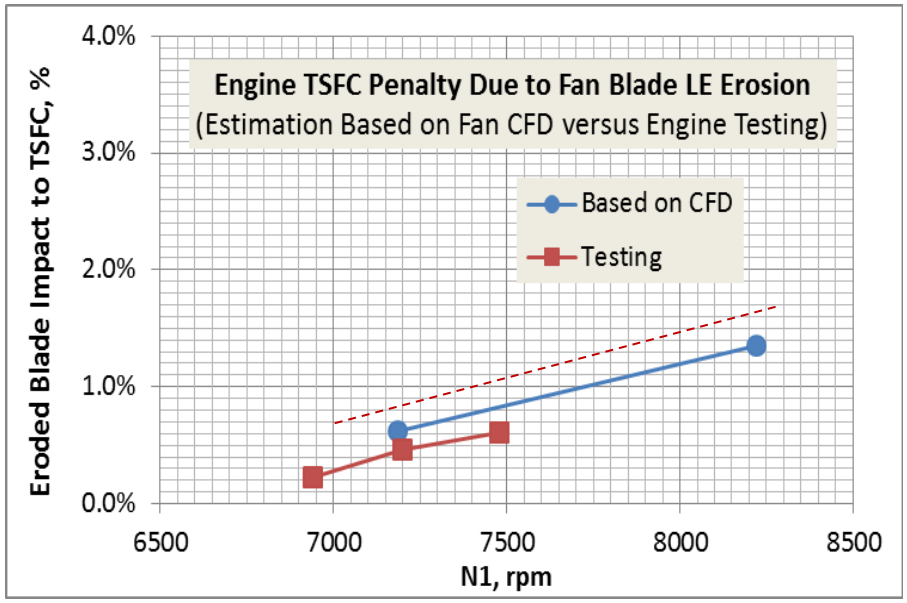
- Supplement engine tests with CFD analysis

CFD Work Scope

- U. Maryland to conduct CFD analysis on following engine types w/ restored & eroded LE:
  - V2500
  - CF34
  - CFM56
  - PW4000 or CF6
- Fan blade scans of restored and eroded LE to be supplied by Delta
- Boundary and operational conditions to be supplied by Delta & United
- CFD Analysis will compare results from one engine test
  - Probably compare to V2500 but could be another engine

Phase I – Data Collection

Engine Test Data vs CFD Analysis TSFC



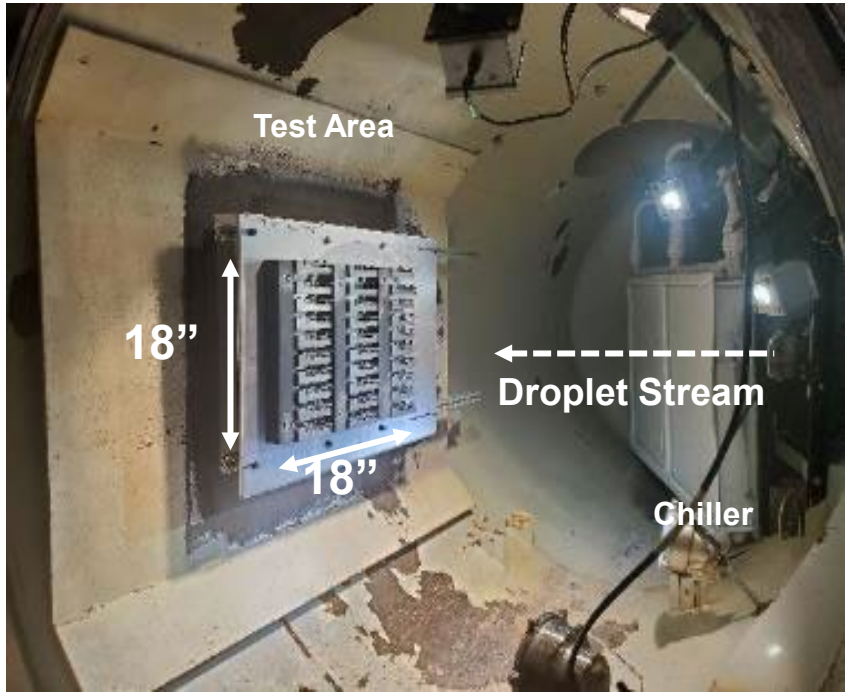
TSFC comparison
Engine Test Data and CFD Analysis

Flight Condition	CFD (TSFC)	Engine Test (TSFC)
Fan Design Speed for Take-Off	1.35%	1.10%*
Max Continuous Thrust for Cruise	0.62%	0.40%

* Extrapolated values from test cell data

SuRE Test Rig

Chamber became very hot during testing (~30°C) from exposure to Mach 2 droplets



Droplets stream rasters along x-y directions on the specimens in the test area

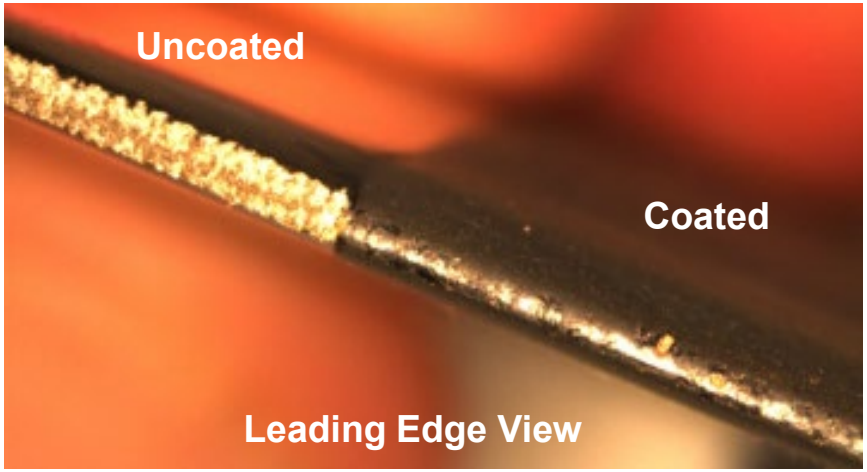
AFRL Supersonic Rain Erosion Test

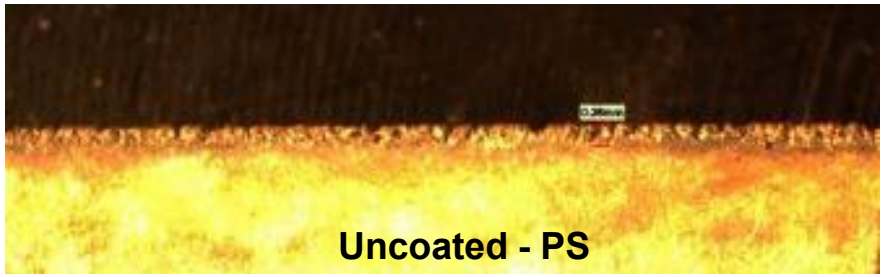
AFRL Supersonic Rain Erosion Test

CFM56 Test Specimen

After 80 passes

C3-1 Location
BlackGold® v12.1

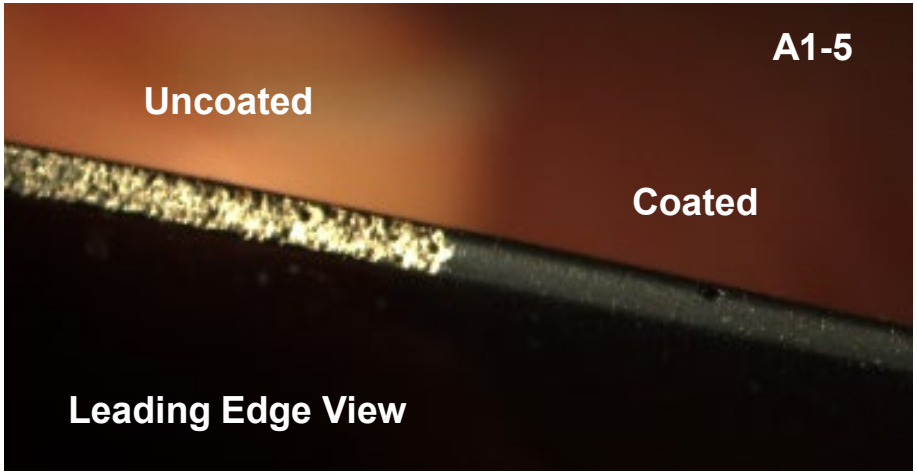


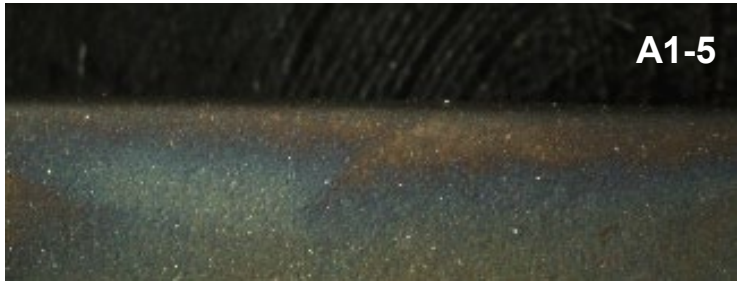


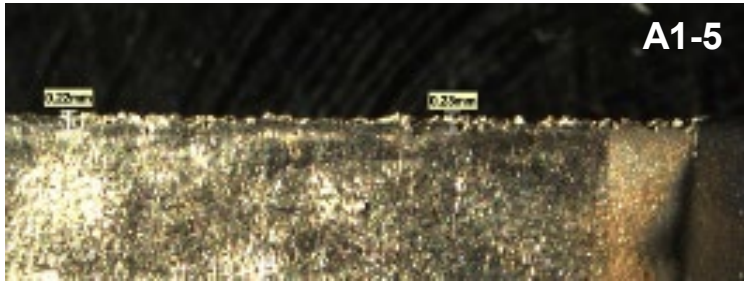
PW2000 Test Specimen

After 100 passes

BlackGold® v12.2
With coating enhancements





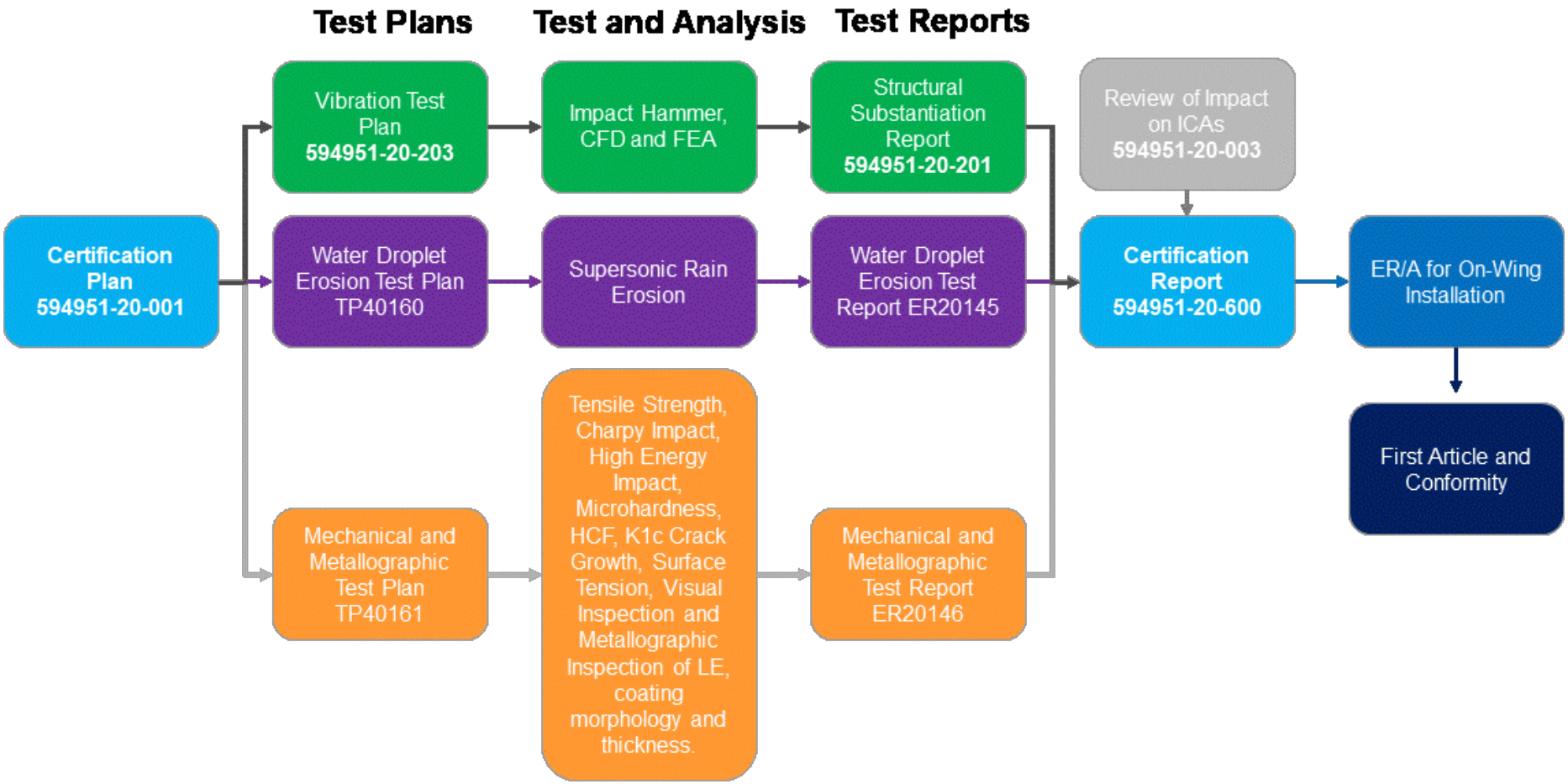


Phase III – PW2000 Certification

- Contracted FAA Authorized RS-DER
- Approval using Major Alteration
  - PW2000 Type Certificate E17NE Rev 15
- Current work:
  - Prepare part specific certification plan (594951-20-001)
    - List regulations and
    - Proposed testing
  - Complete CFD / FEA analysis on loaded fan blades
  - Prepare familiarization plan for FAA
  - Coordinate with ACO for Multi-Use Major Alteration

PW2000 Certification

Certification Overview



PW2000 Certification

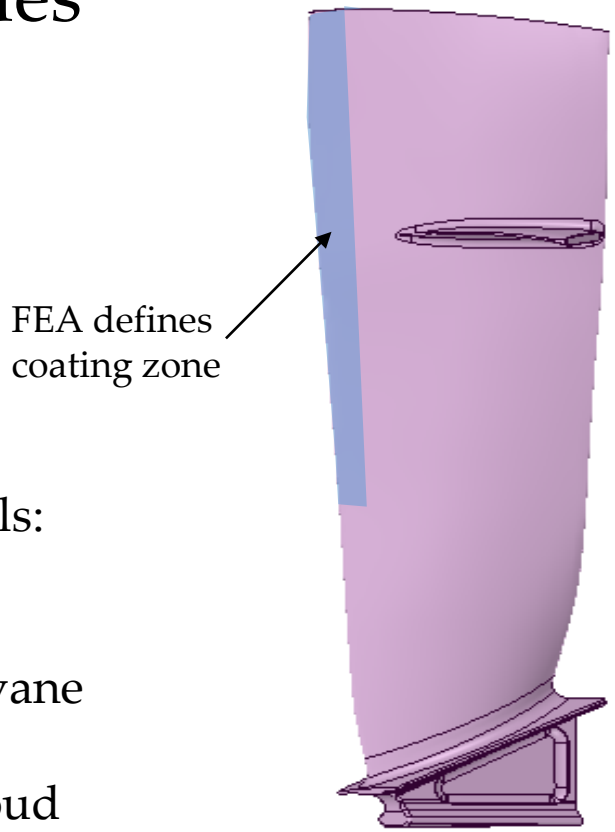
Compliance Matrix

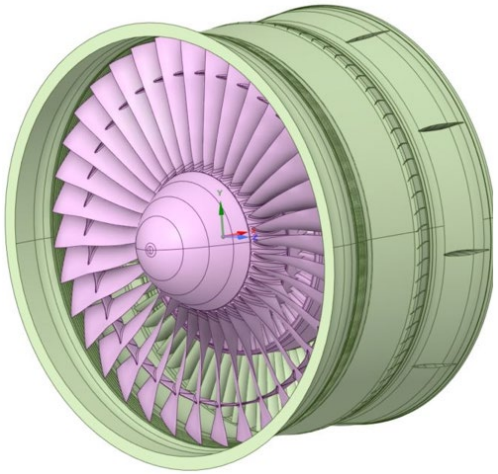
Excerpt from PSCP 594951-20-001

CFR Section and Title	Para	Means of Compliance								Document or Drawing Reference		Comments	DER or FAA
		EO Sect	A	T	D	MU	ML	DM	O				
33.15 Materials Amdt. 33-10	all		☒	☒	☒	☐	☐	☐	☐	ER20145 ER20146		The coating and processing does not affect the structural strength, toughness, crack growth, wear, corrosion, other material property. Although, the coating does impact fatigue of the material, there is no impact on the TC blade because coating area is limited to low stress zones	
33.19 Durability Amdt. 33-10	(a)		☒	☒	☒	☐	☐	☐	☐	594951-20-201 ER20146		CFD and FEA of fan blade to map high stress areas of the fan blade. To ensure that HCF debit does not affect durability of the TC blade, the coating area to be limited to lower stress areas at the leading edge where erosion protection is required	
33.27 Turbine, compressor, fan, and turbosupercharger rotors. Amdt. 33-10	all		☒	☒	☐	☐	☐	☐	☐	594951-20-201		The loads on rotor are unaffected since the coating has no appreciable change on the weight the Fan blade	
14 CFR 33 Subpart C – Design and Construction; Reciprocating Aircraft Engines. Not applicable													
14 CFR 33 Subpart D – Block Tests; Reciprocating Aircraft Engines. Not applicable													
14 CFR 33 Subpart E – Design and Construction; Turbine Aircraft Engines													
33.62 Stress analysis Amdt. 33-6			☒	☒	☐	☐	☐	☐	☐	594951-20-201		FEA and vibration analysis will demonstrate no change in the system stresses.	
33.63 Vibration Amdt. 33-10			☒	☒	☐	☐	☐	☐	☐	594951-20-201		The testing will show the coating has no appreciable change in the natural frequencies. Natural frequencies will be measured with & without the coating applied. FEA and vibration analysis will show no change in mode shapes	
33.65 Surge and stall characteristics Amdt. 33-6			☐	☒	☐	☐	☐	☐	☐	ER20146		Coating has no appreciable effect on blade dimensions. Coating area is limited to a thin strip along the leading edge. Change in dimension is well within variation in serviceable and eroded blades.	

PW2000 Certification

- CFD and FEA of PW2000 fan blades
  - Aerodynamic loads on the fan blades
  - Natural frequencies and mode shapes
  - Stress fields for significant modes
  - Determining the coating zone





PW2000 models:
- Fan Blade
- Casing
- Exit guide vane
- Stator vane
- Fan-to-Shroud
- Fan-to-Disk

Summary

Data Collection

- Expanded data collection. Photographs and LE depth measurements on various engine types including military engines.
- LE cavitation confirmed as low as 2,000 hours.
- LE cavitation depth tends to increase to 5,000 hours and appears to flatten-out (constant mean pit depth) for remainder of tour

Engine Test / Full Consumption Analysis

- V2500 engine test at United Airlines
- CFD analysis by U. Maryland on CF34, CFM56, PW4000 / CF6 and GTF

Summary (continued)

PW2000 Certification

- Certification & Test Plans approved by FAA ODA
- Expose uncoated & coated fatigue test specimens at SuRE facility
- Conduct HCF tests on fatigue test specimens
- Conduct jelly ball impact test at UDRI
- Conduct material evaluation tests

First full PW2000 coated sets supplied by MDS Coating, 2Q / CY23

First full PW2000 coated sets installed by Delta Airlines 3Q / CY23

Saving 1% of fuel results in:

$114M USD

1.15M barrels of oil

495,717,516 kg of CO_2

107,570 cars off the road

81,793,390 Trees

Thank You

Delta Air Lines consumed 4.566B gal of fuel in 2019
Based on $2.50 / gal fuel price
https://www.epa.gov/energy/
greenhouse-gases-equivalencies-calculator-calculatios-and-references

MDS COATING

DELTA TechOps

GKN AEROSPACE