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

Presented to: FAA Office of Environment and Energy

By: Delta TechOps (DTO)

MDS Coating Technologies (MCT)

America's Phenix, Inc. (AP)

Date: 8 May 2019

LE Protective Coating Against Fluid and Particulate Erosion for Turbofan Blades

Benefits:

Based on 1% fuel savings for Mainline and Regional commercial carriers:

- Fuel savings between 80M to 100M gal per year
- 750M to 1.0B kg CO_2 / year
- 700M to 1.0B g NO_x / year

Risk

- Potential fatigue debit impact of coating Ti blades
- Insufficient coating durability

Mitigation

- Adjust coating process parameters
- Test & compare to eroded blades in operation

Objectives:

- Quantify performance degradation
- Optimize coating protection via component tests
- Demonstrate coating protection on operational a/c

Work Statement:

- Conduct engine tests on degraded & O/H[1] blades
- Conduct CFD analysis on degraded & O/H[1] blades
- Conduct fluid erosion tests at AFRL[2] SuRE[3] rig
- Flight certify optimal coating candidate
- Conduct flight service evaluation

[1] Overhaul [2] Air Force Research Lab [3] Supersonic Rain Erosion

Accomplishments / Milestones

- Engine test completed with used and new blades
- CFD[4] model completed on used blade
- SuRE test successfully completed
- Flight certification tests completed

Schedule:

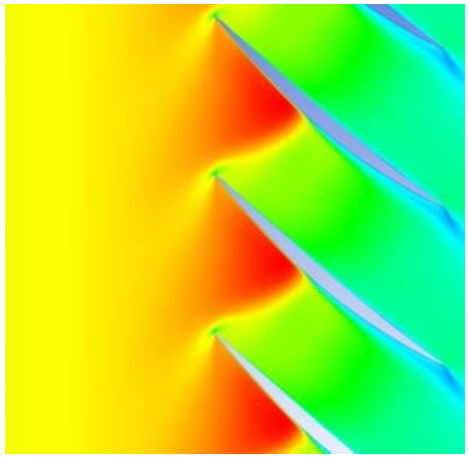
- Blade Condition / Operational Analysis – **COMPLETE**
- JT8D Fluid Erosion Component Test – **COMPLETE**
- Other Engine Types Fluid Erosion Test – **COMPLETE**
- Flight Certification – **COMPLETE**
- Flight Service Evaluation – **April 2018 to Dec 2020**

[4] Computational Fluid Dynamics

Phase I – Data, Test & Simulate

Blade Condition Analysis

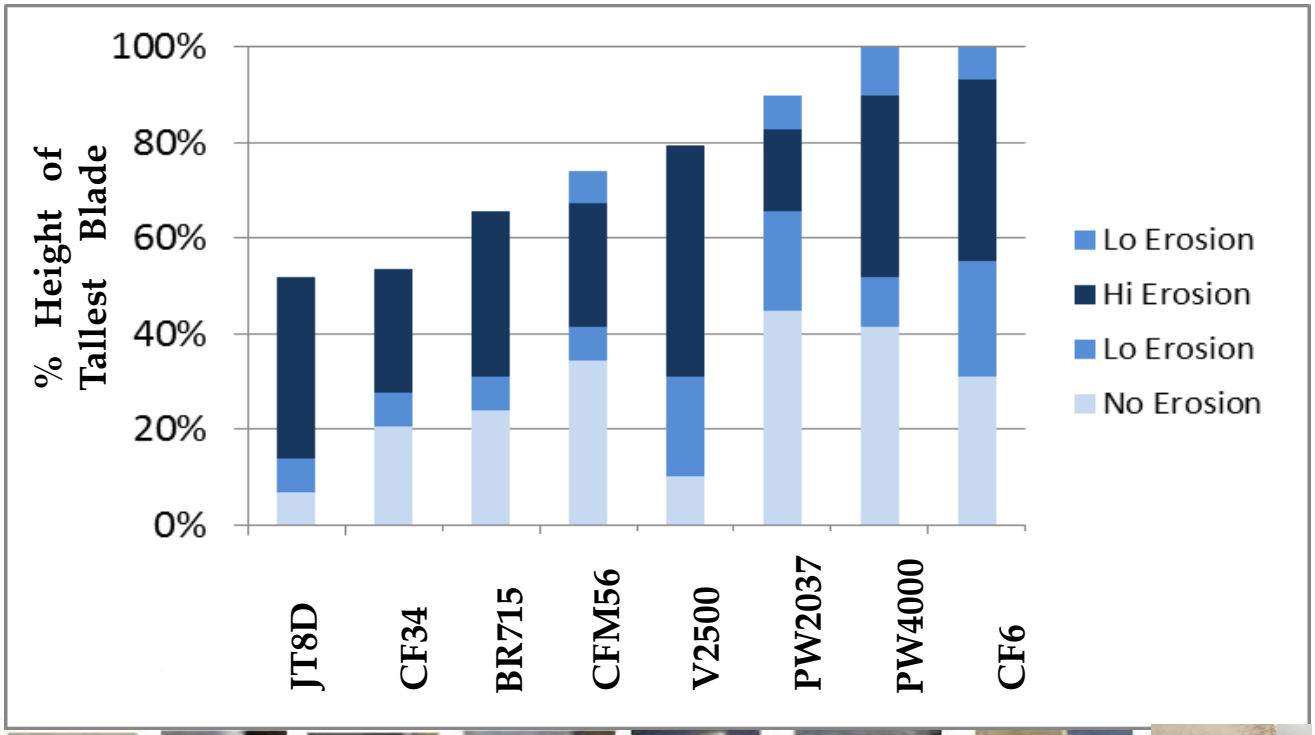
Engine Test Data

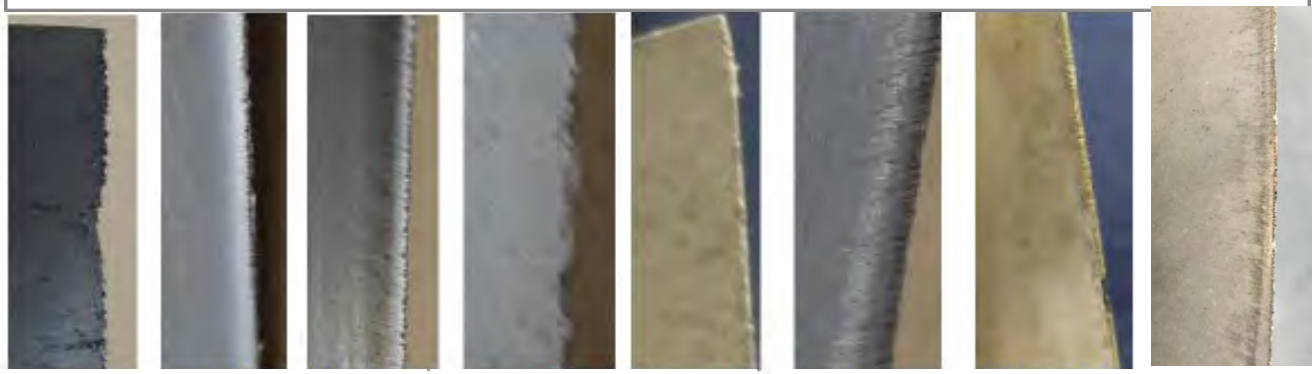


CFD Analysis

- Following 1st stage fan blades inspected and analyzed:
  - JT8D
  - BR715
  - CFM56
  - PW4000
  - V2500
  - CF34
  - PW2037
  - CF6
- Engine test completed on inducted JT8D engine with:
  - existing 1st stage fan blades
  - serviceable condition 1st stage fan blades
- CFD Analysis completed on serviceable and used blades at following conditions:
  - Take-off
  - Cruise

Phase I – Blade Condition Analysis

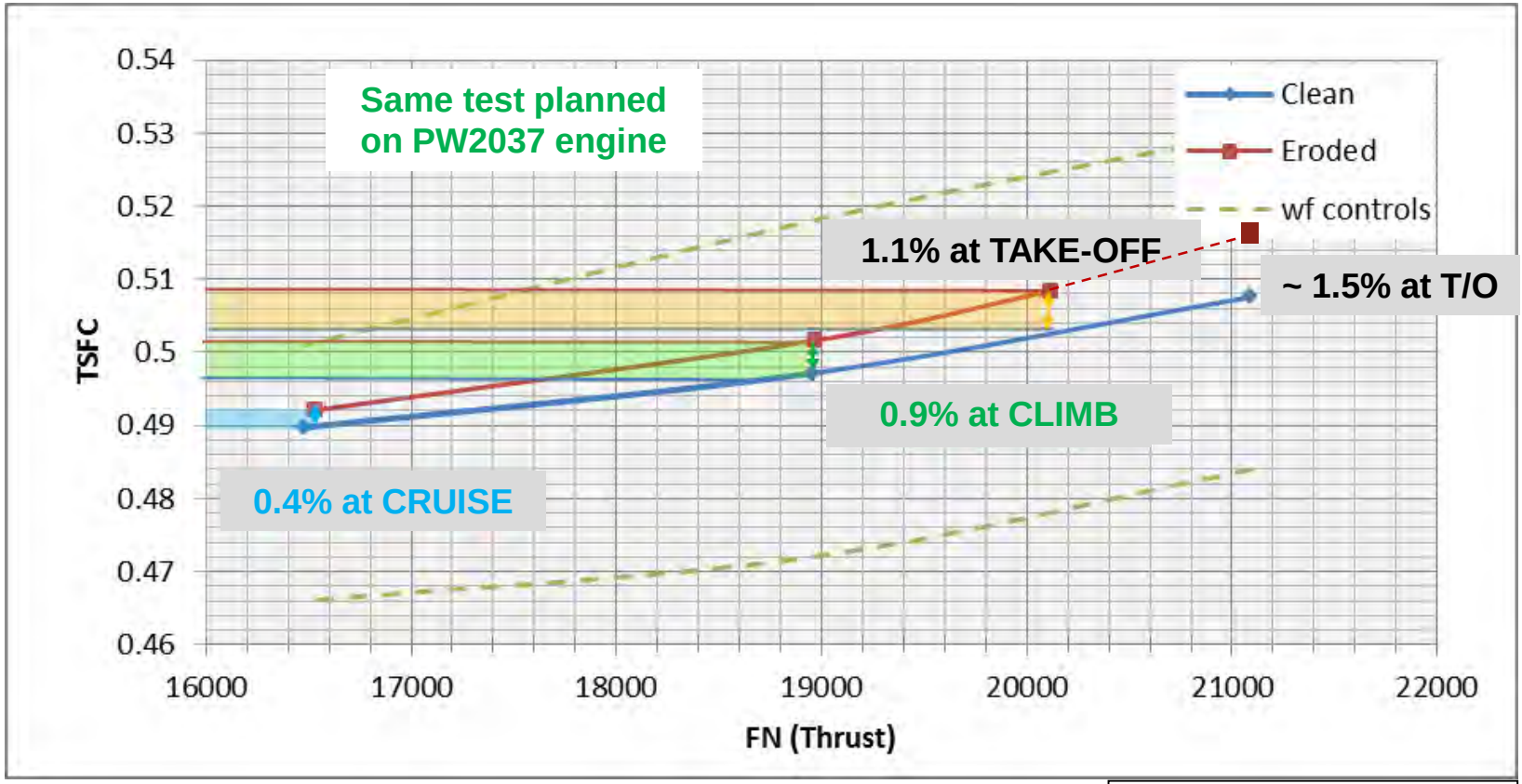




JT8D CF34 BR715 CFM56 V2500 PW2037 PW4000 CF6

Phase I – Engine Test

Thrust Specific Fuel Consumption (TSFC) Comparison
Eroded vs. Serviceable Fan blades



Clean = repaired, serviceable fan blades

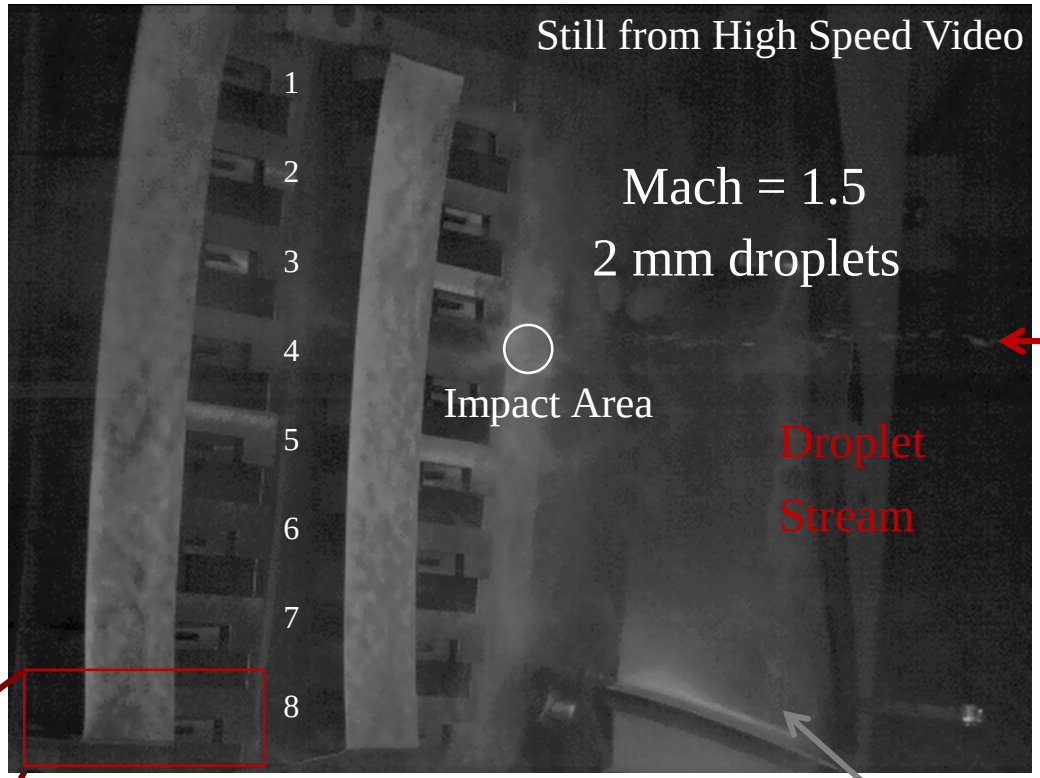
JT8D Engine S/N 726044
Inducted May 2015
TSO = 3126 hours
Tests / Engine Service Manual: PN773128

Phase II – Fluid Erosion Test

@ AFRL – Supersonic Rain Erosion (SuRE) Rig

Specimen Preparation

Specimen Tooling



Uncoated Blade Specimen

BlackGold® Coated Blade Specimen

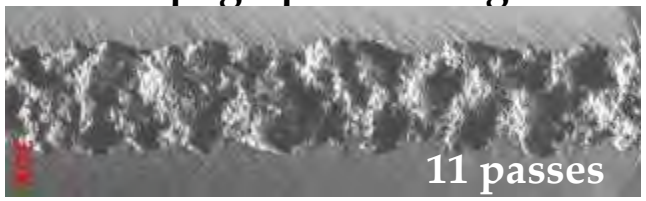
Coated Blade

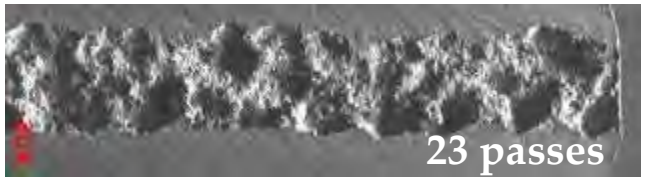
Fluid Erosion Tests @ AFRL

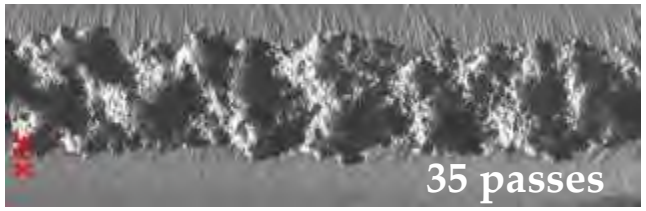
Optical images

Uncoated PW2000 LE Surface

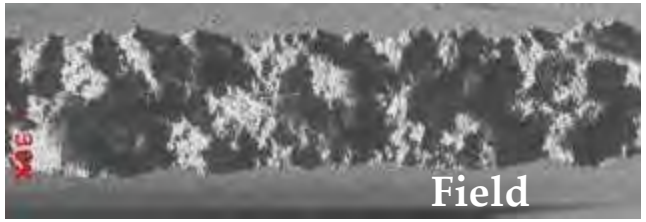
SEM Topographical images







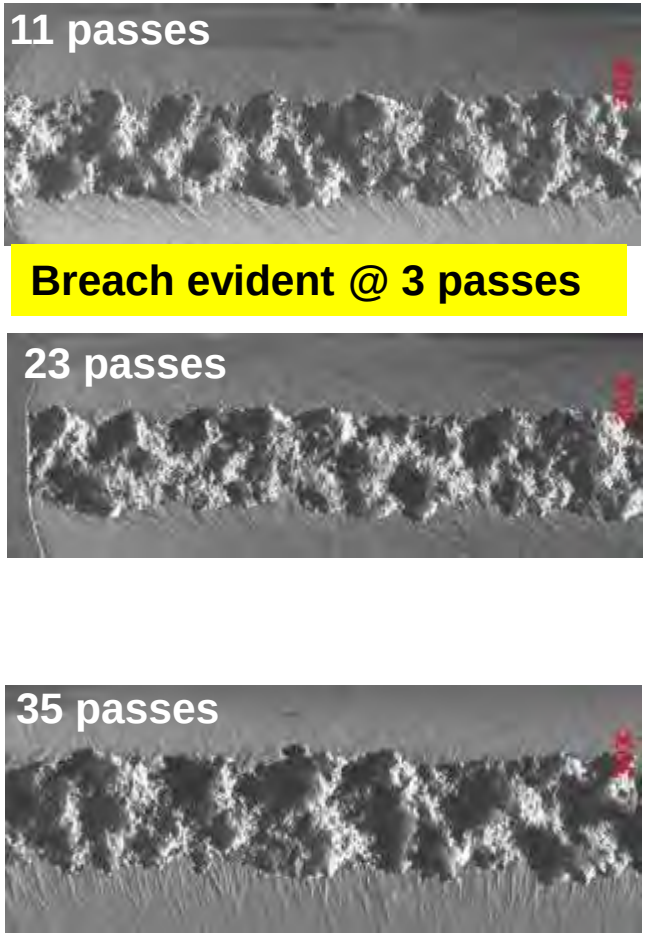
Similar depth damage



Field part ≈ 5,000 cycles & 14,000 hours

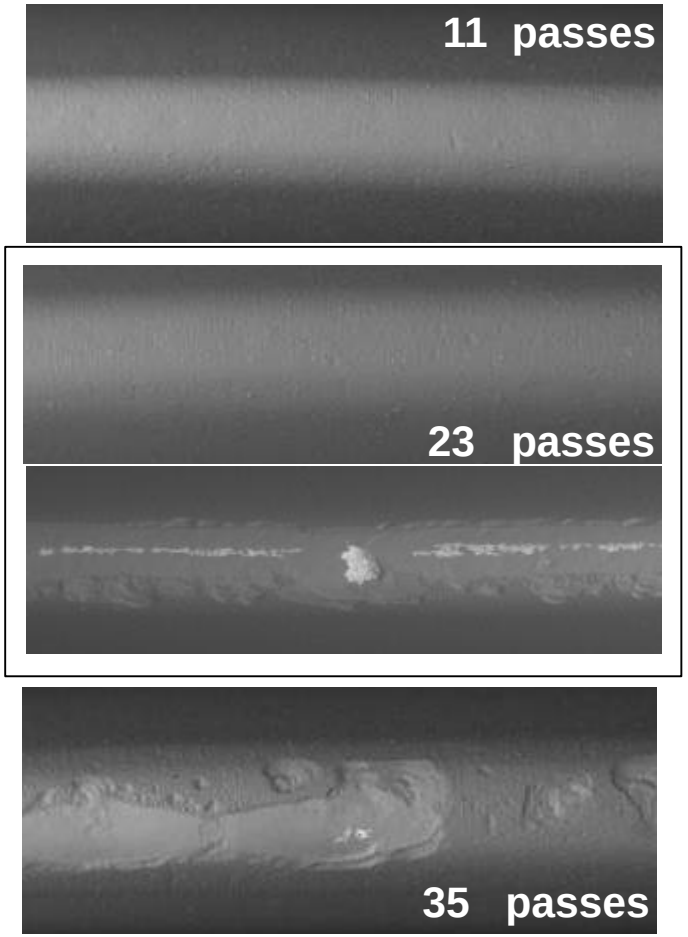
Fluid Erosion Tests @ AFRL

Uncoated PW2000



Breach evident @ 3 passes

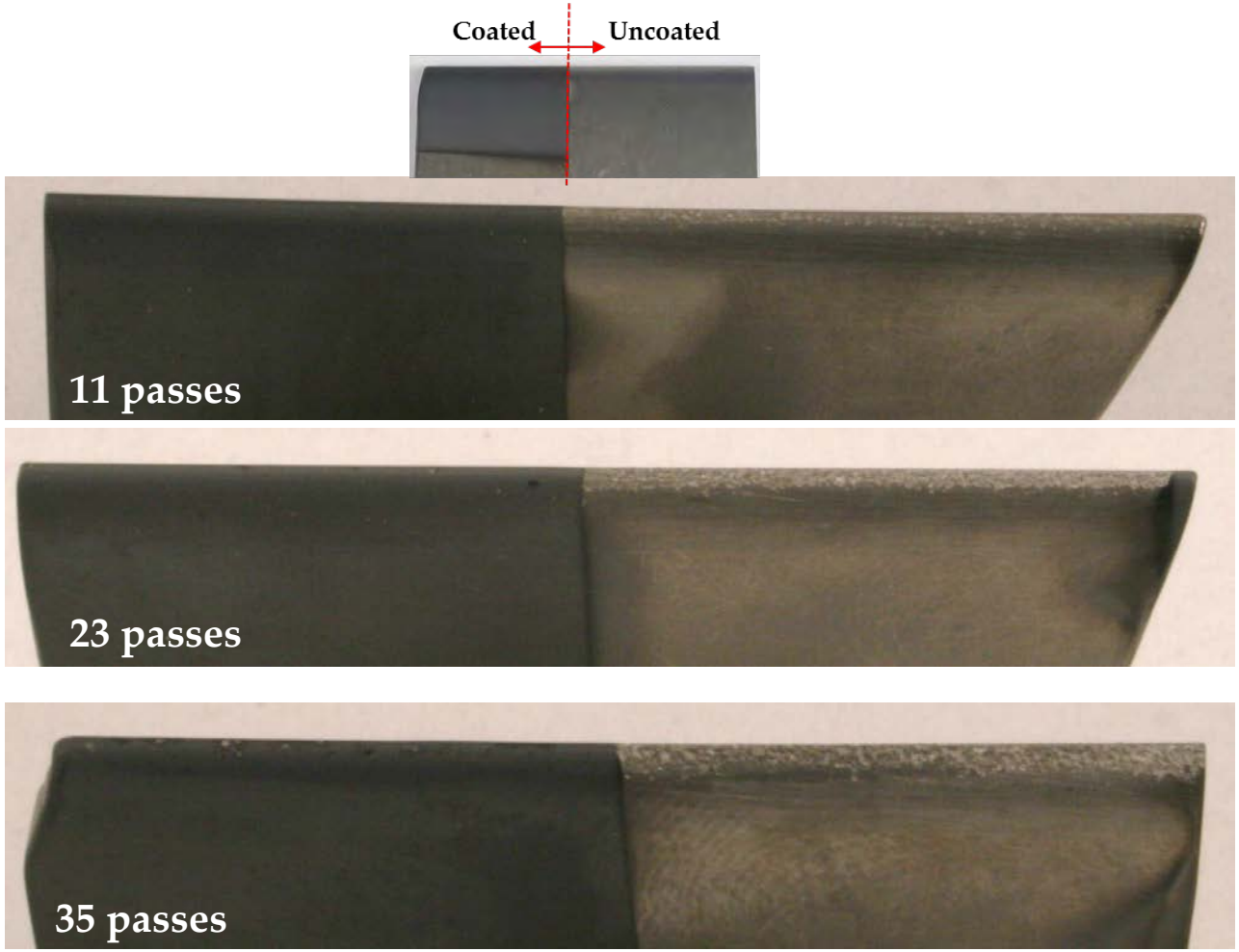
BlackGold® Coated PW2000



First substrate damage noticed after 23 passes

Fluid Erosion Tests @ AFRL

Fluid Erosion Comparison Ti Strips



Fluid Erosion Tests @ AFRL

Conclusion

- AFRL's SuRE rig test closely reproduced damage observed on field blades
- BlackGold® coating provided protection
  - Projected improvement of ≈ 8X based on first breach point observed on uncoated (3 passes) and coated (23 passes) test specimens

PW2000 Uncoated 35 passes

PW2000 Field part
≈ 5,000 cycles & 14,000 hours

Similar depth damage

Phase III –
Air Worthiness Certification Tasks

- FAA Certification Plan Approval
- FAA Test Plan Approval
- Weight Analysis
- Metallographic Analysis
- Stress Analysis
- Frequency Analysis
- High Cycle Fatigue Tests
- Mechanical Property Tests
- Impact (Jelly Ball) Tests
- Ice Adhesion Analysis
- Compressor Wash Analysis

Phase IV – Flight Demonstration

Phase IV – Flight Demonstration

Field Engine Op Status

Engines 4 and 5 installed with only two (2) coated blades in order to maintain four (4) flight demo aircraft

Phase IV – Flight Demonstration

Inspections Completed

1st Engine Installed 11 Apr 18		Planned Inspection Intervals (Hours)						
		500	750	1,000	1,500	2,000	2,250	2,500
Engine #	ESN	Actual Inspections (Hours)						
1	718045	549	744	912	1,426	1,845	2,299	
		26-Jun-18	25-Jul-18	24-Aug-18	3-Dec-18	12-Feb-19	12-Apr-19	
2	725536	571	823	1062	1,608			
		8-Aug-18	27-Sep-18	2-Nov-18				
3	725558	284	Engine removed off-wing due to in-flight shutdown					
		No Longer Tracking						
4	709968	Engine built. Awaiting on-wing install.						
		Two (2) coated blades installed.						
5	718150	242						
		Two (2) coated blades installed.						

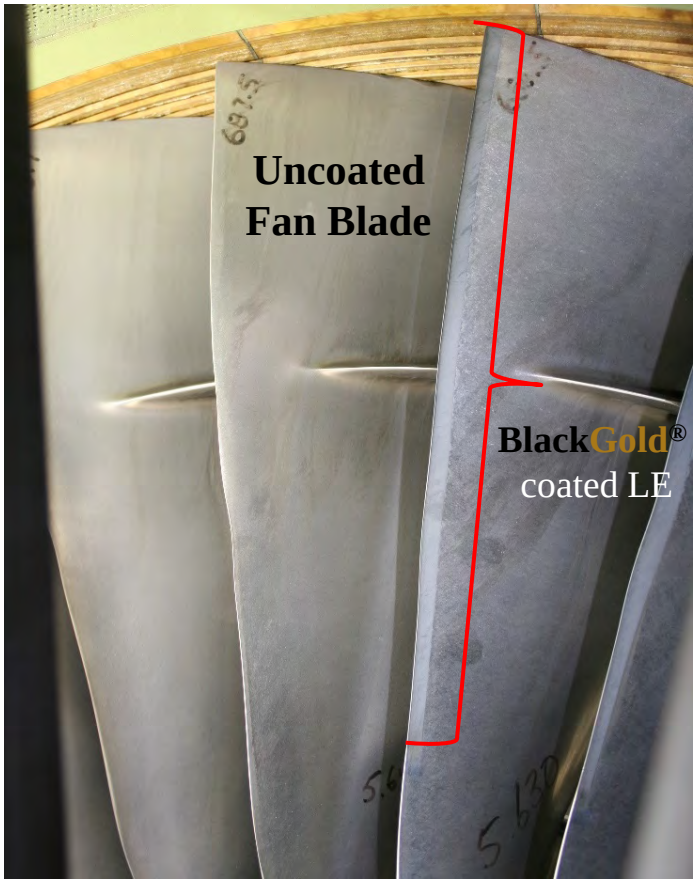
Nine (9) Inspections completed to date

Phase IV – Flight Demonstration

Phase IV – Flight Demonstration
Fan Blade Inspections

- **BlackGold® coated 1st stage turbofan blades installed on four (4) JT8D engines for flight operations on MD88 aircraft**
  - Inspections ≈ every 250 to 500 hours

JT8D 1st Stage Fan Blades



Phase IV – Flight Demonstration

Inspection Progression
2nd Engine

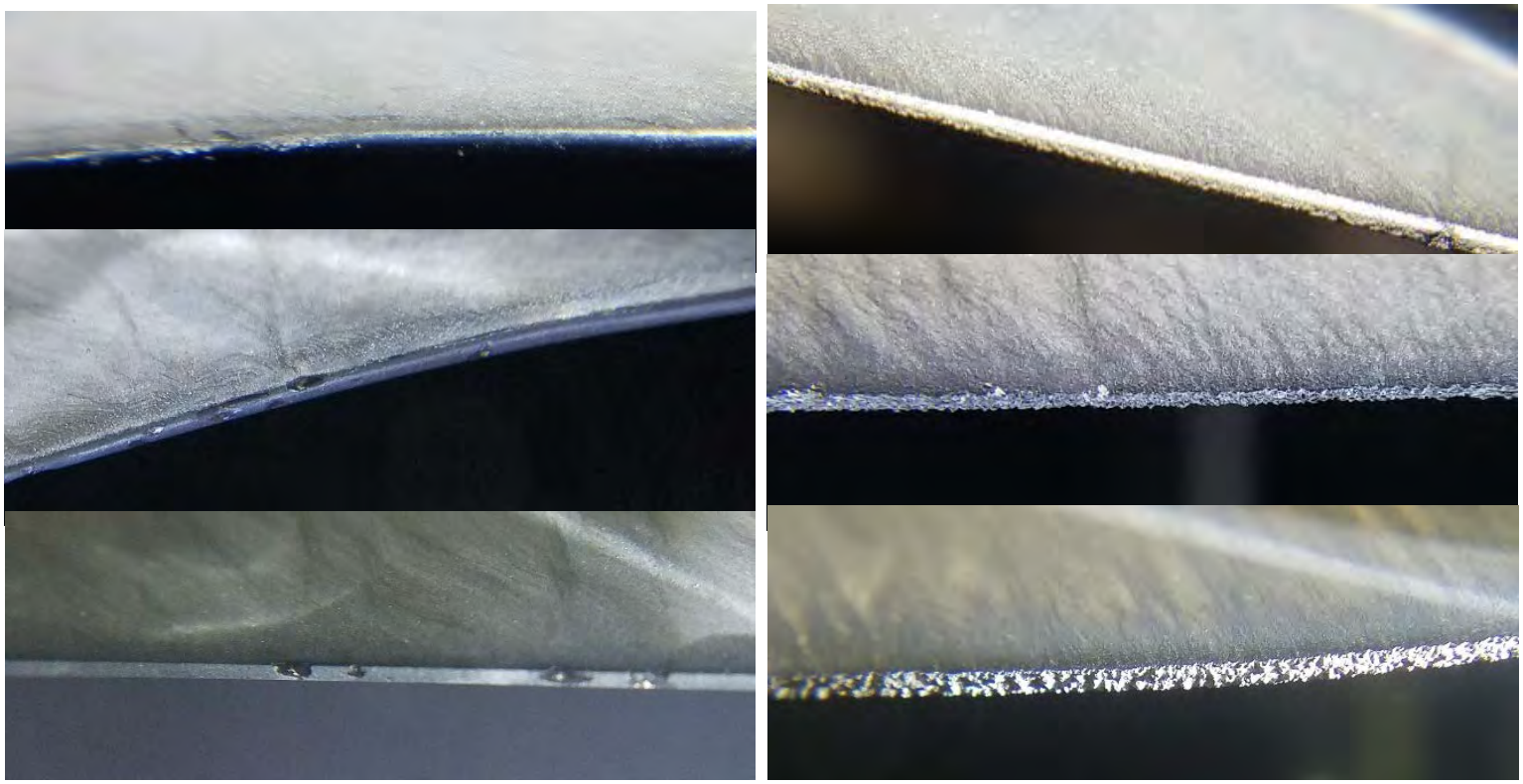
Ship No:
Engine S/N: 725536

Coated **Uncoated**

359hrs

500hrs

800hrs



Phase IV – Flight Demonstration

Engine Inspection @ 912 hours

Ship No: 9008
Engine S/N: 718045

Uncoated

Mold imprints @ 912 hours

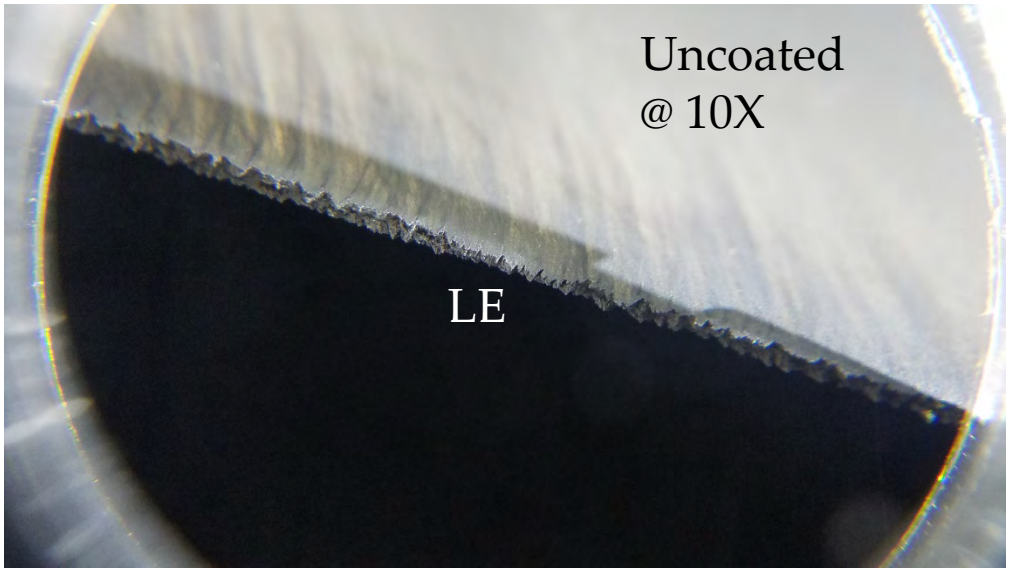
Coated

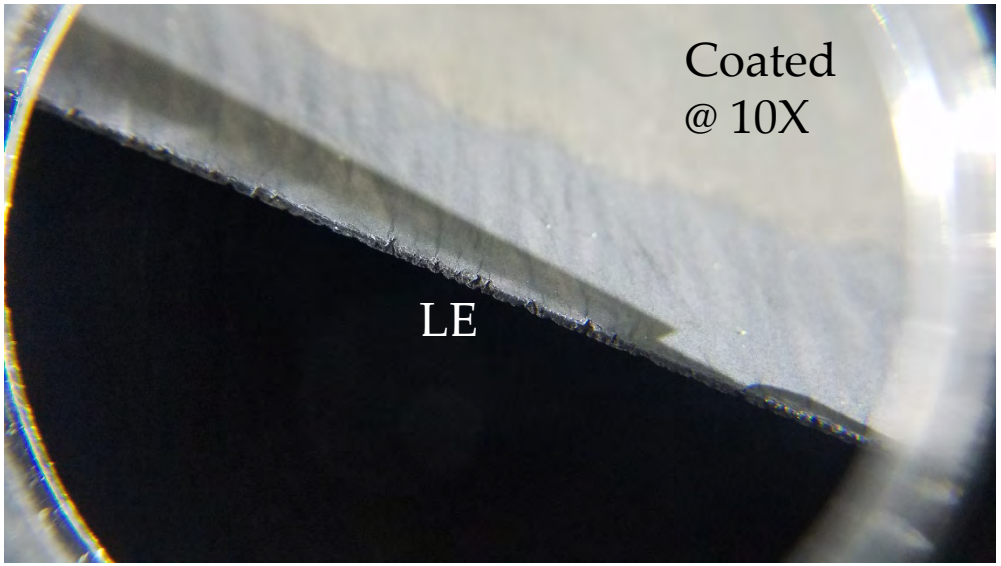
Phase IV – Flight Demonstration

Inspection at 1,845 hours, 12 Feb 19

Phase IV – Flight Demonstration

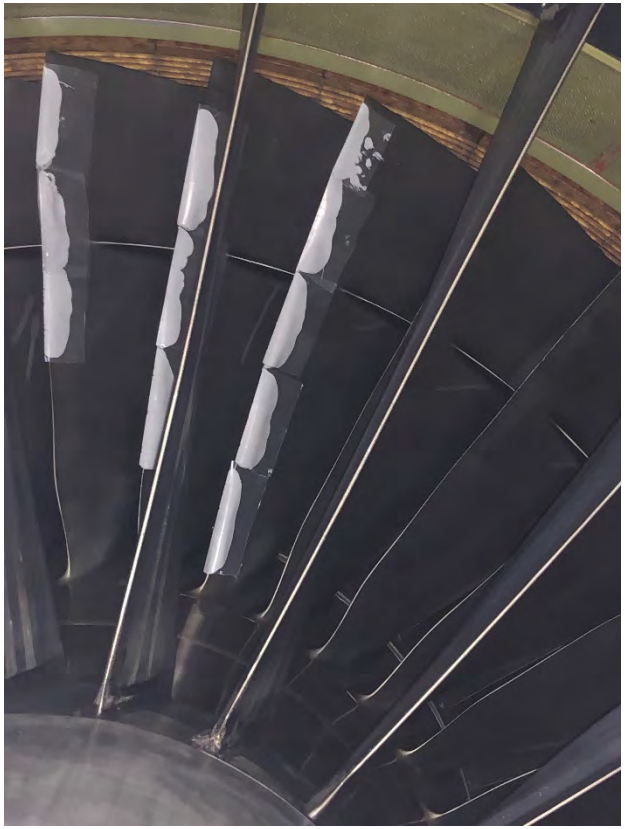
Inspection at 2,299 hours, 12 April 2019





Phase IV – Flight Demonstration

3D Scans of "Dental Mold" LE Blade Specimens



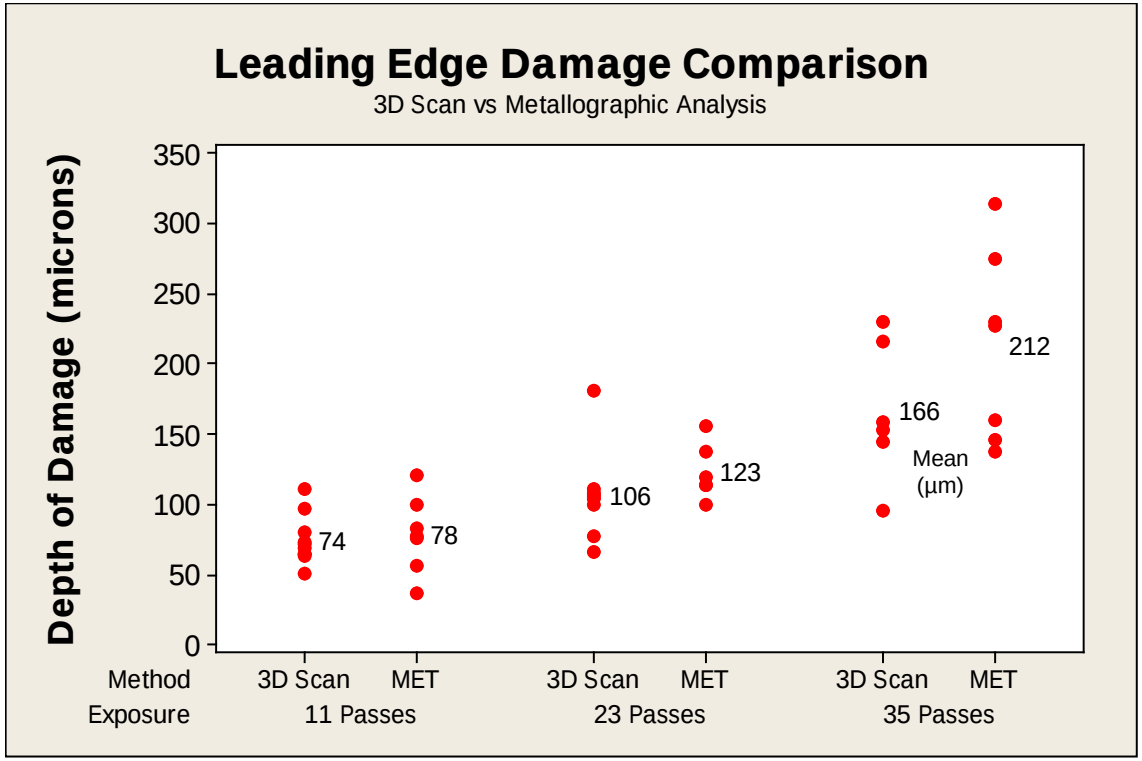
JT8D Fan Blades with Molds

3D mold scans

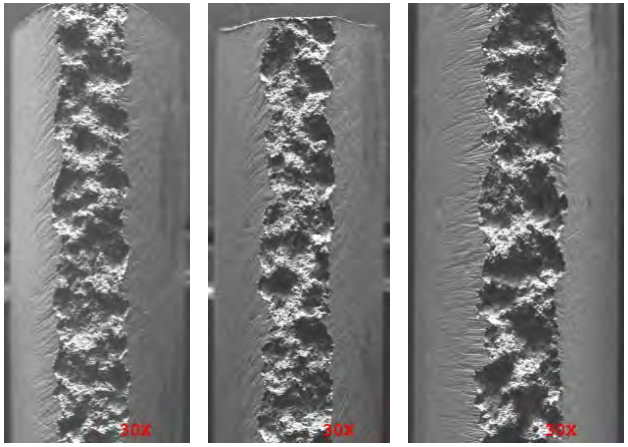
- LE molds placed in erosion area from tip towards root.
- Molds scanned with white-light 3D scanner.
- Damage depth measured along LE from scanned image and processed with appropriate software.

Uncoated AFRL 3D Scans vs MET

- **AFRL specimens - damage depth measured using both optical microscopy of metallographic cross sections (MET) and 3D scans of repli-set molds.**



SEM of Uncoated AFRL Specimens



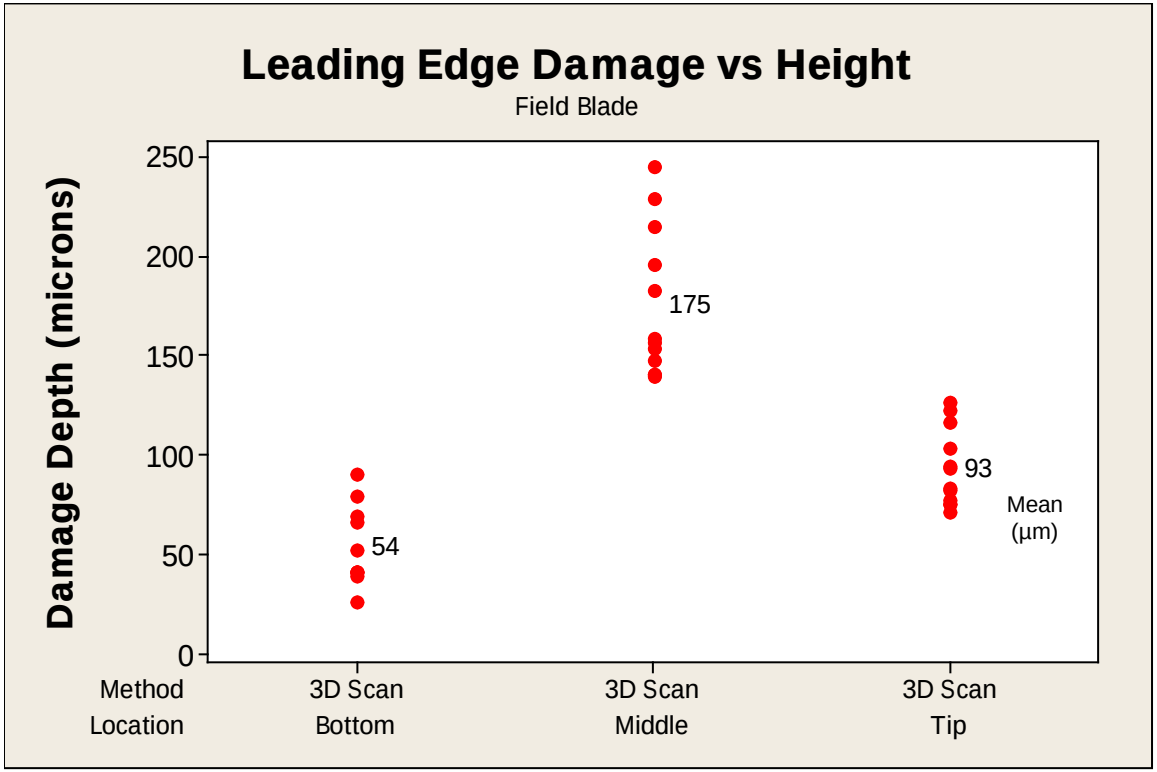
11passes 23 passes 35passes

Metallographic analysis and 3D scans of molds show same trend.

Metallographic analysis gives a higher mean; 3D scans may be losing some detail.

Phase IV – Flight Demonstration

Uncoated Damage vs Height

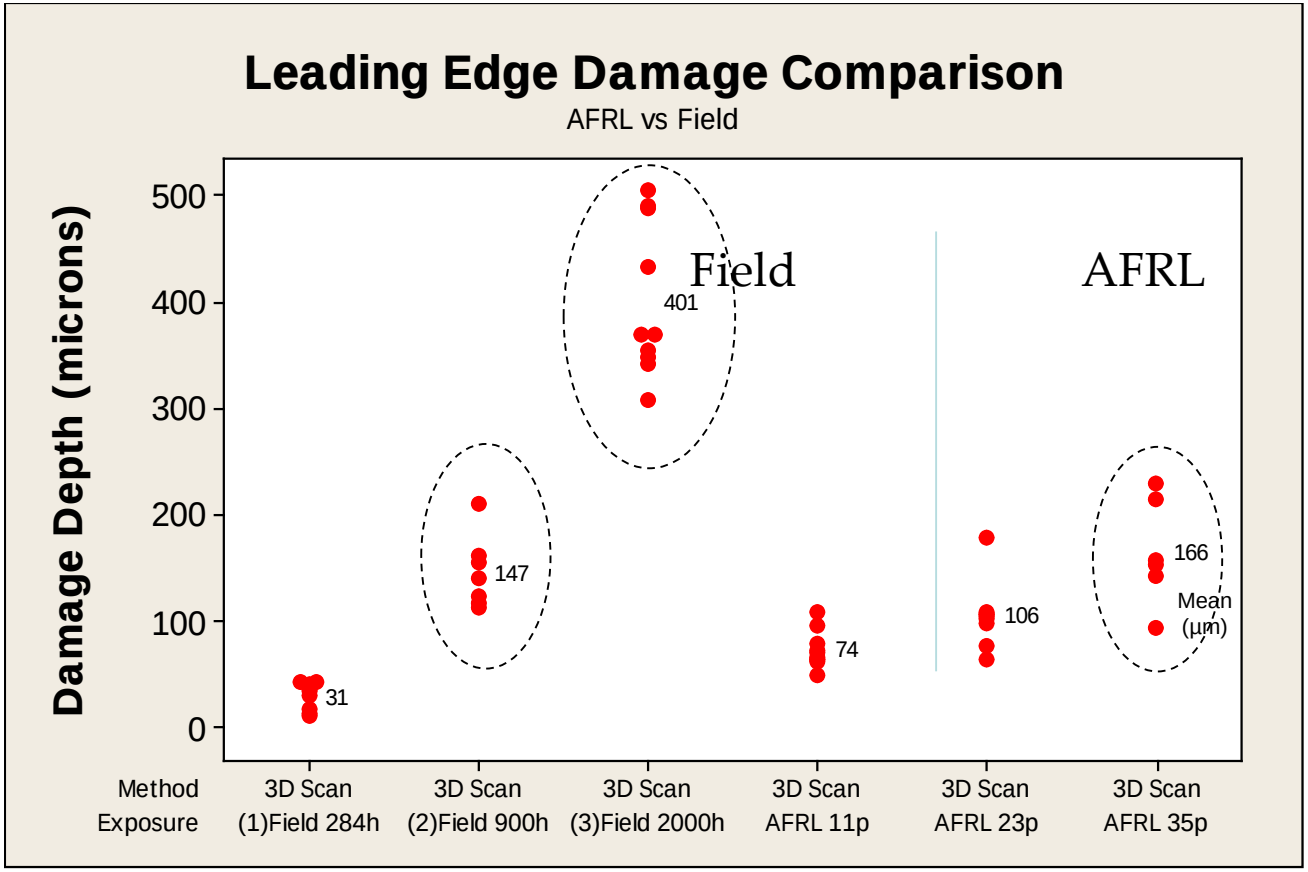


JT8D Blade

Maximum Damage of flight demo blade at 912 hrs is in the middle-span region near the mid-span shroud

Phase IV – Flight Demonstration

Uncoated Damage AFRL vs JT8D-219 Field



Uncoated JT8D flight demo blade at 900 hours ≈ to AFRL specimens with 35 passes of exposure

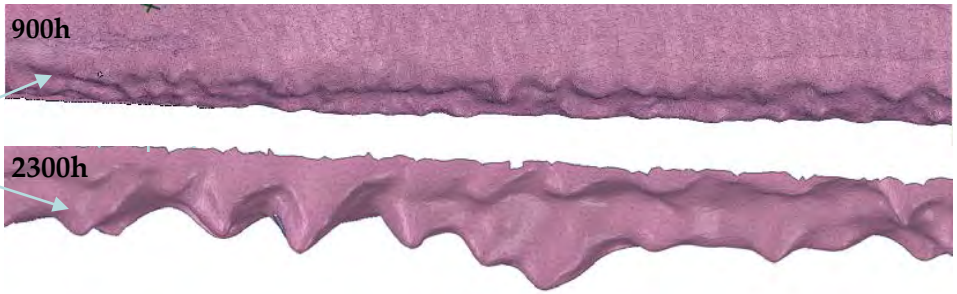
Field erosion damage observed at 2000 hours exceeds damage observed during AFRL testing

Phase IV – Flight Demonstration

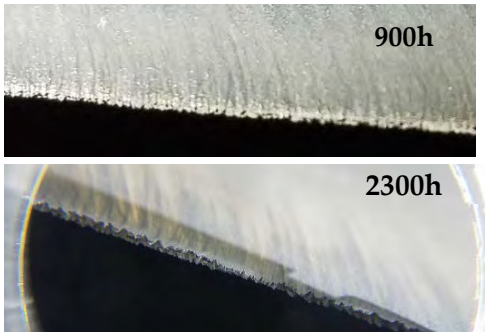
Coated vs Uncoated Mid Span

AVG Damage:
900h = 147µm
2000h = 401µm

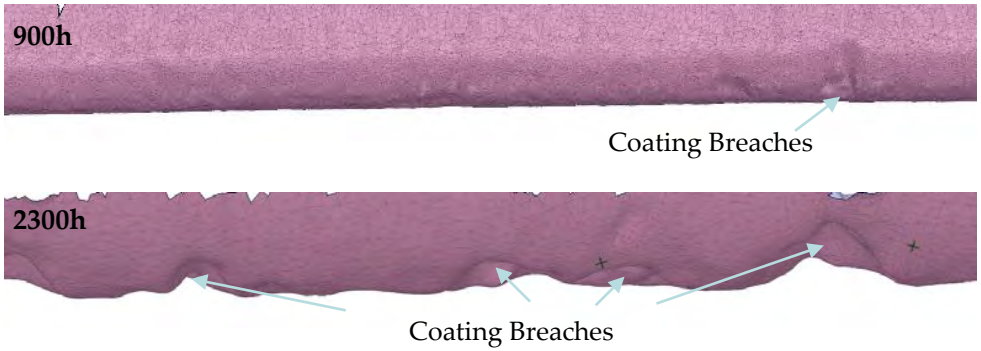
3D scan of uncoated field blade LE mold



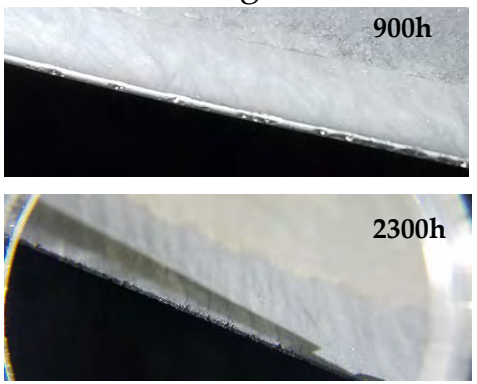
Uncoated Flight Demo



3D scan of coated field blade LE mold



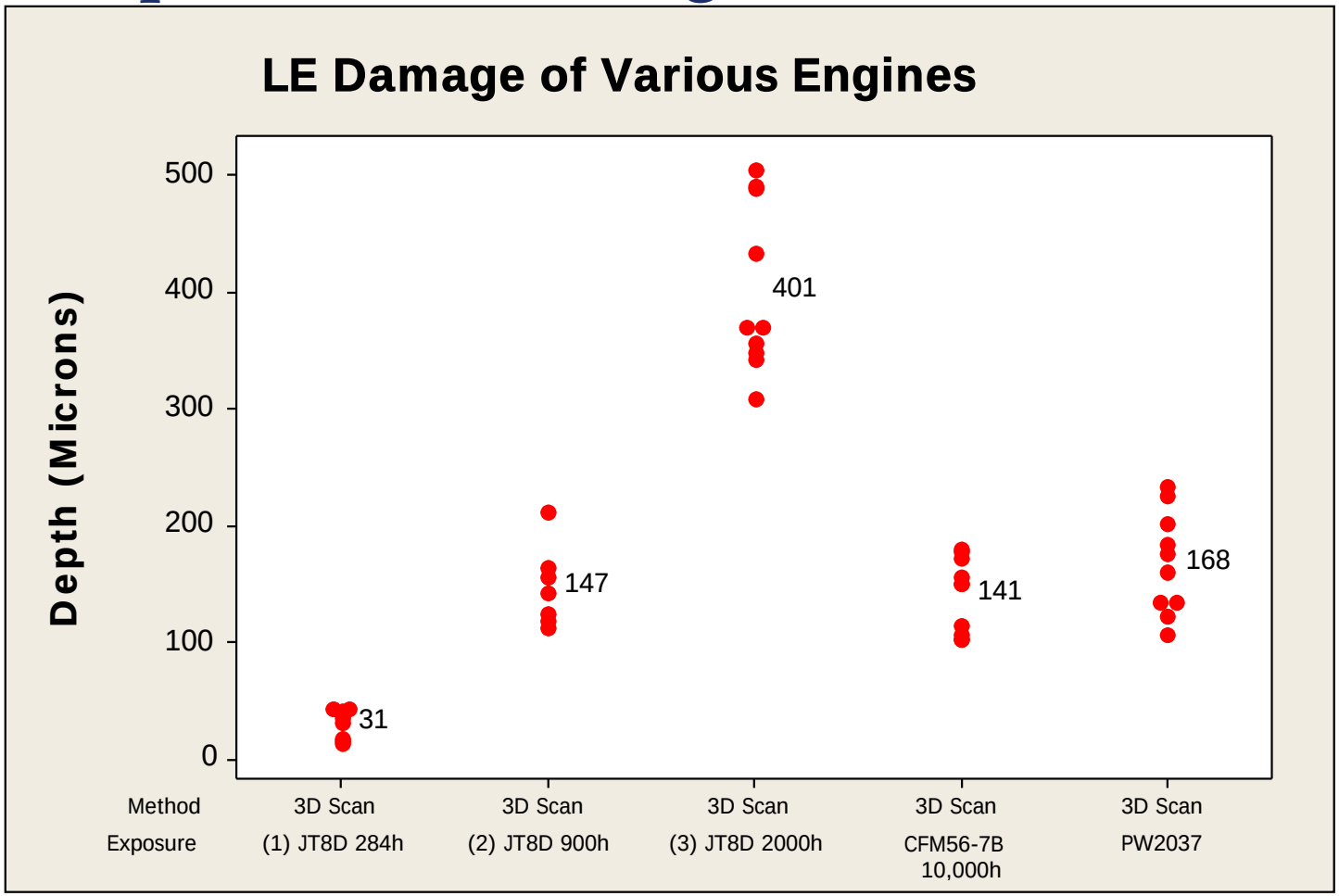
Coated Flight Demo



Coated blades much smoother than uncoated blades.
Coating Breaches are now more frequent after 2000h

Phase IV – Flight Demonstration

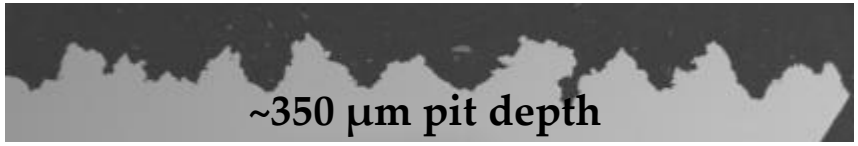
JT8D compared to other Engines



Leading edge damage on CFM56-7B and PW2037 fan blade similar to JT8D @ 900 hrs

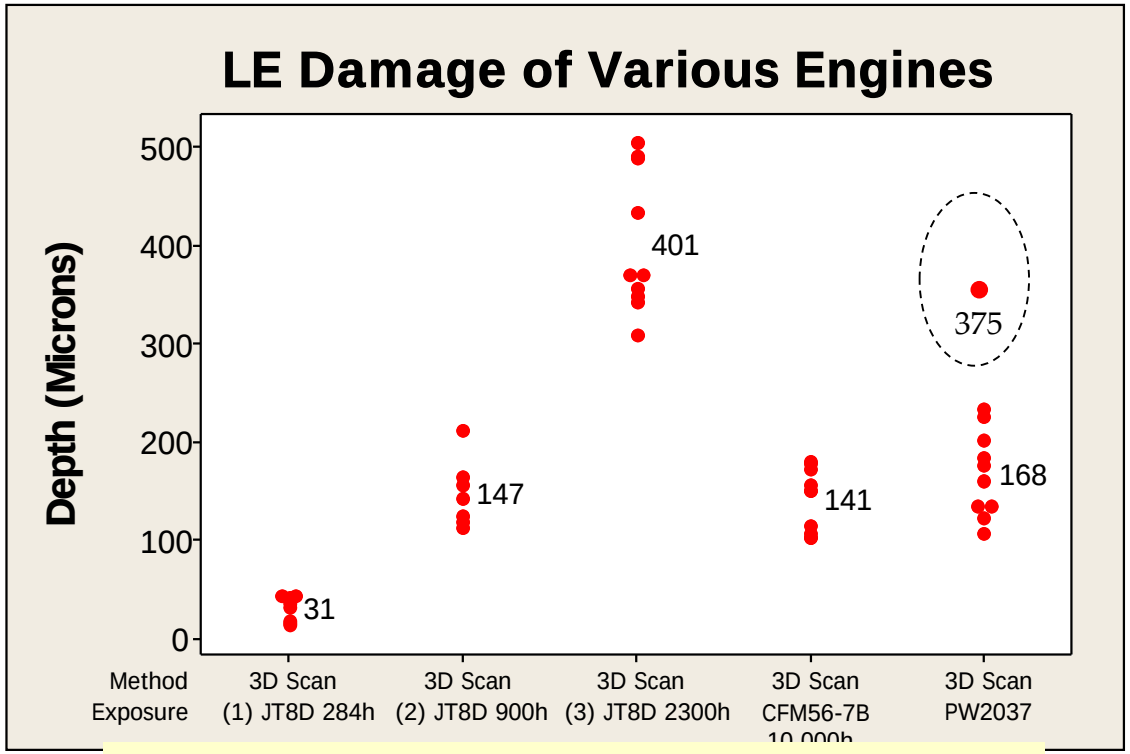
Phase IV – Flight Demonstration

Correlating JT8D data to PW2037



PW2000 Field part ≈ 5,000 cycles & 14,000 hrs

Average tour ≈ 15,000 hrs => estimated pit depth ≈ 375 µm



PW2037 1st Stage Fan Blade with coated LE could protect throughout engine tour

Phase IV Schedule

Estimated remaining inspection schedule

- **Engine # 1 ≈ 2,300 op hours.**
  - 2,500 hours by 1 June 2019
  - 3,000 hours by 15 August 2019
  - 4,000 hours by 15 January 2020
  - **6,000 hours by 15 November 2020**
- **Engine # 2 ≈ 1,608 op hours**
  - 2,500 hours by 1 Sep 2019
  - 3,000 hours by 15 Nov 2019
  - 4,000 hours by 15 April 2020
  - **5,700 hours by 31 Dec 2020**
- **Engine # 4 ≈ 250 op hours**
  - 500 hours by 1 June 2019
  - 1,000 hours by 15 Aug 2019
  - 2,000 hours by 15 Jan 2020
  - 3,000 hours by 15 Jun 2020
  - 4,000 hours by 15 Nov 2020
  - **4,300 hours by 31 Dec 2020**
- **Engine # 5 awaiting on-wing installation**

Operational Hours as of 3 May 2019

Estimates based on an average of 50 hours / week

Delta's MD-88 fleet scheduled for sunset at the end of CY2020

CLEEN II Program Summary

- **Blade Condition and Operational Analysis complete:**
  - LE erosion documented
  - Engine test confirmed 1.1%+ TSFC increase
- **Coating Component Level Tests complete:**
  - For JT8D, PW2037, CF6 and Ti strips
- **Flight Certification Tests Complete**
- **Flight Demonstration Engines**
  - Over 5,000 op hours
  - Visual and measured results confirms coating protecting LE
  - Project over 16,000 op hours by end of CY20
- **Installing four (4) completely coated engines to track fuel savings benefits**

DELTA TechOps

MDS COATING

AMERICA'S PHENIX

AEROSPACE CONSULTANTS for the Americas

THANK YOU