Turbine Surface Degradation with Service and Its Effects on Performance

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SCIES Project 02- 01- SR104

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

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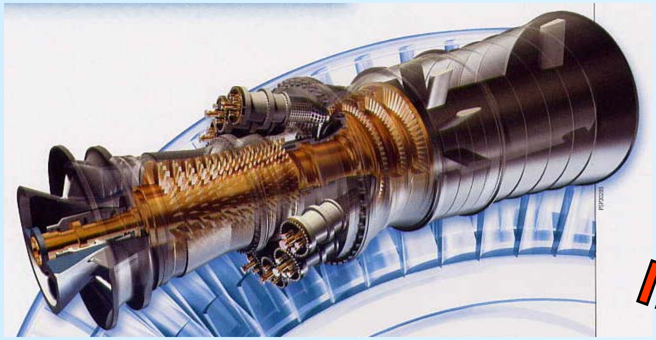
Richard Wenglarz, Manager of Research, SCIES

Project Awarded (06/01/02, 36 Month Duration)

$563,712 Total Contract Value

GAS TURBINE NEED



TURBINES ARE ROUGH!

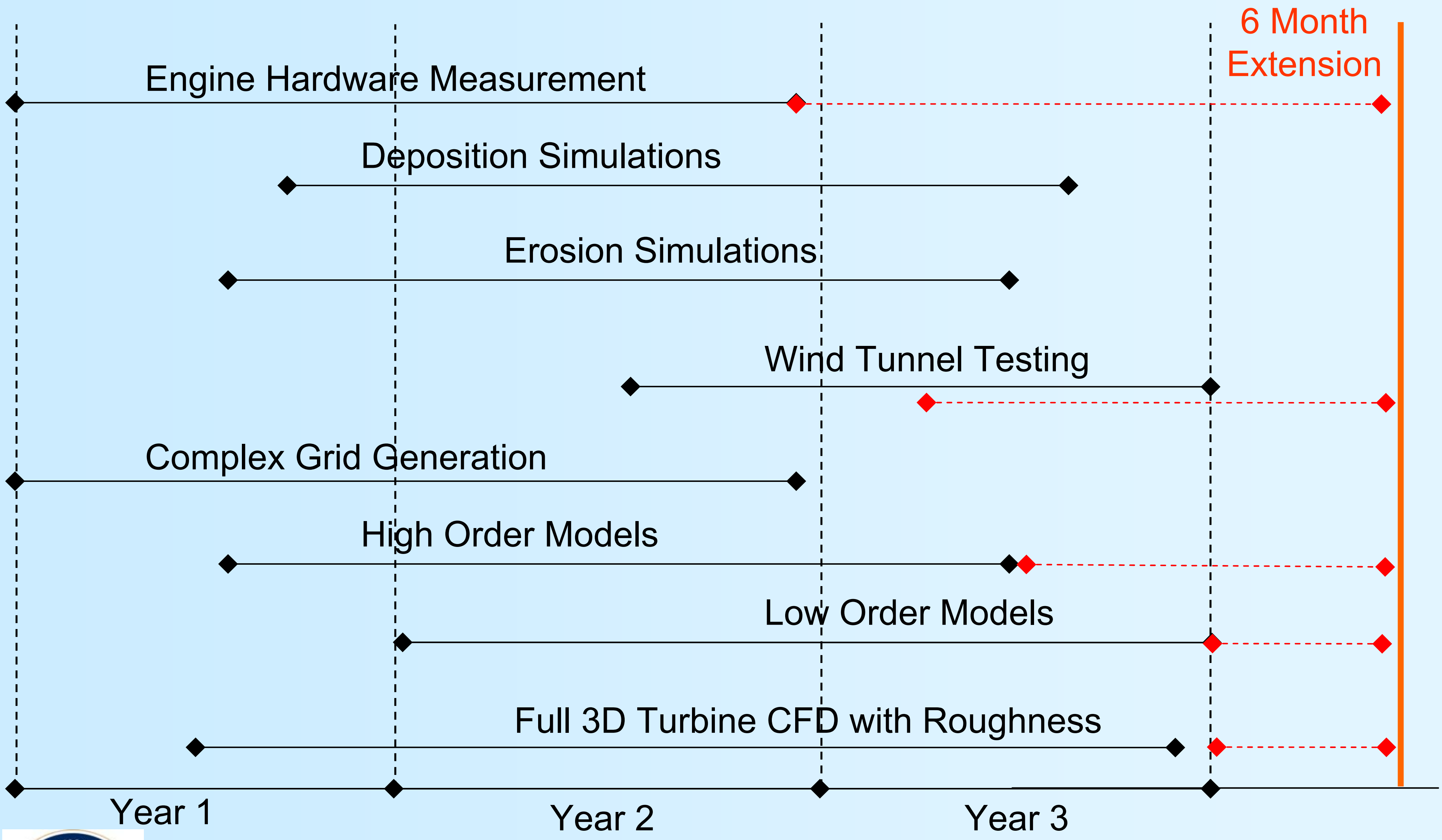
Surface Degradation
- **Increases Heat Transfer**
- **Reduces Efficiency**

The Gas Turbine Community NEEDS adequate tools to estimate the associated loss in engine performance with service time.

OBJECTIVES

- Document evolution of surface degradation from in-service hardware. (BYU & AFRL)
- Establish laboratory simulations of erosion and deposition for detailed study. (BYU & UC)
- Create suitable CFD models for roughness. (ISU)
- Validate CFD models with experimental data. (AFRL, BYU, & ISU)
- Incorporate evolution of surface condition into full 3D GT particle tracking simulations. (UC)

Project Timeline



Accomplishments To Date

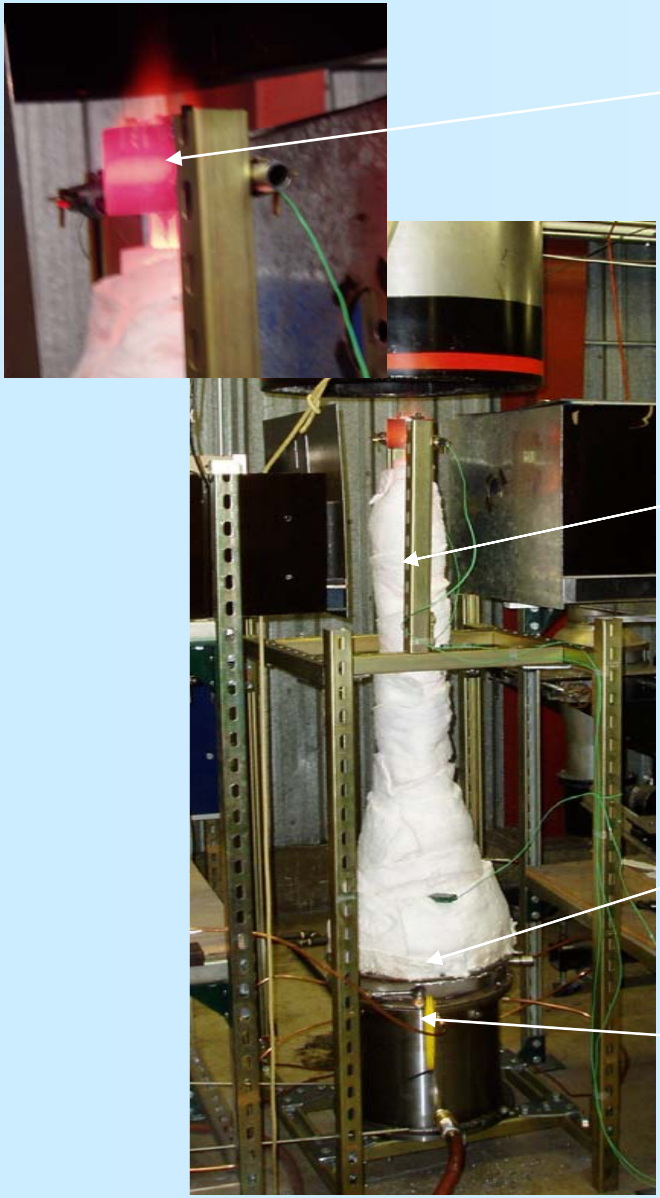
- Documented well over 100 specimens of turbine roughness as a function of service time (aero & land-based). [BYU/AFRL]
- Laboratory simulation of deposit evolution with service time. [BYU]
- Wind tunnel study with scaled models of evolved deposits. [BYU]
- Laboratory simulation of erosion. [UC]
- 3D CFD simulation using real roughness models. [ISU]
- 2D roughness study to develop suitable empirical roughness correlations for industry. [ISU]
- Surface erosion modeling incorporated in fully scaled gas turbine flow simulation. [UC]

Technical Results

Order of Presentations:

1) BYU/AFRL/UC – Jeffrey Bons
2) MSU/ISU – Tom Shih

Turbine Accelerated Deposition Facility



Test coupon held inside exit cup at 90, 60, 45, or 30 deg.

Particle acceleration and thermal equilibrium tube.

Particulate injection

Natural gas combustor

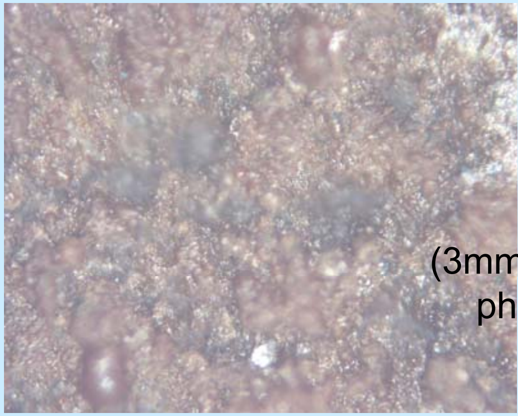
- Design Parameters to match: temp, velocity, angle, materials, particle size, chemistry, and concentration.
- Clean burning combustor with known particles added in known concentrations.
- Inconel construction allows max jet temperature of 1200C (for now).
- Exit velocities up to 400m/s – deposition by inertial impaction.
- Coupons donated from GE, S-W, Solar, and Praxair.
- Particle characterization:
    - Mass mean 15μm
    - Filtered oxide particles from urban air
- Match net particle throughput:

8000hrs x 0.1ppmw ≈ 4hrs x 200ppmw

Test Facility Validation

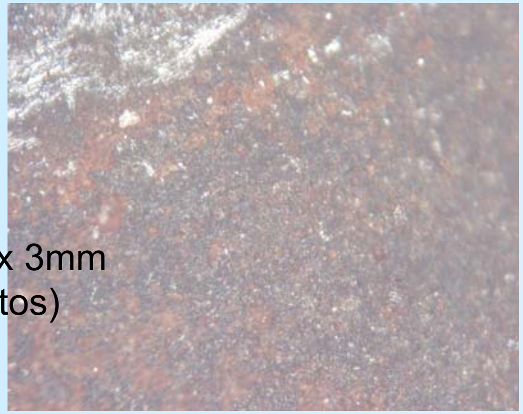
Similar Surface Roughness

4hr test with 60ppmw, 1150C, 220m/s



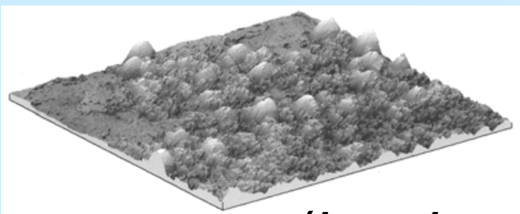
Ra = 27.8μm

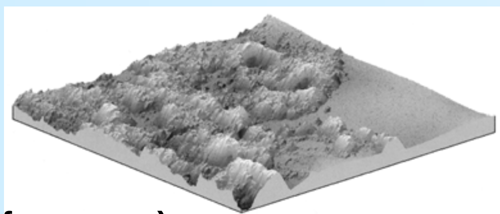
1[st] Stage Turbine Blade: 25000hr



Ra = 31.5μm

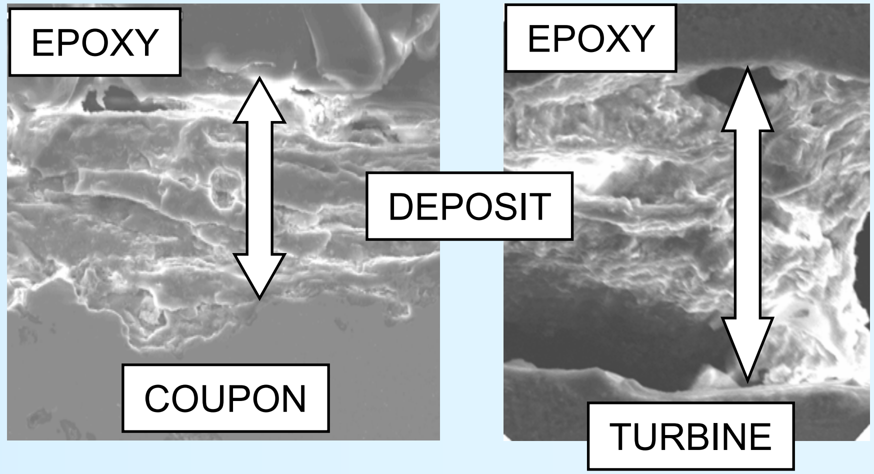
(3mm x 3mm photos)



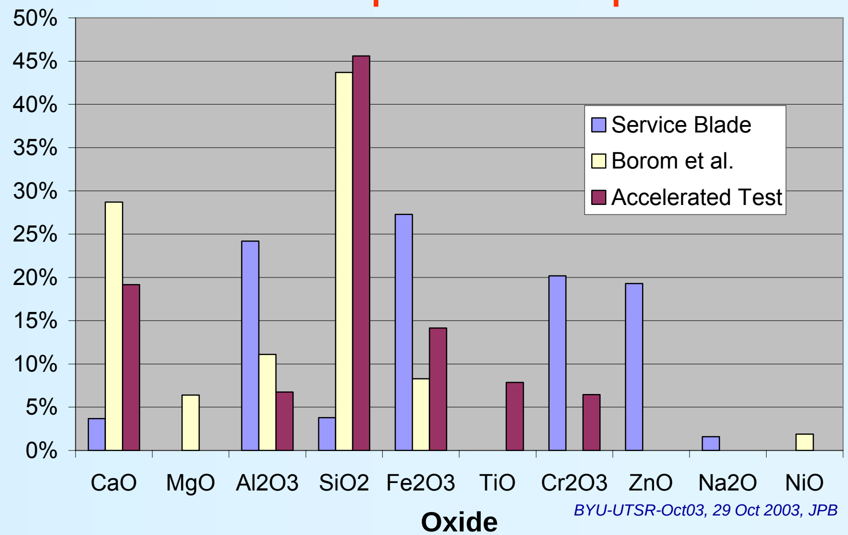


(4mm x 4mm surface maps)

Similar Deposit Thickness & Structure



…and Deposit Composition



BYU-UTSR-Oct03, 29 Oct 2003, JPB

Reported at IGTI 2004 in Vienna.

Deposit Evolution

Constant test conditions: 1150C, 220m/s (M = 0.32), 45° impingement, 25ppmw

0 hours	2 hours (3 months*)	4 hours (6 months*)	6 hours (9 months*)	8 hours (1 year*)

*[*Assumed 0.025ppmw particulate loading]*

Tested 3 Different Material Systems

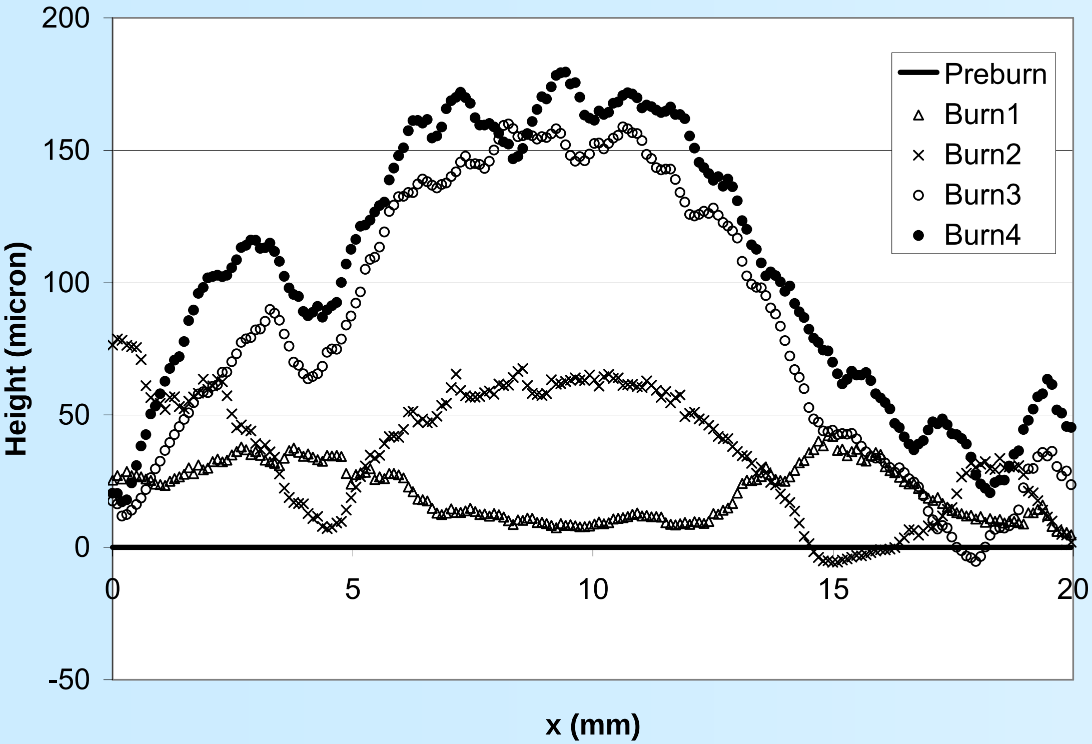
-Bare, polished metal substrate

-APS YSZ TBC (polished)

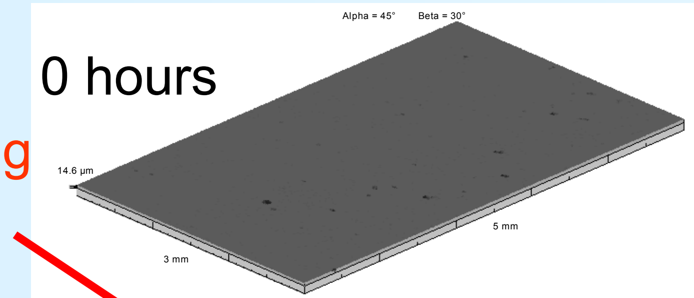
-“As-applied” oxidation resistant coating

Deposit Evolution on Polished Substrate

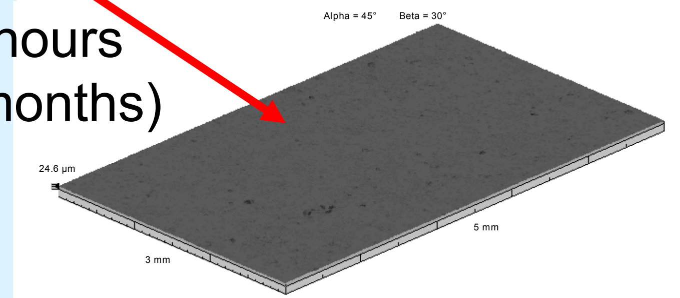
Deposit flaking due to initial Ra<0.5µm



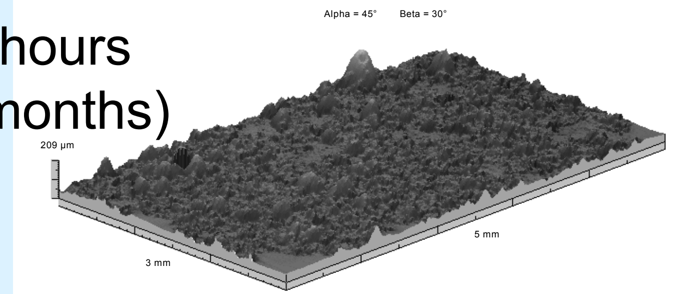
0 hours



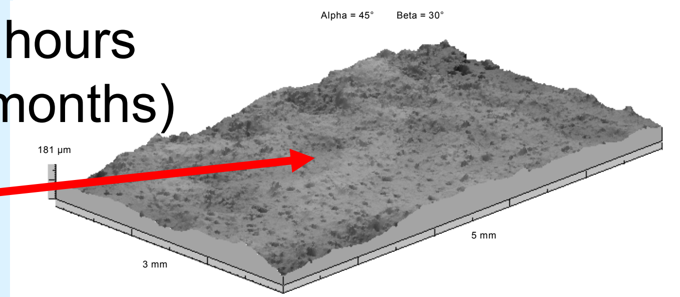
2 hours
(3 months)



4 hours
(6 months)

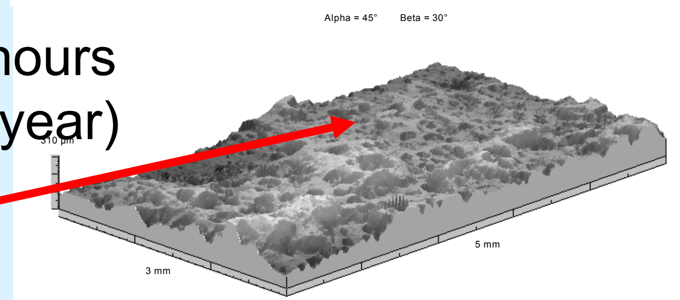


6 hours
(9 months)



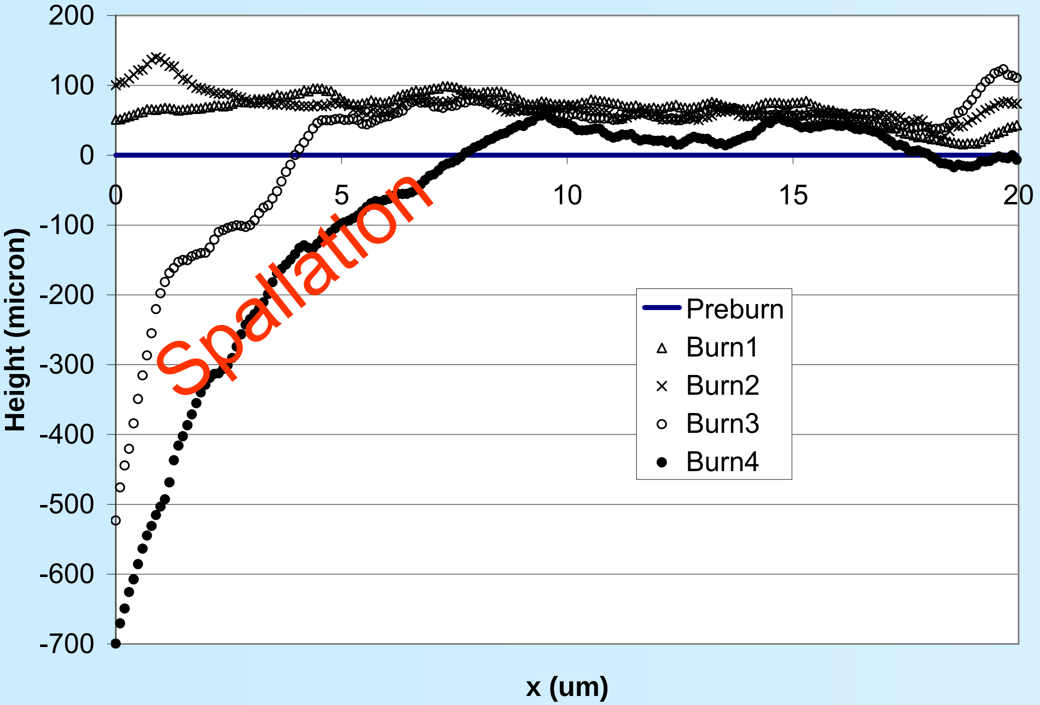
Deposits fill voids, effectively smoothing surface.

8 hours
(1 year)



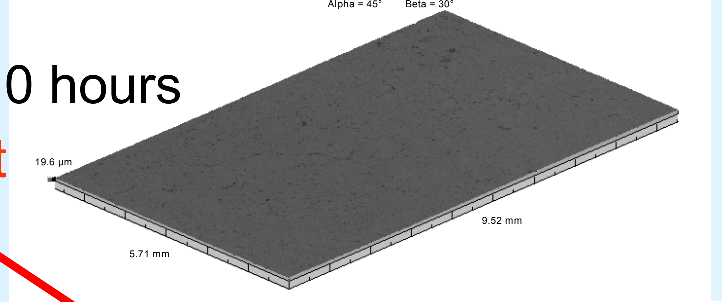
New peaks resurface.

Deposit Evolution on TBC Coupon

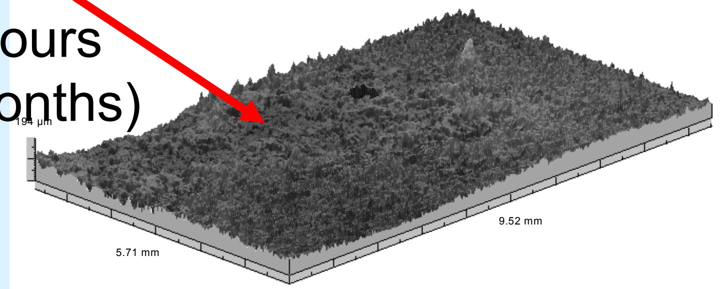


Minimal deposit flaking

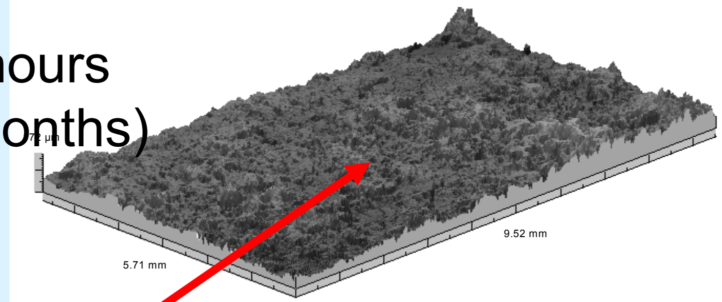
0 hours



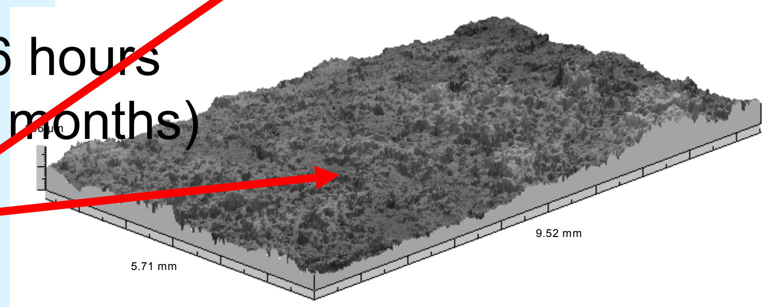
2 hours
(3 months)



4 hours
(6 months)

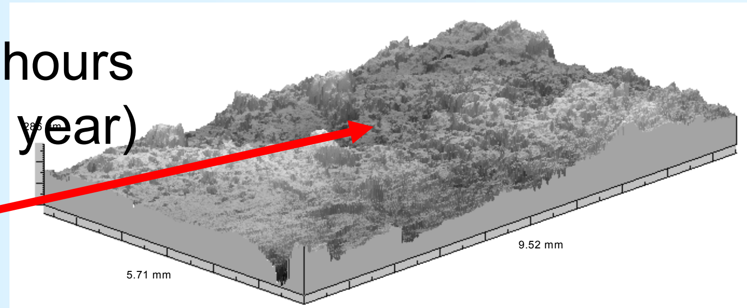


6 hours
(9 months)



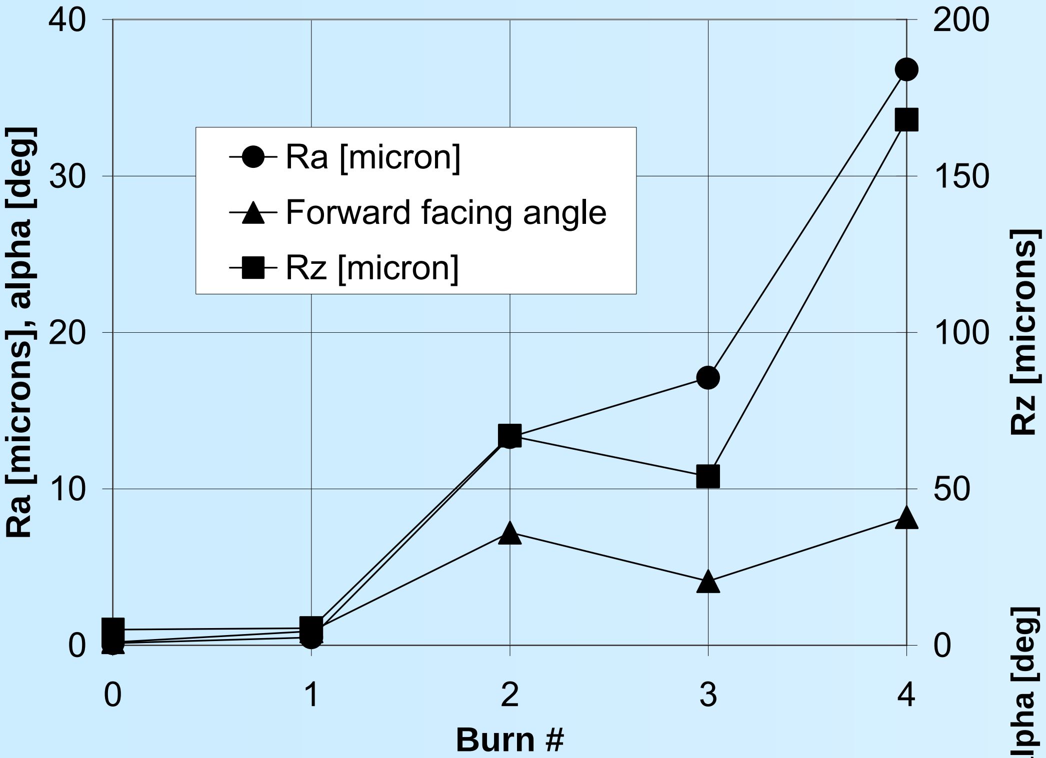
Deposits fill voids, effectively smoothing surface.

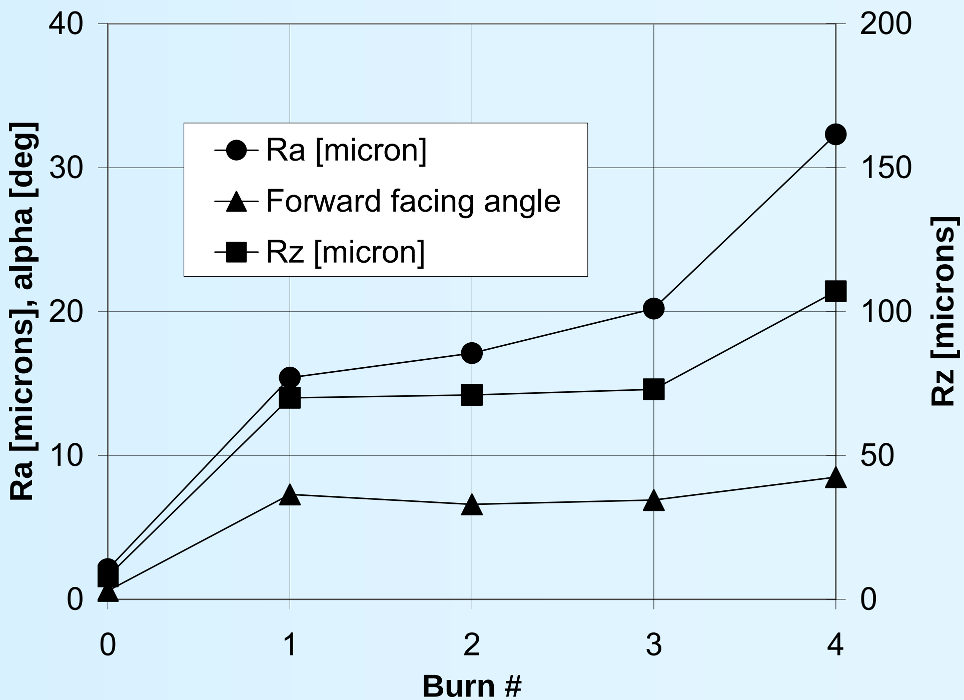
8 hours
(1 year)



New peaks resurface.

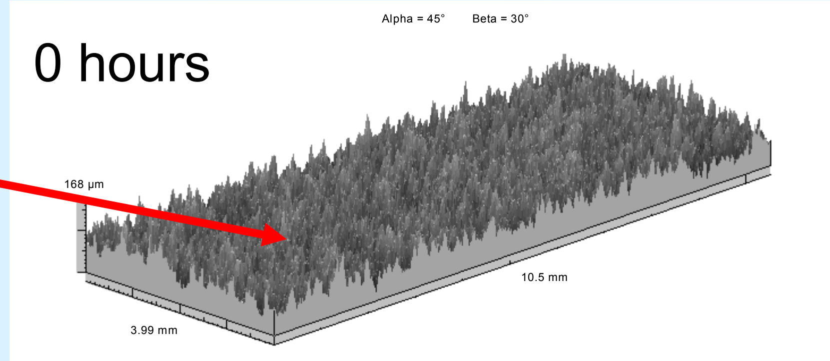
Evolution of Roughness Statistics

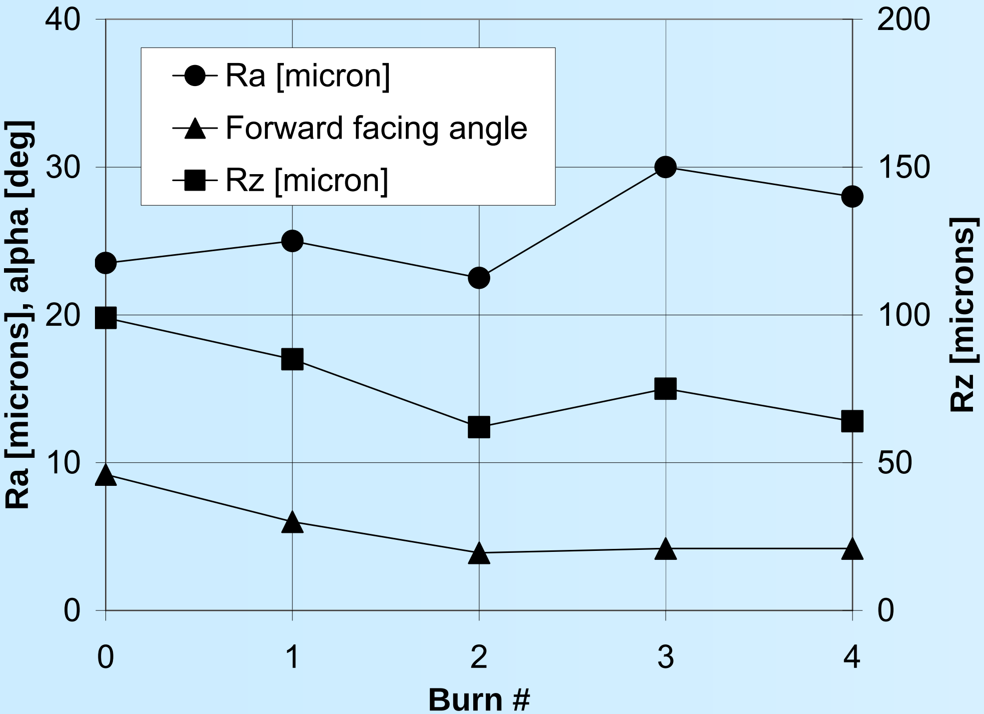


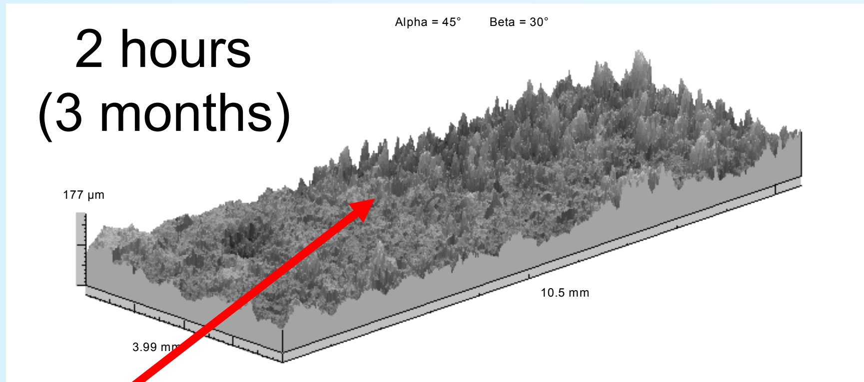


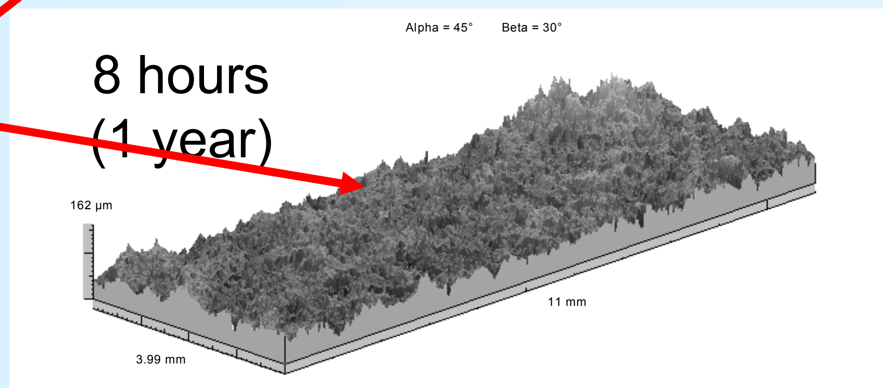
Deposit Evolution on "As-Applied" ORC

Virgin coupon with Oxidation Resistant Coating – no surface polishing.



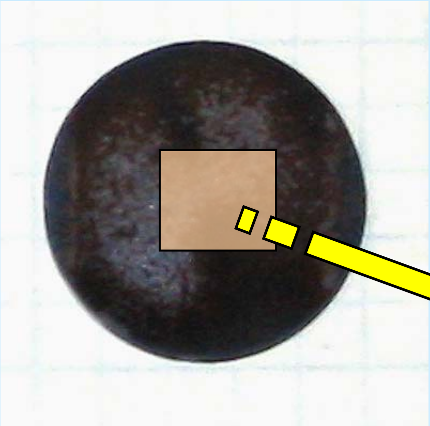




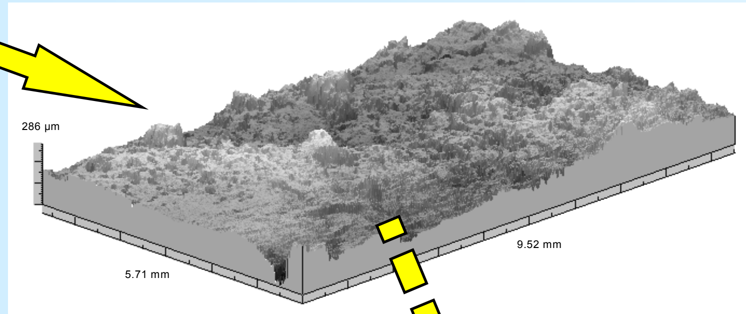


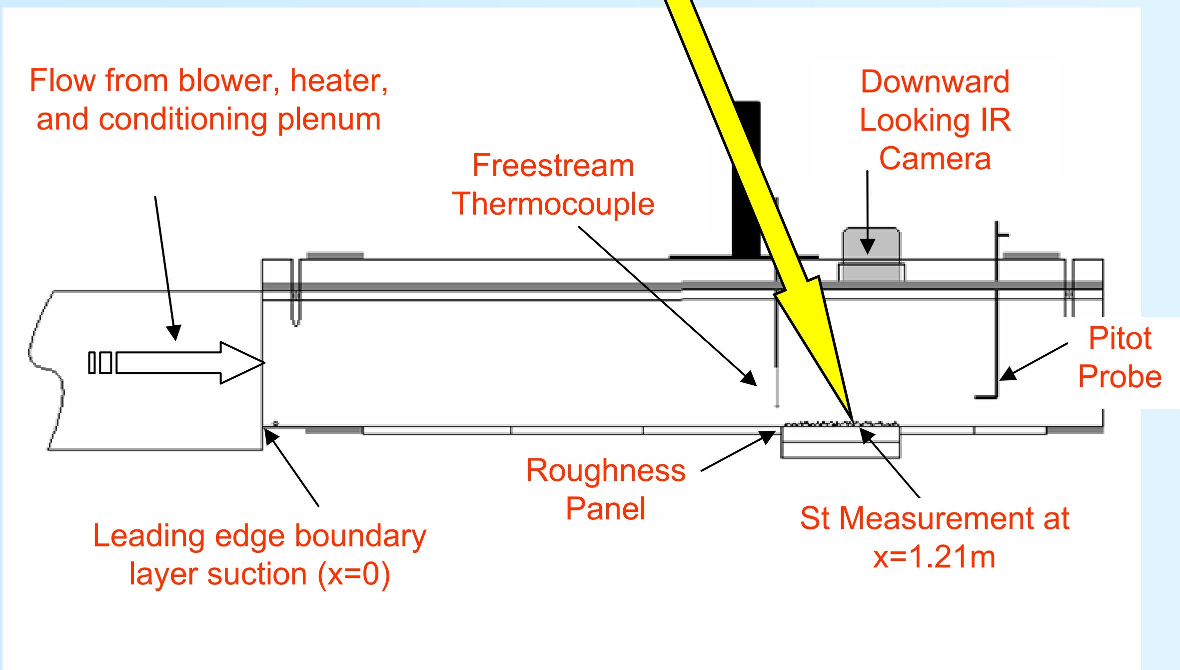
Deposits partially fill voids, effectively smoothing surface.

Experimental St Measurement

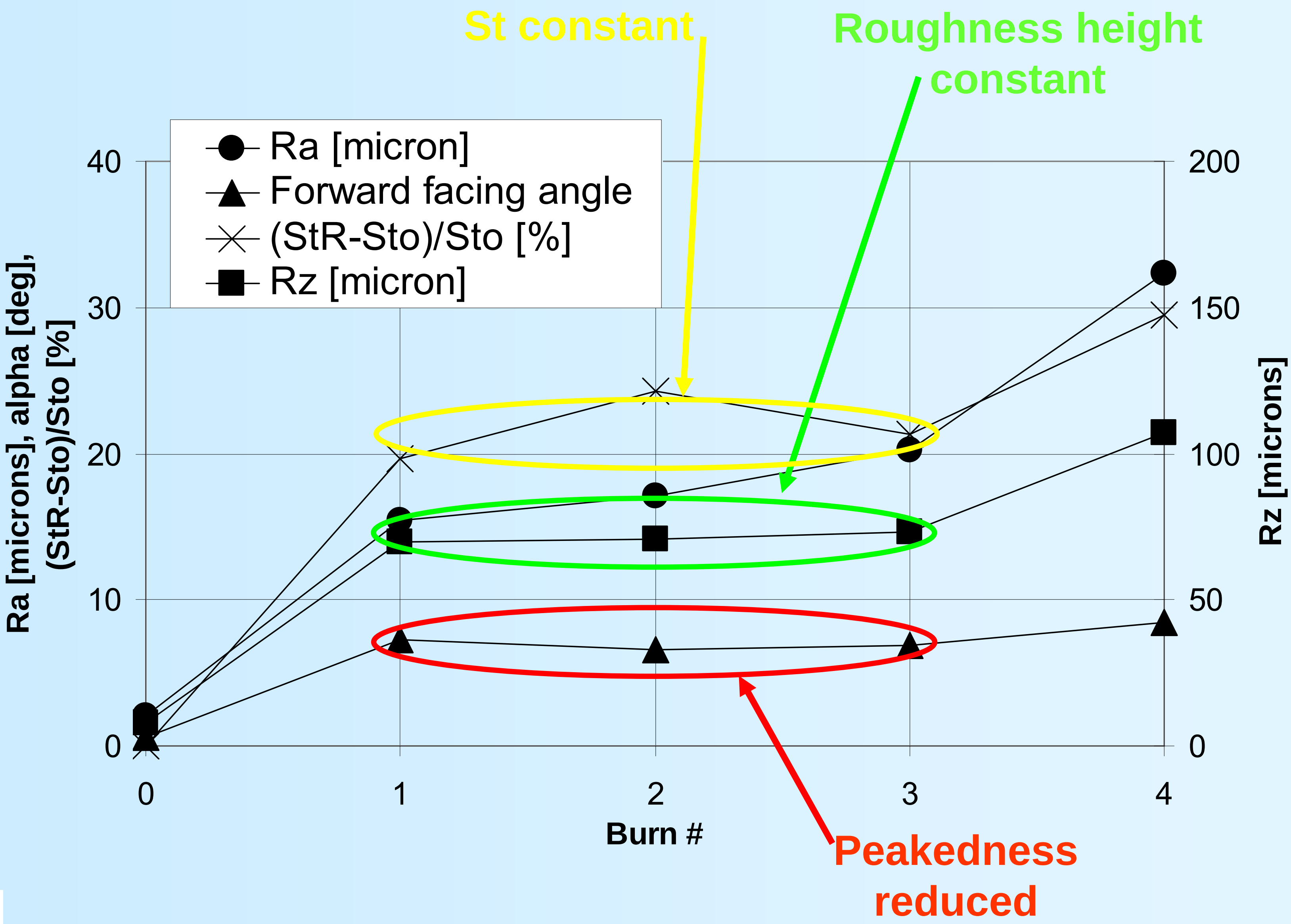


Scaled TBC Deposit as f(time)



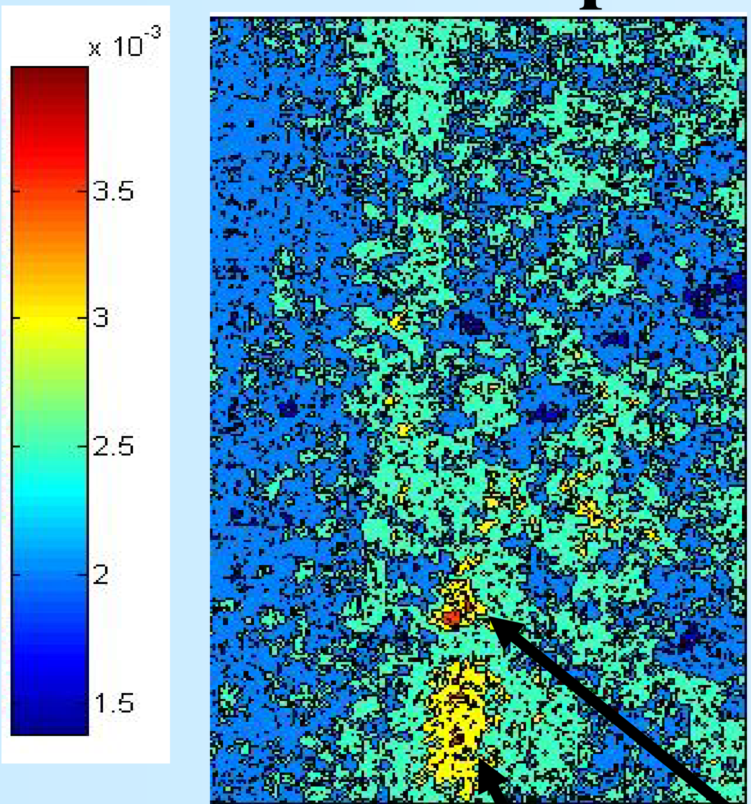


Experimental St Measurement

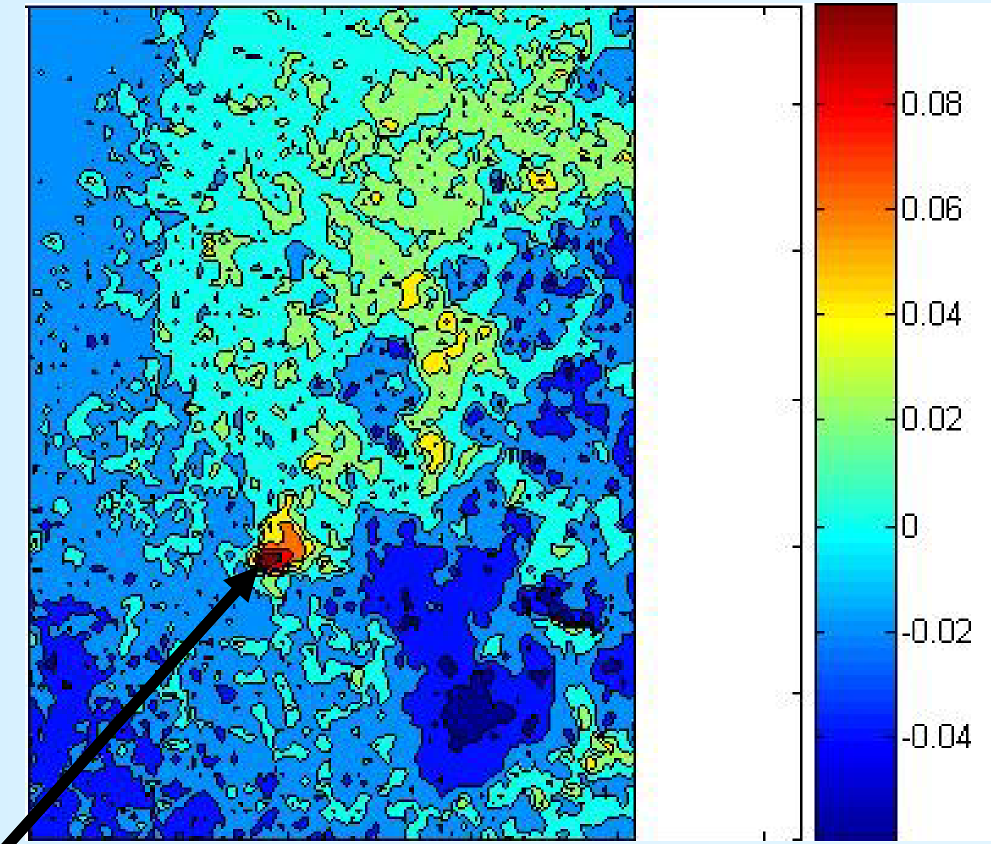


Experimental St Measurement

St Map



Roughness Map



Large Roughness Peak

Elevated St in wake of roughness peak

Dr. Richard Rivir
Air Force Research Laboratory
Wright-Patterson AFB

AFRL MEASUREMENTS AND SIMULATIONS

Taylor Hobson contact surface measurement system
- 2D and 3D traverses
- 50mm stroke length
- 2mm max height
- 5-25nm Δx spacing
- ±25nm height accuracy

Objective: Examine aircraft turbine blading to obtain time histories of roughness.

Results to Date :

1. 2D and 3D measurements completed on 25 HPT blades and vanes and 20 LPT blades and vanes with service times from 1 to 10,000 hours.
2. 2D measurements provided for 16 coated coupon samples for UC erosion tests.
3. 2 roughened vanes tested in AFRL's Turbine Research Facility (TRF).

Next Step:

1. Measurements at USAF engine overhaul facility (Oak City)
2. Continued TRF testing and data processing

Aero-engine blades with @ 256.9,476.6, 551.2, 2151.9 service hours. Increased Deposits, Discoloration, Erosion

Spallation Characteristics

Large sites of coating delamination near cooling holes (leading edge):

HPT P Surface 3D

Sa ~10- 100µm

St~100- 300µm

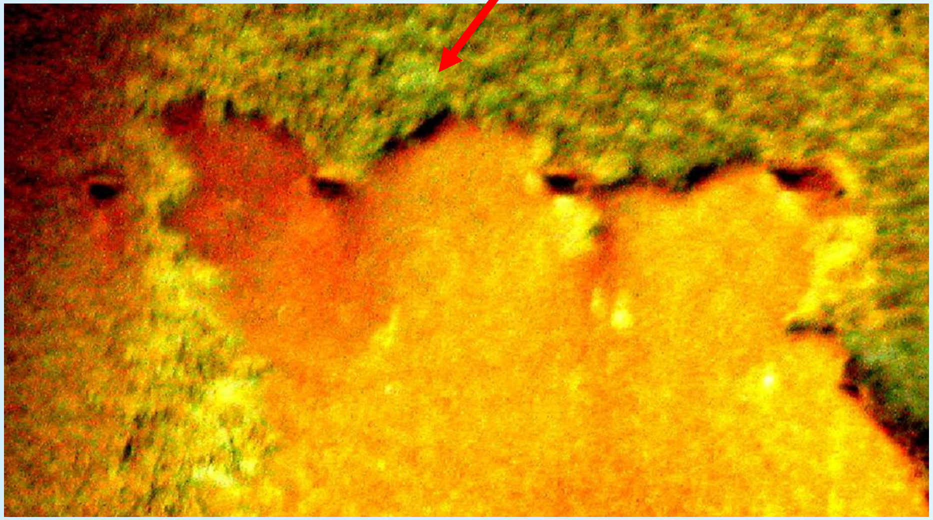
(Spalled in Service Blades)

Residual coating exhibits elevated roughness:

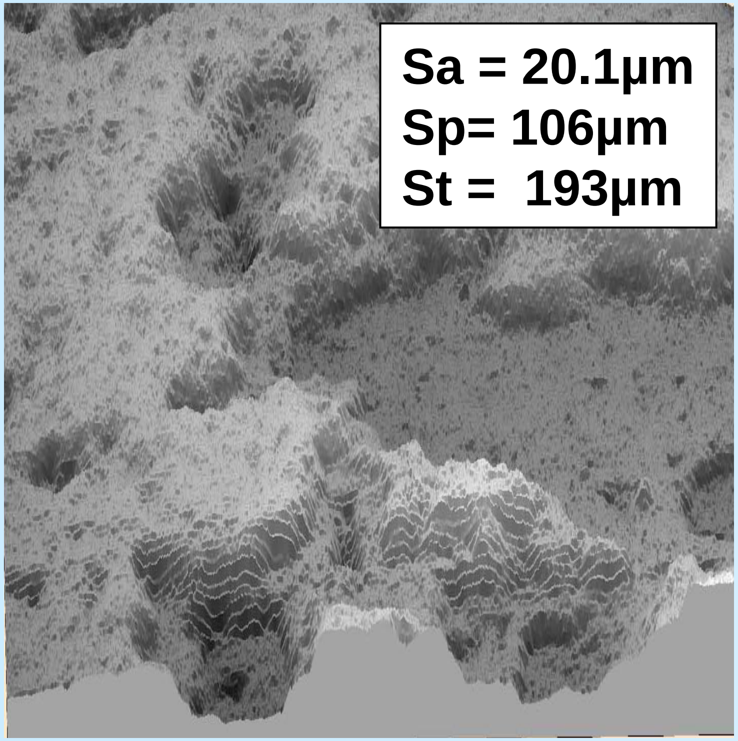
Pressure Side HPT

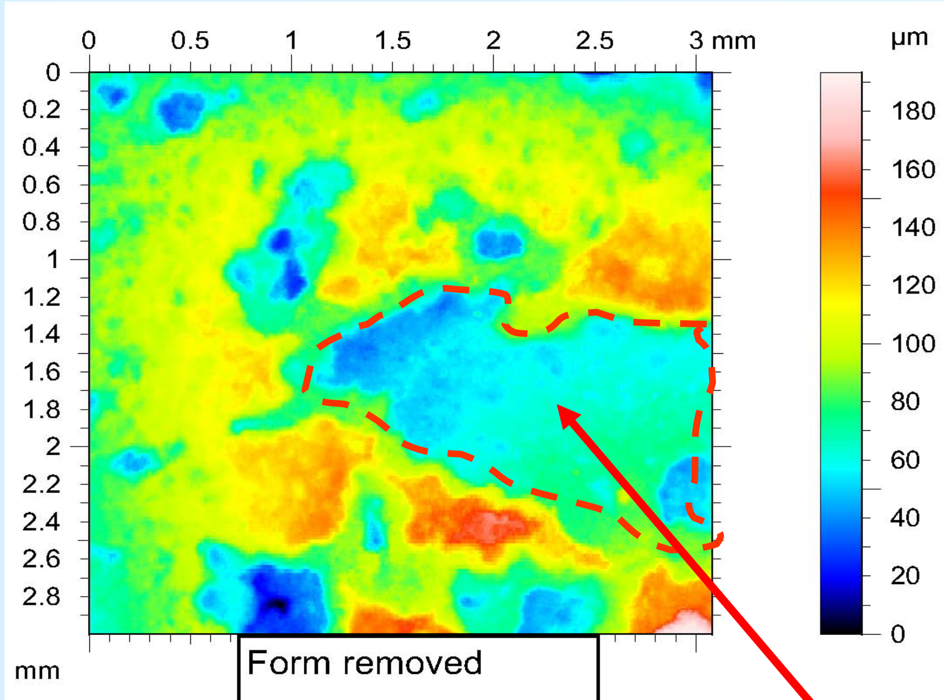
Sa = 89µm

Sp= 301µm



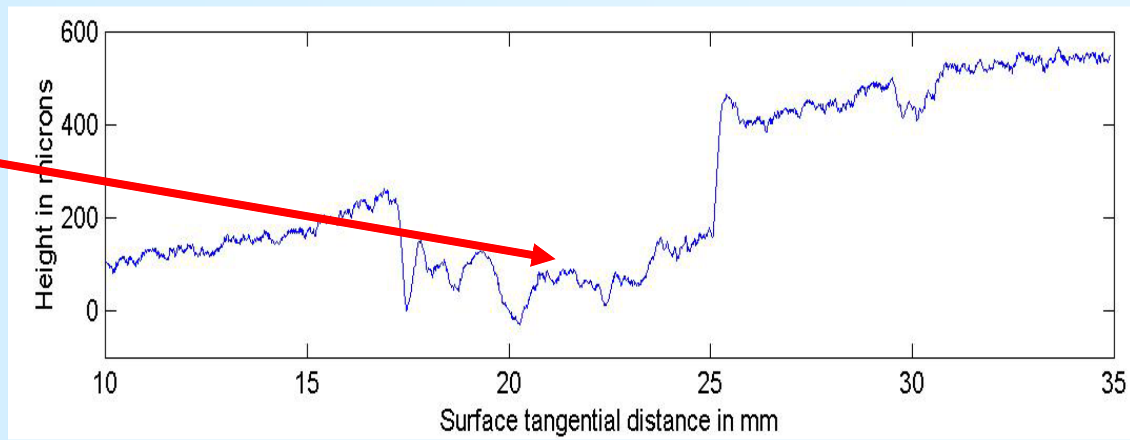
Sample 3D surface measurements of suction surface spallation





3D Spallation Zone

2D trace shows abrupt transition at Spallation site



Gas Turbine Erosion prediction methods at University of Cincinnati

Dr. Awatef Hamed

Dr. Widen Tabakoff

Gas Turbine Erosion & Roughness Studies at University of Cincinnati

Experimental studies of particle surface interactions

- Erosion Tests and surface roughness measurements
- Measurements of particle restitution characteristics

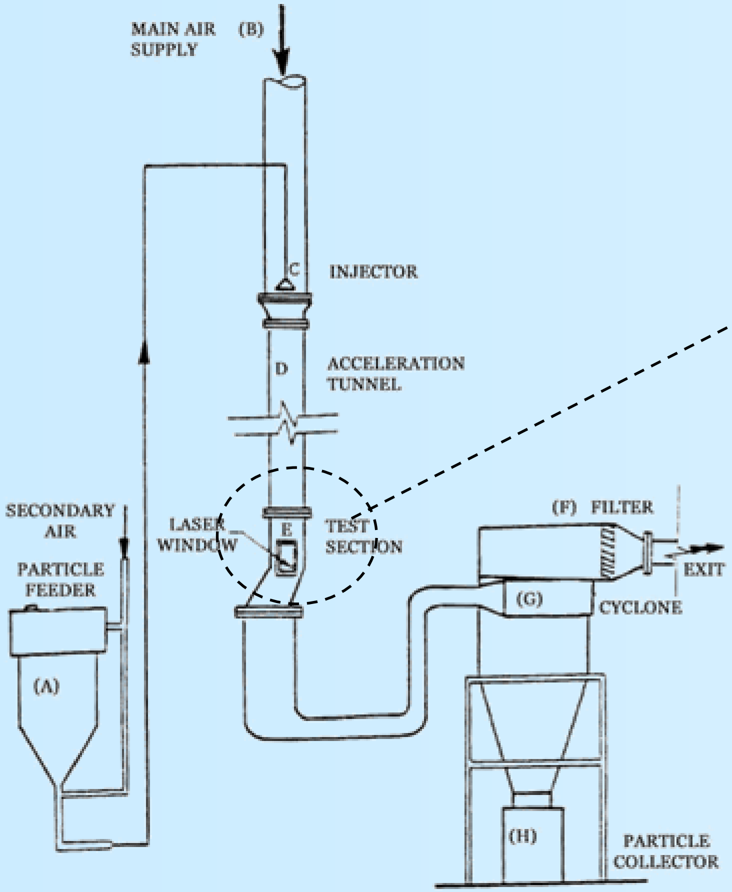
Particle Trajectory Simulations

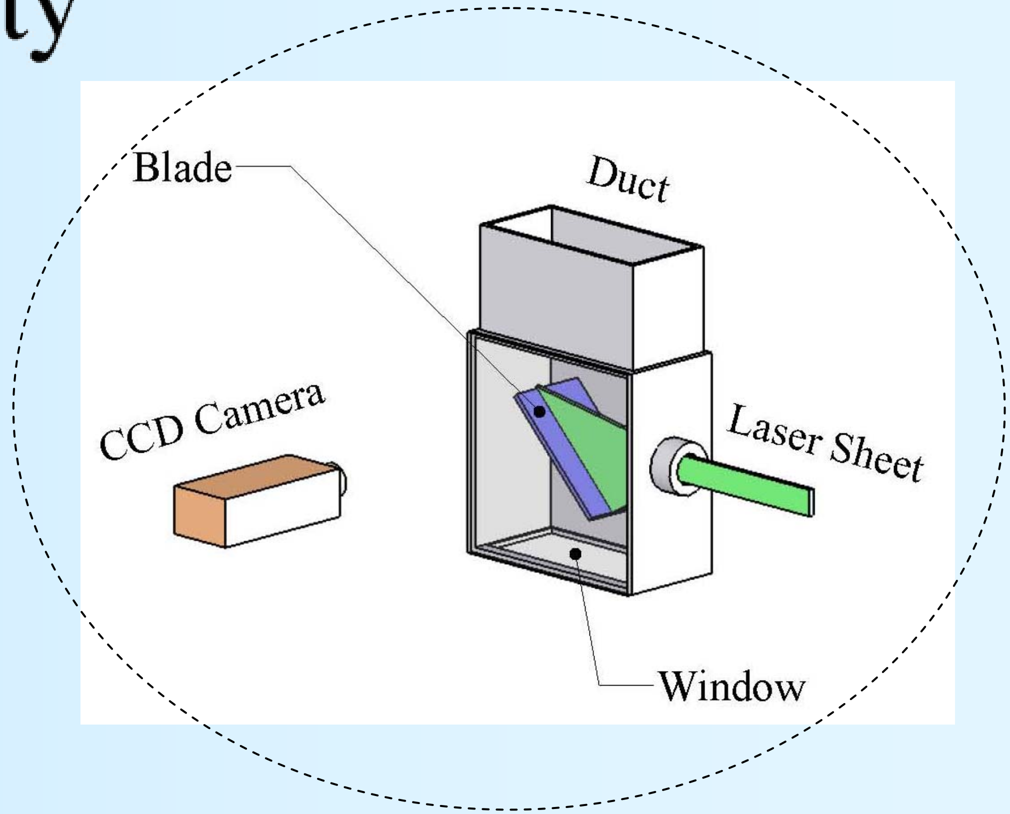
- 3-D modeling of turbine flow and blade passage geometry
- Particle dynamics incorporates experimental surface restitution models

Blade Surface Erosion and Roughness Predictions

- Trajectory simulations provide surface impact statistics
- Predictions incorporate erosion and roughness measurements

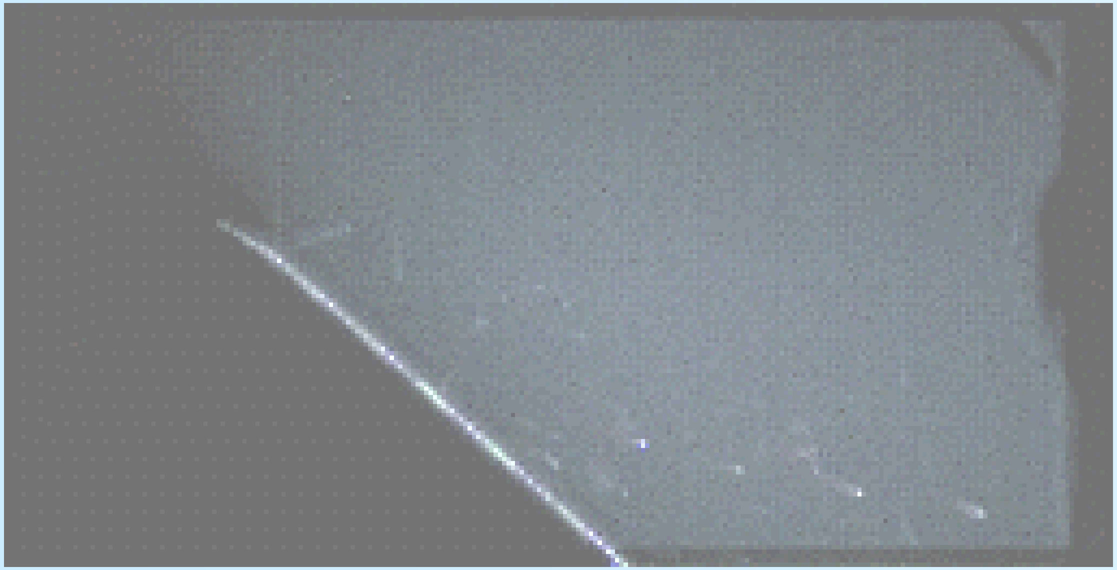
Rebound Test Facility



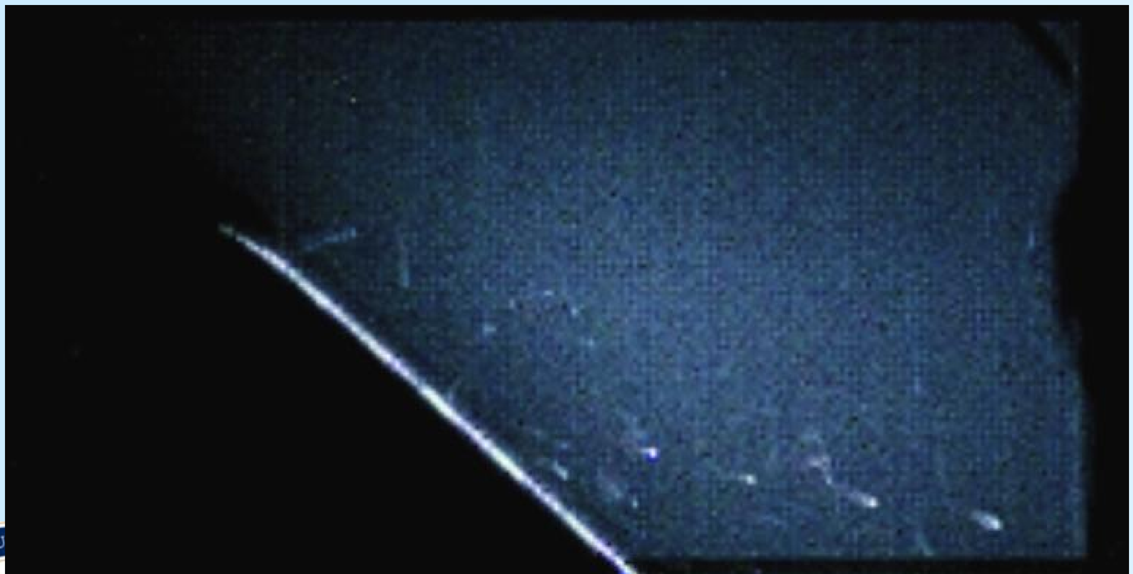


U =60 m/s

CCD Camera: Phantom High speed camera, 128 pixel x 256 pixel, 48000 fps, exposure time 4 ns



Original Image

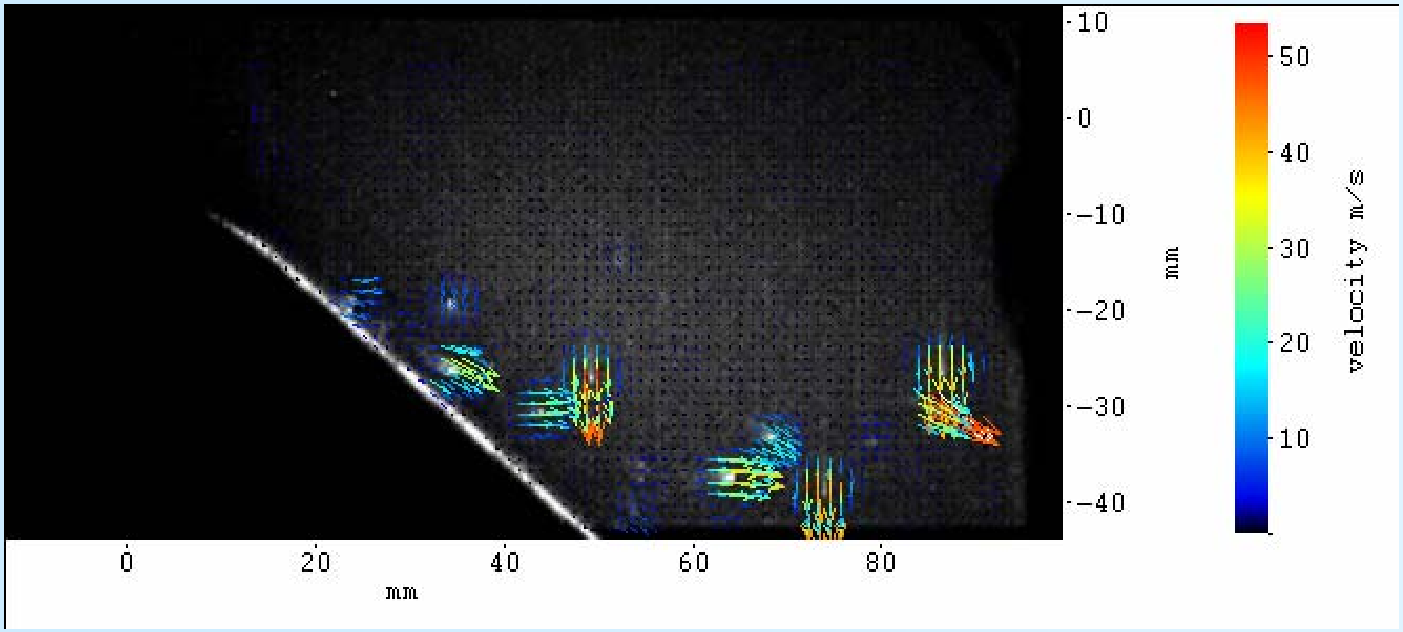


Enhanced Image

Velocity Vector Calculations

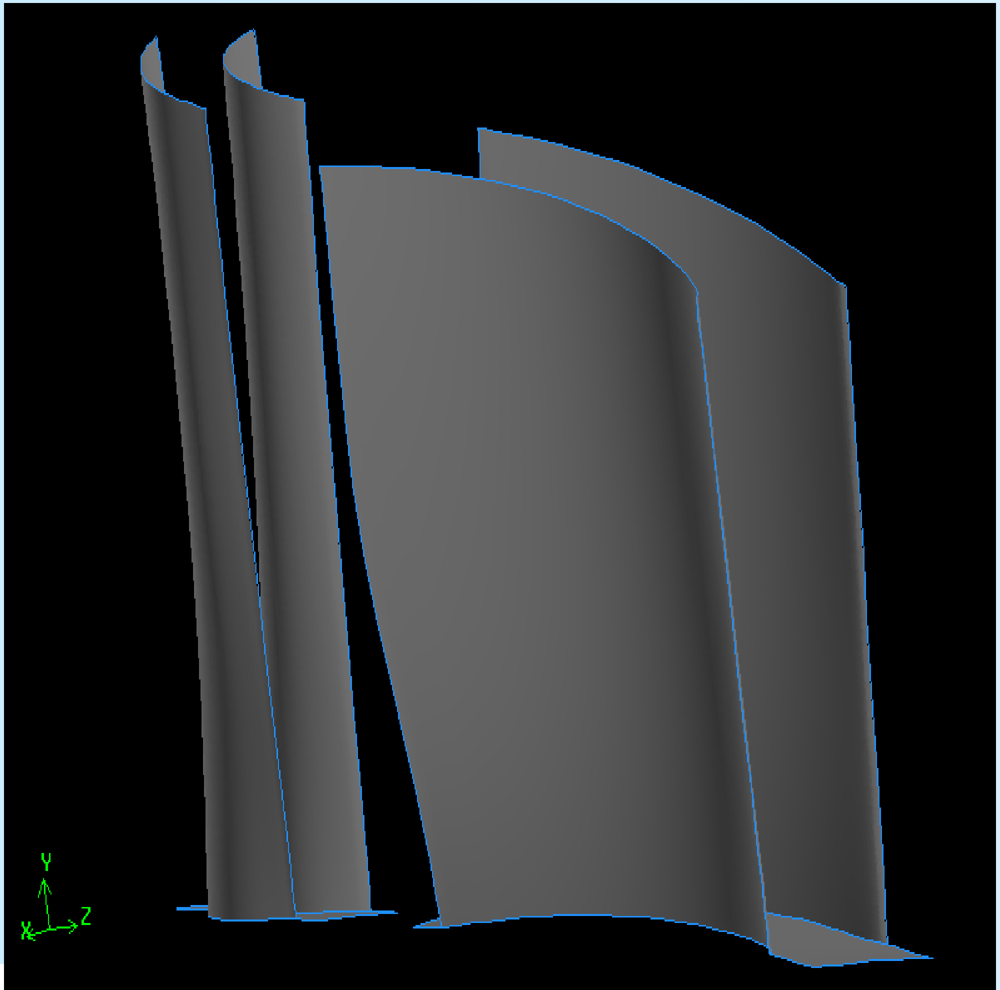
• Using Davis 7.0 Software

• Time-series cross-correlation with dt = 21 micro sec between the frames (singe frame single exposure)



Computational Results

1st Stage GE E^3 LP Turbine



Stator

- Blade Height : 3.35”
- Mid-span Pitch : 1.10”
- Mid-span Chord : 2.1”

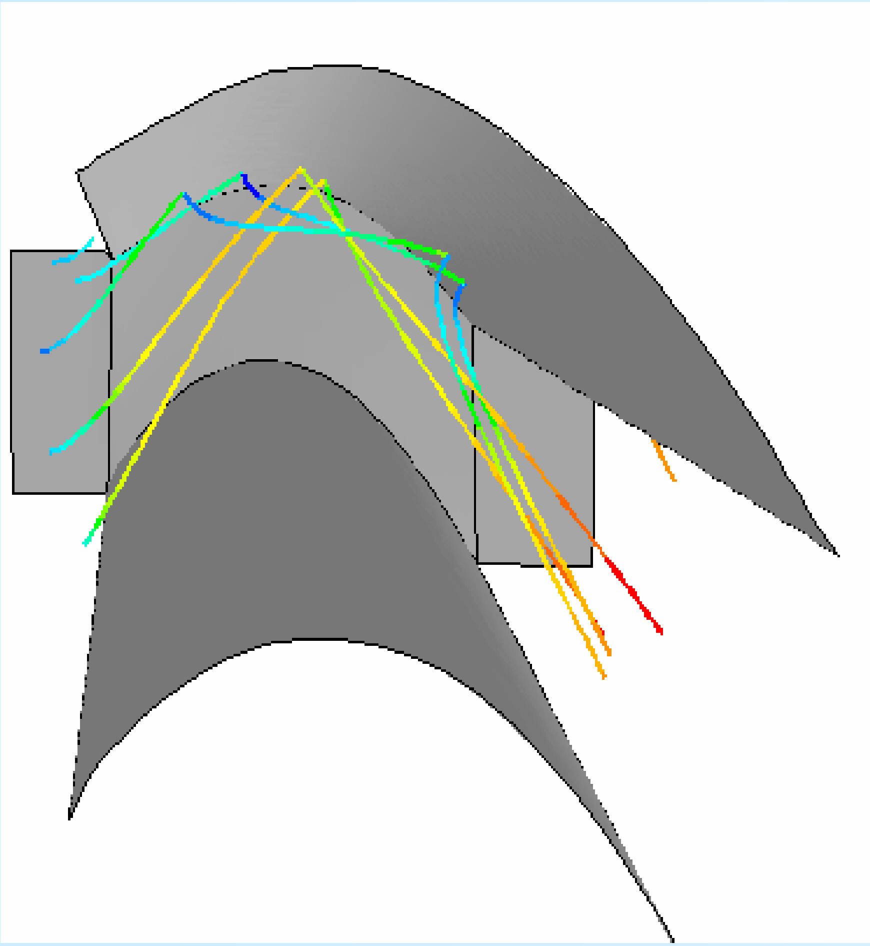
Rotor

- Blade Height : 4.13”
- Mid-span Pitch : 0.68”
- Mid-span Chord : 1.16”

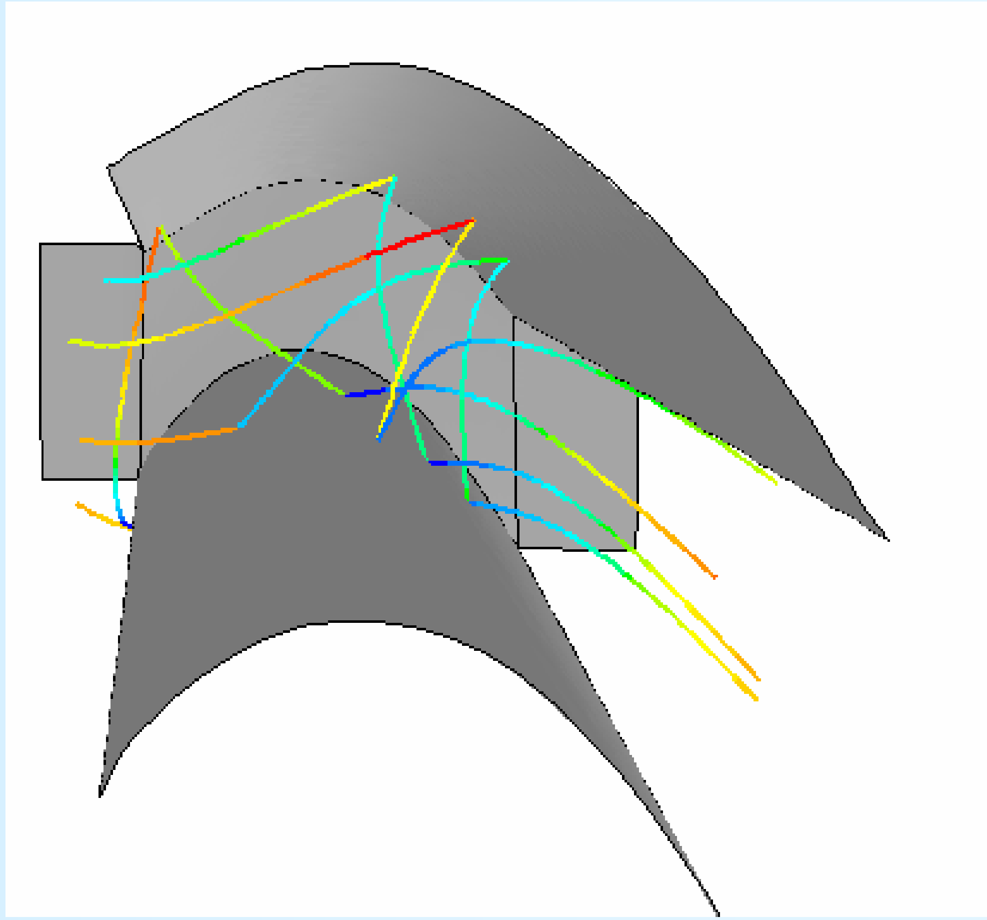
Operating Conditions

- Inlet Stagnation Temperature: 2001.6^{o}R
- Inlet Stagnation Pressure: 36.94 psia
- RPM: 3450
- Stage Pressure Ratio: 1.3
- Stage Temperature Drop: 131.4^{o}R

Sample Particle Trajectories Through Rotor



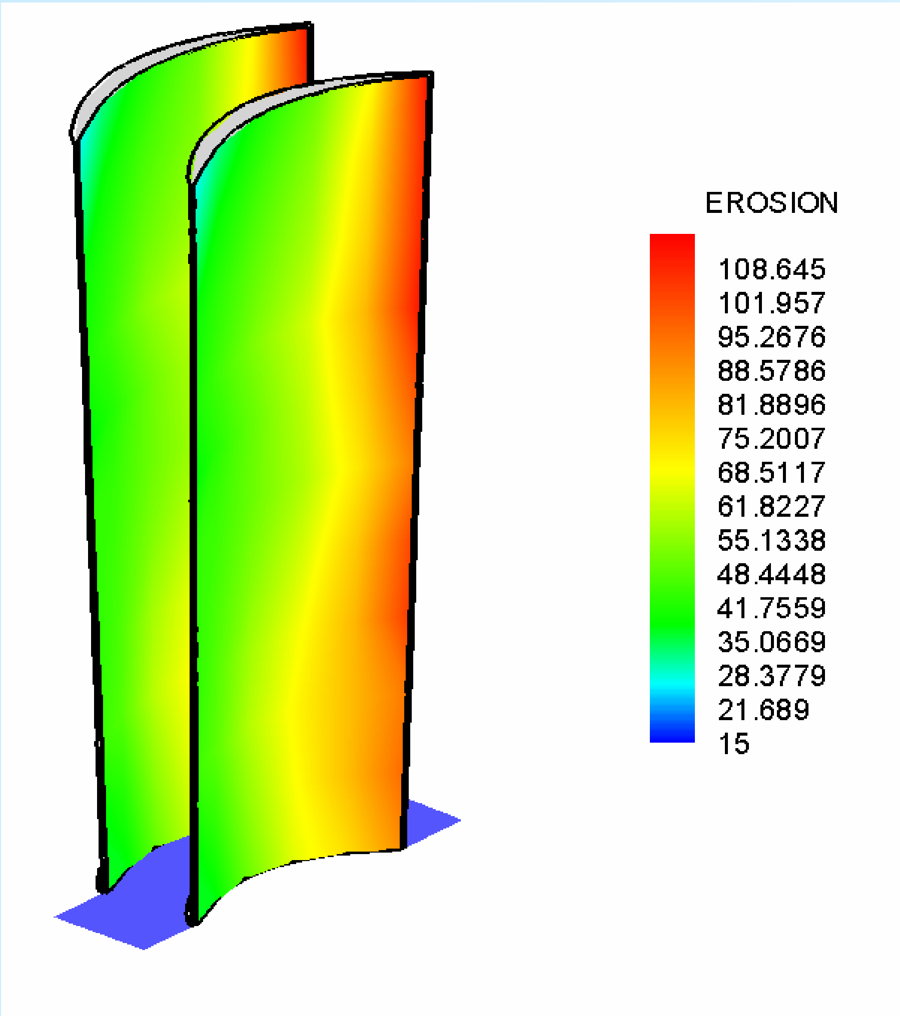
10 micron particles



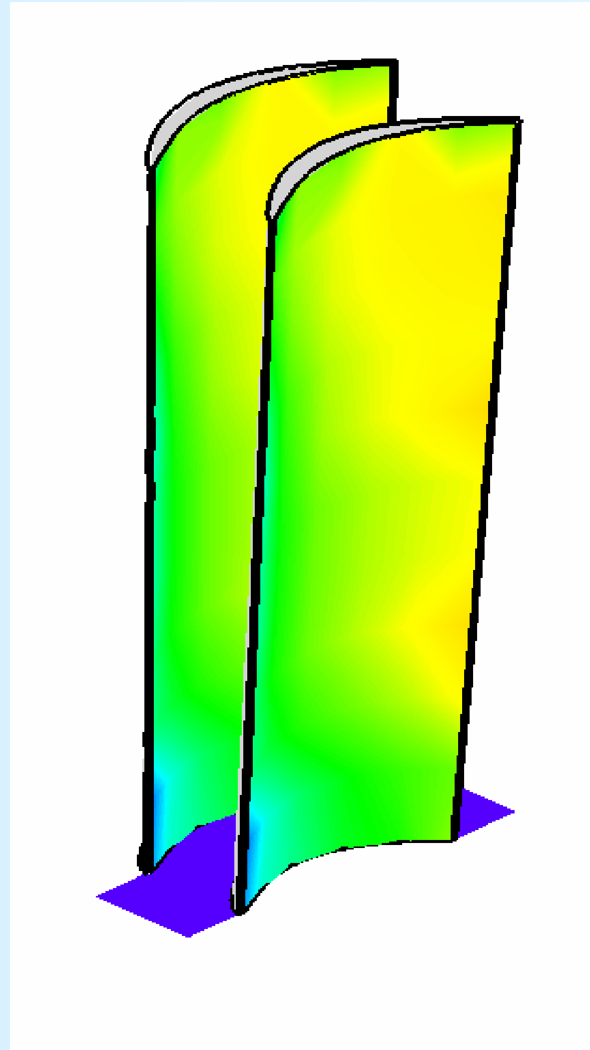
50 micron particles

Predicted Erosion Rate on Rotor Pressure Surface

Mg/g/m2

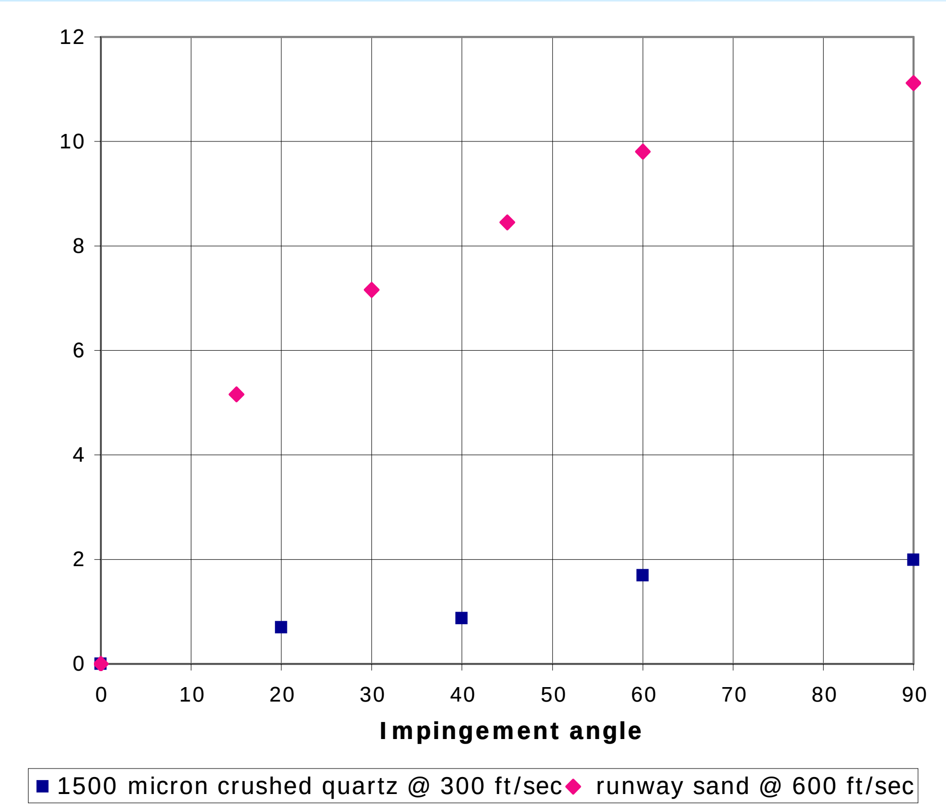


10 micron particles

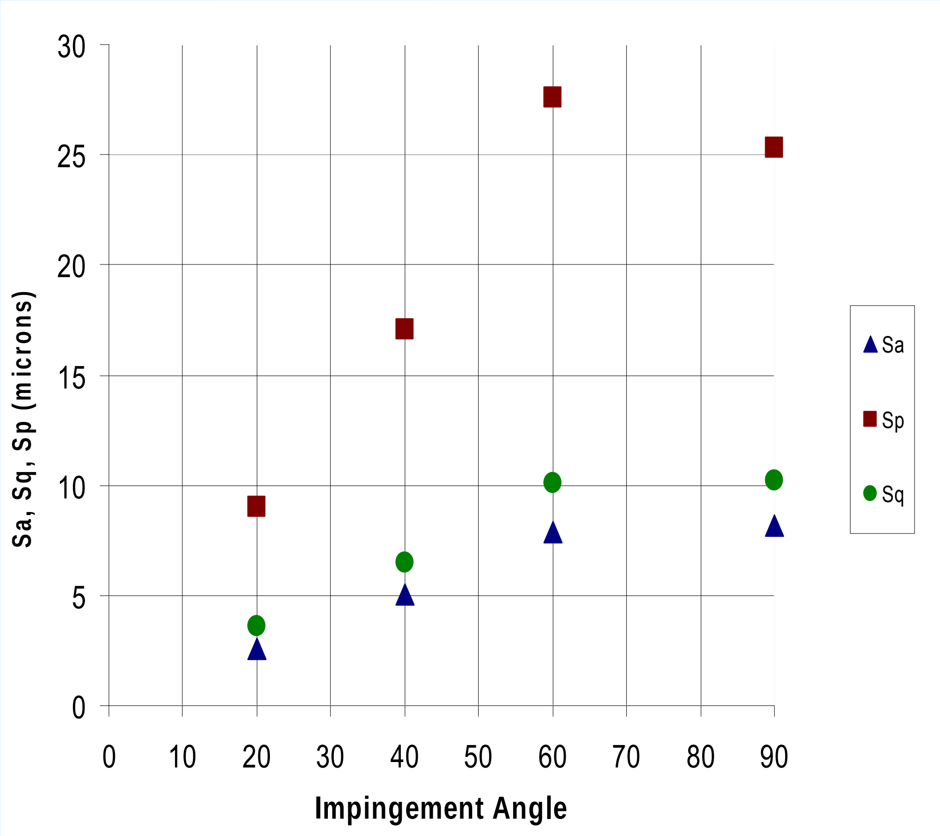


50 micron particles

Experimental Studies of Erosion and Roughness



Erosion Rate (mg/g)

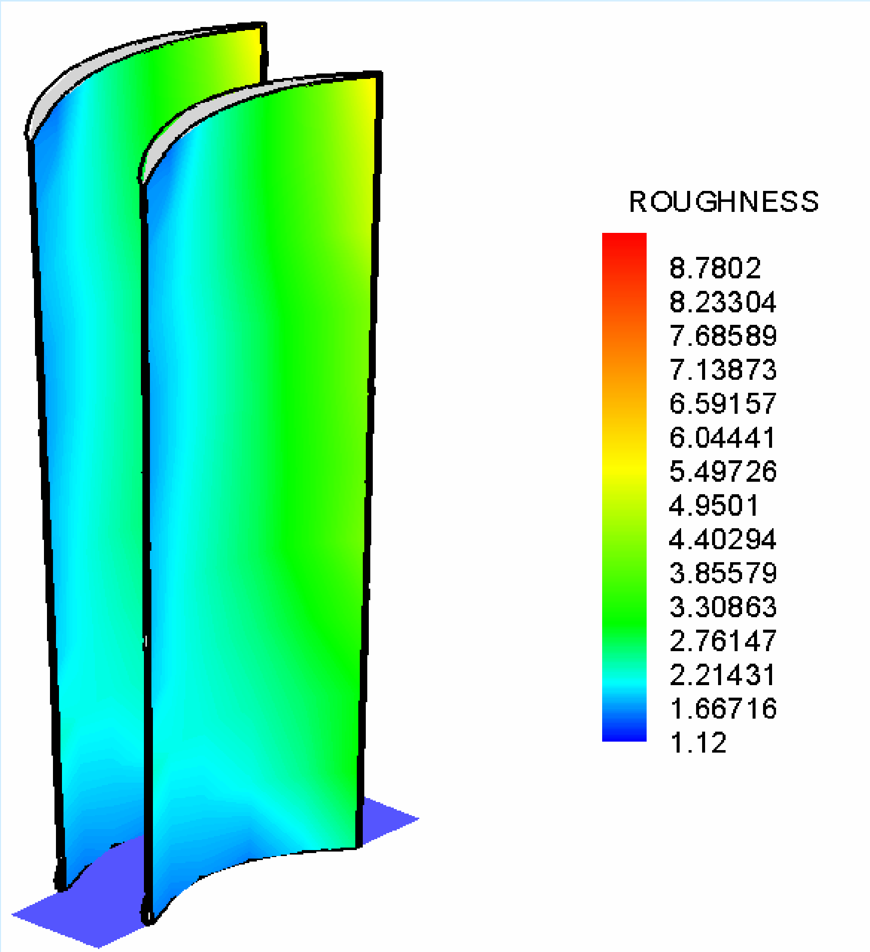


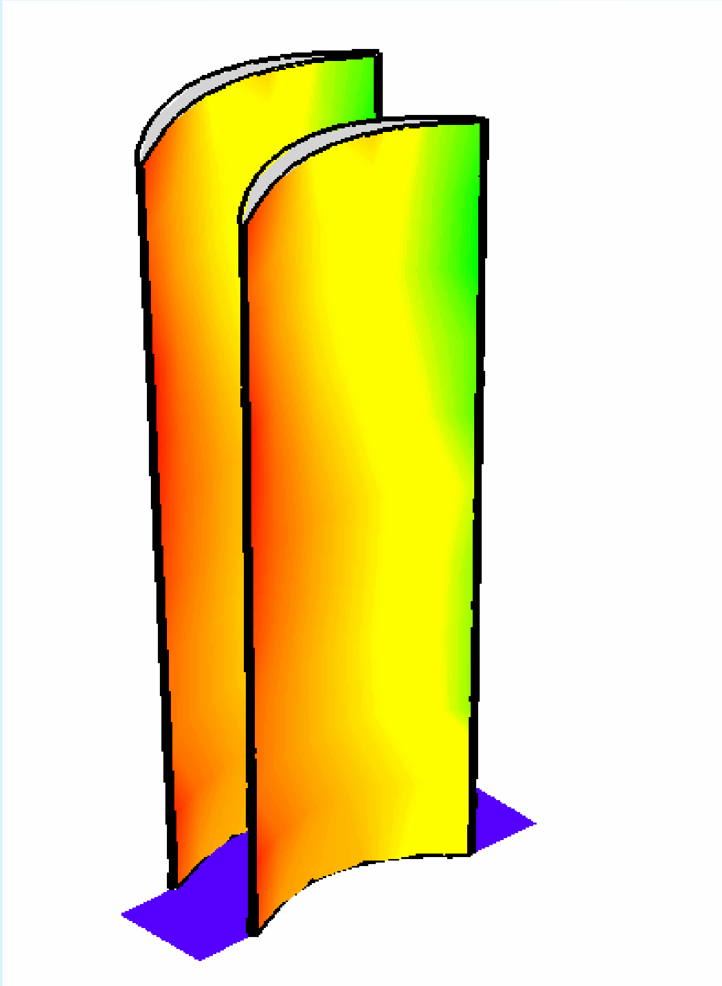
Surface Roughness (runway sand @ 600ft/sec)

- **Erosion rate and roughness increase with impact velocity; impingement angle and particle size**

Predicted Roughness on Rotor Pressure Surface Ra

Micron





10 micron particles

50 micron particles

Summary of Blade Erosion & Surface Roughness Predictions

Stator Blade	Pressure Surface (10 micron)	Suction Surface (10 micron)	Pressure Surface (50 micron)	Suction Surface (50 micron)
Maximum Erosion Rate ($mg/gm/m^2$)	.0009	.0002	0.0015	0.0006
Total Erosion Rate (mg/gm)	.0576	0.0004	0.0975	0.015
Maximum Surface Roughness (μm)	3.5	1.12	6.74	3.5

Rotor Blade	Pressure Surface (10 micron)	Suction Surface (10 micron)	Pressure Surface (50 micron)	Suction Surface (50 micron)
Maximum Erosion Rate ($mg/gm/cm^2$)	0.0112	0.0005	0.00605	0.00878
Total Blade Erosion Rate (mg/gm)	0.31	0.0044	0.20	0.22
Maximum Surface Roughness (μm)	5.51	1.12	8.99	3.90


QUESTIONS?