Evaluation of Mechanical Reliability of Silicon Nitride Vanes After Field Tests in an Industrial Gas Turbine

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ASME TURBO EXPO 2002, Amsterdam, The Netherlands, June 3-6

Research is sponsored by U.S. DOE, Office of Power Technologies, Microturbine Materials Program, under Contract DE-AC05-00OR22725 with UT-Battllee, LLC.

Outlines of Presentation

- ***Background***
  - Motivation for present effort
- ***Experimental Approach***
  - Silicon nitride ceramic vanes tested
  - Rolls-Royce Allison engine conditions
  - Characterization approaches
- ***Results***
  - Microstructural and phase analyses
  - Recession measurements
  - Mechanical properties
- ***Conclusions***

Background

- Long-term mechanical reliability of Si_3N_4 ceramics strongly influenced by two factors
  - ***Intrinsic:*** ***matrix microstructure and chemistry (thus stability) of secondary phase(s)***

    > Mass production of components required modifications in processing parameters to obtain consistent properties.
  - ***Extrinsic:*** ***application environments***

    > Difficult to reproduce in laboratory tests

Key Issue ?

Are the properties of complex-shaped components comparable to those obtained from simple-shaped test specimen ?

Significance of Ceramic Component Evaluation

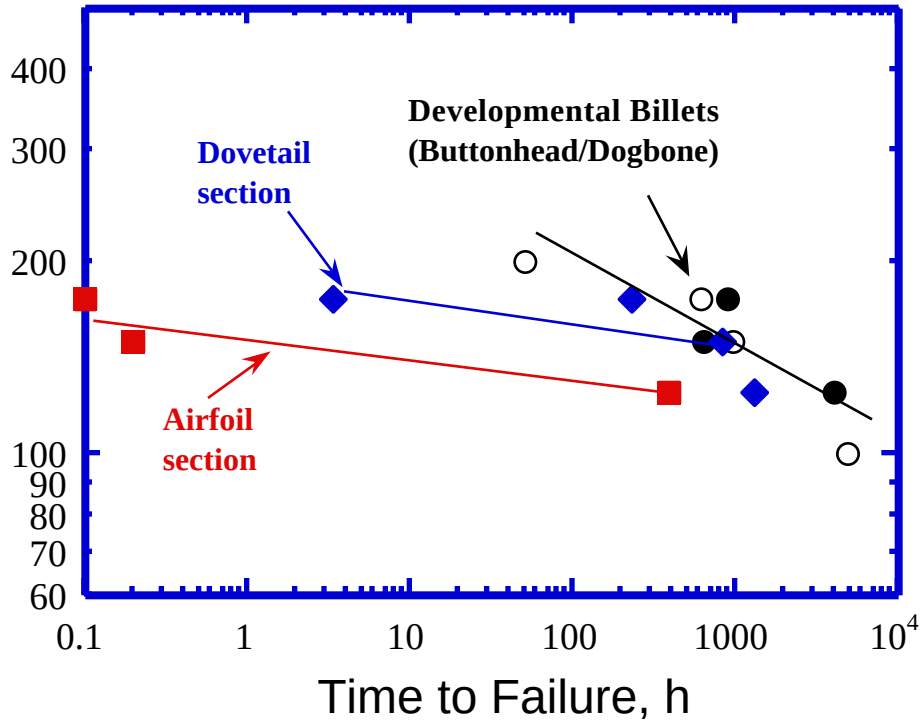
- Allow end uses to verify the mechanical properties of components and compare the results to those obtained from simple shaped test coupons.

- Provide component database to end users for life modeling and advanced design capabilities.

- Provide assessments of ***environmental effects*** on the mechanical reliability and chemical stability of materials that could not be reproduced in laboratory.

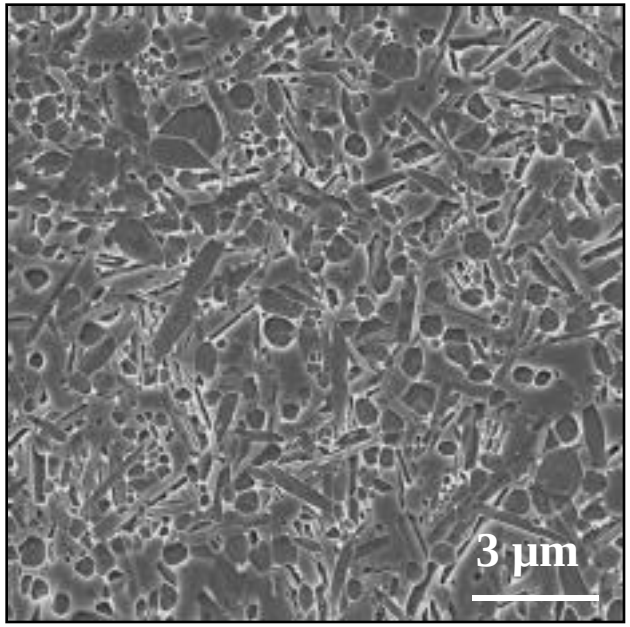
Ceramic Component Subtask Was Motivated by Earlier Studies on NT164 Turbine Blade

Solar Turbines first stage turbine blade



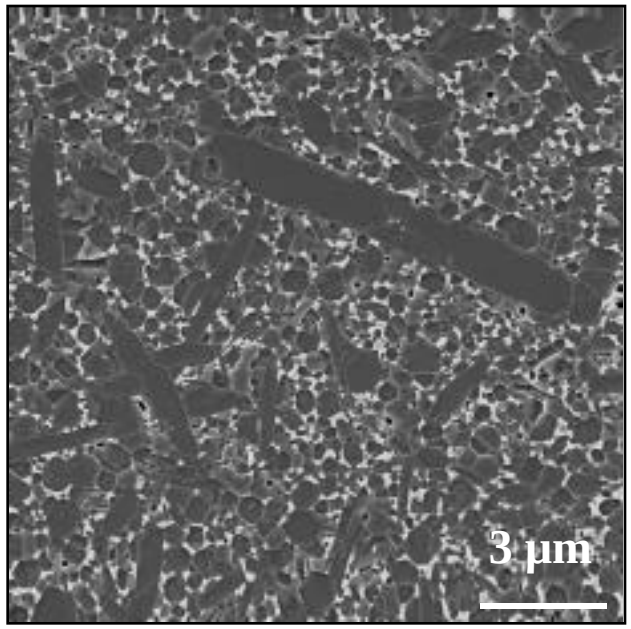
"The database generated from production billets overestimated the lifetime of components"

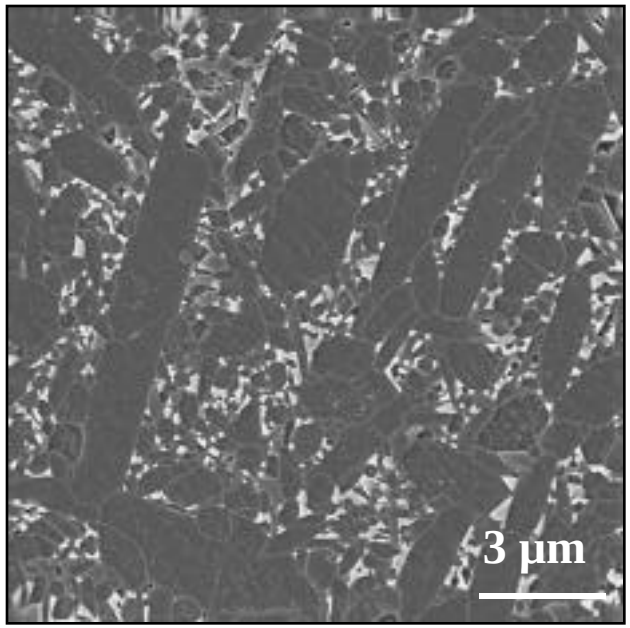
Poor Creep Properties of Component is Due to the Higher Glassy Phase Content and Finer Grain Microstructure



Airfoil Region

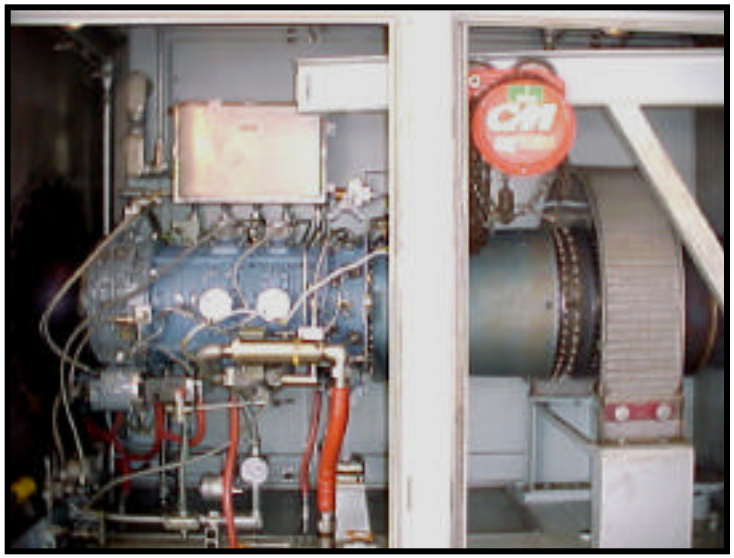
Dovetail Region



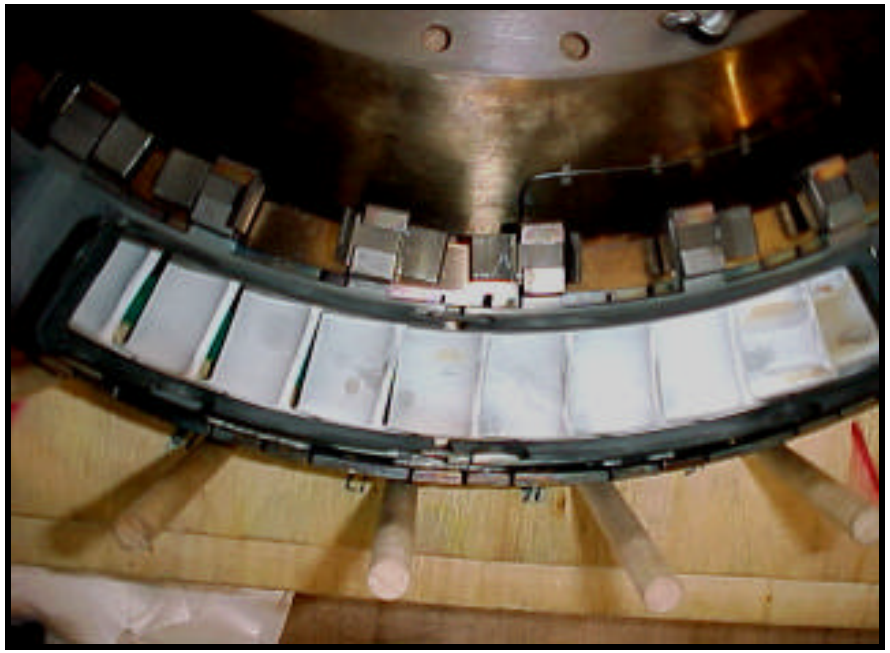


Production Billets

Phase I Testing of Silicon Nitride Vanes Was Successfully Completed by Rolls-Royce Allison in 1999



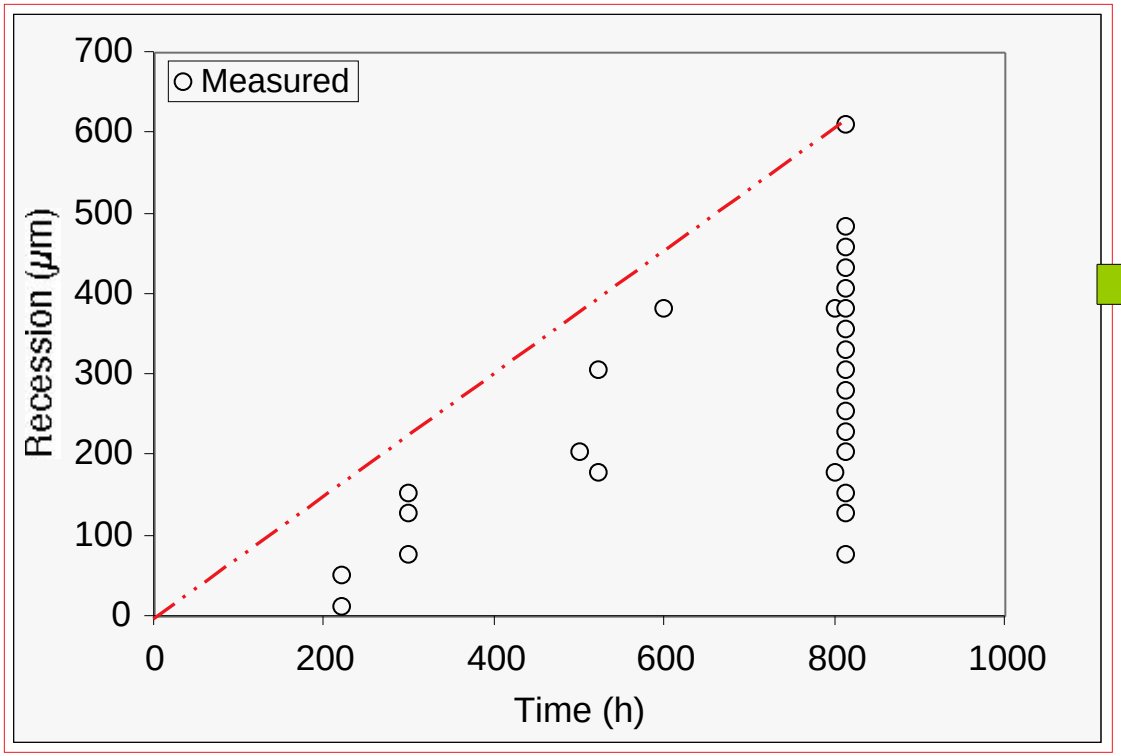
Model 501K Turbine
Exxon - Mobile, AL - 6/29/99

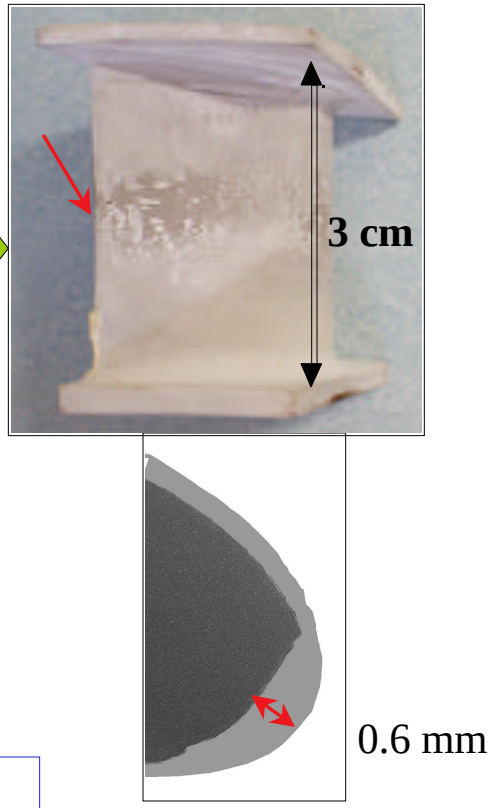


200 hr Interval - Exxon - 6/29/99

Honeywell uncoated AS800 vanes

However, Significant Material Recession of Airfoils Was Measured for Midspan of The Trailing Edge Region





Cross-section:
815 h/Vane 78

Conclusion:

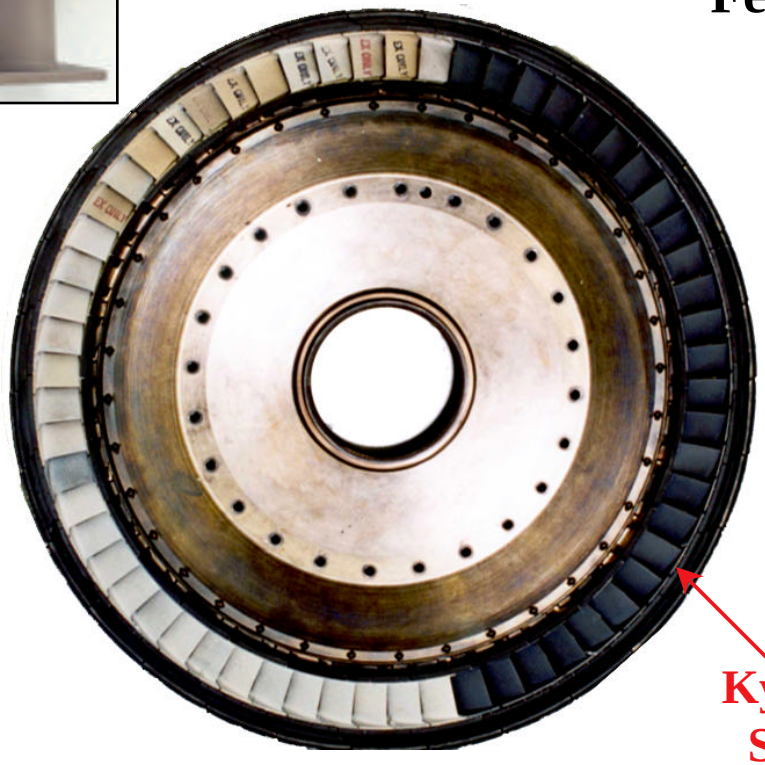
An environmental barrier coating (EBC) is needed to protect Si_3N_4 components from gas turbine environments

Phase II Testing Was Undertaken to Evaluate Silicon Nitride Vanes With EBC

KYOCERA

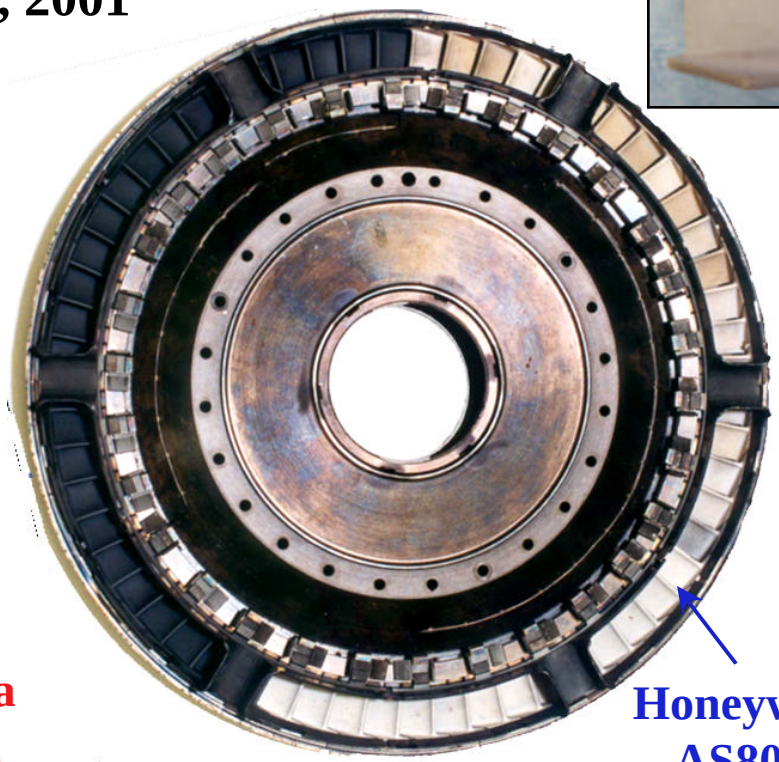
Ceramic Vane Assembly
Feb. 26, 2001

Honeywell



Kyocera SN282 (uncoated)

Looking Forward

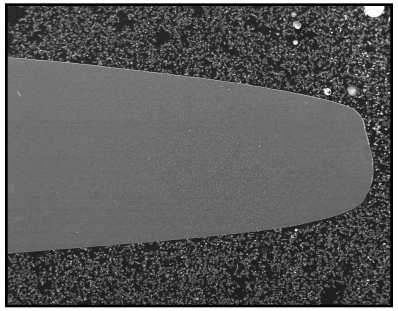


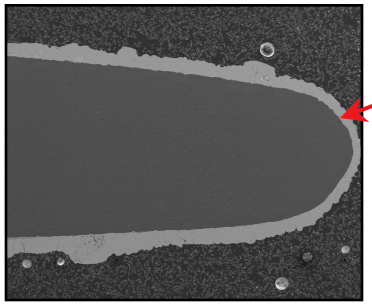
Honeywell AS800 w/ EBC

Looking AFT

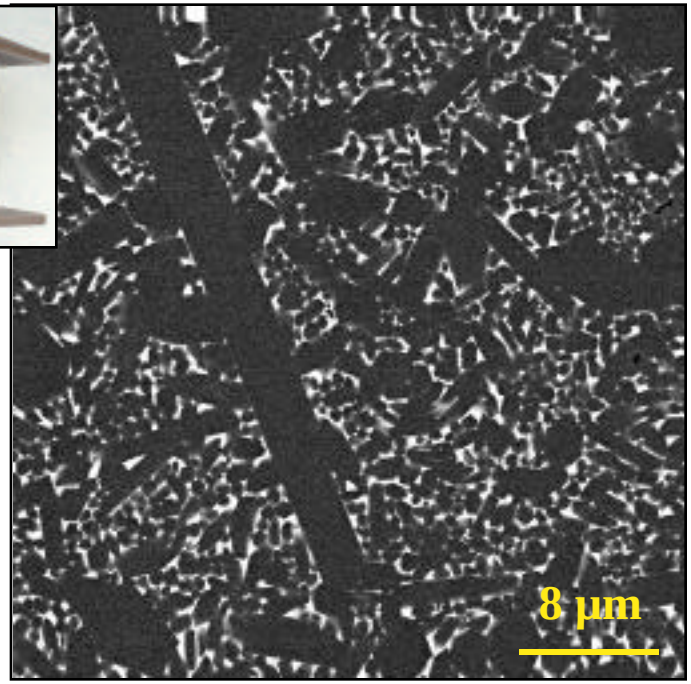
"The first engine test demonstrates the effect of turbine environment on EBC"

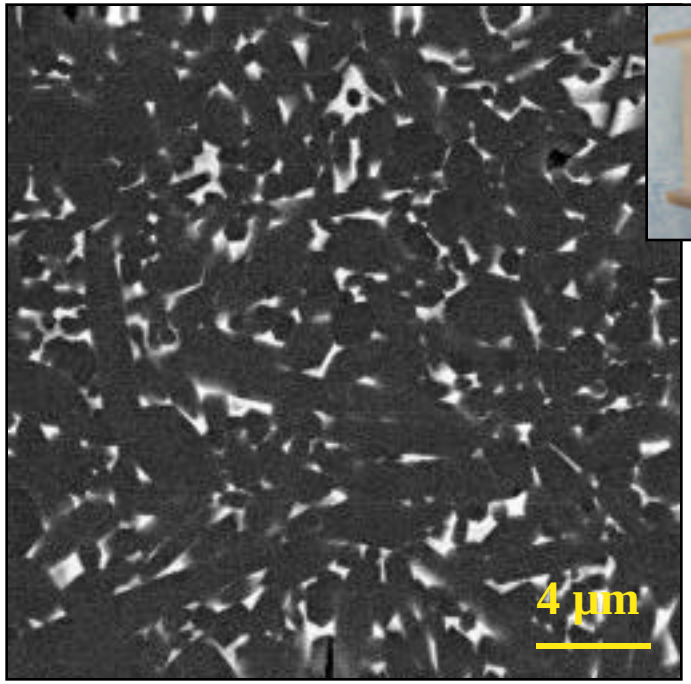
Silicon Nitride Materials Evaluated in Phase II Testing





Honeywell Experimental Plasma-sprayed Oxide-based EBC (~ 150-200 µm)





Kyocera SN282
$Lu_2Si_2O_7$, Lu_2SiO_5

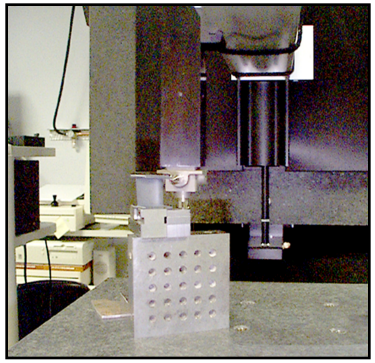
Honeywell AS800
$(Sr_2SiO_5Y_4(SiO_4)_6O_2$

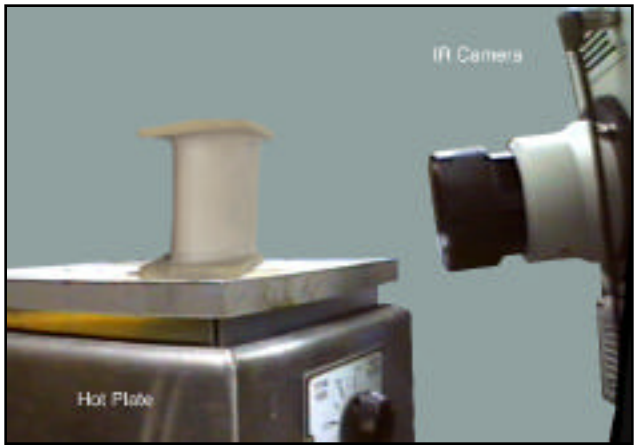
Ceramic Vane Turbine Demonstration Details

- Exxon turbine experienced rigors of commercial operation
  - Maximum continuous power
  - Emergency shutdown (highest stress condition)
- Engine sustained power and performance throughout operation
- ***Operation conditions:***
  - Average temperature - 1066°C (1950°F)
    (Hot spot - 1260°C, 2300°F)
  - Pressure - 8.9 atm (128 psia)
  - Inlet gas velocity - 162 m/s (530 ft/s)
  - Outlet gas velocity - 573 m/s (1880 ft/s)
  - Water vapor - 0.101 mole fraction
- Test was terminated after ~2500h engine test.

Characterization of Silicon Nitride Vanes

Analysis of Recession Data

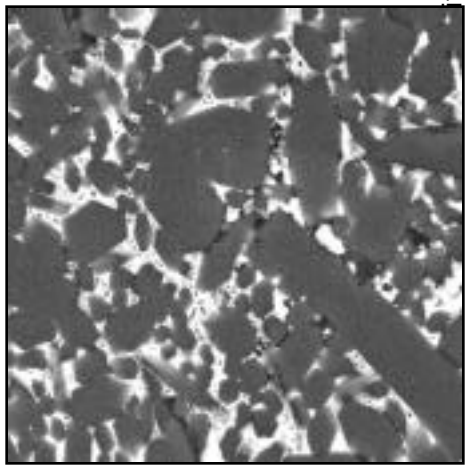


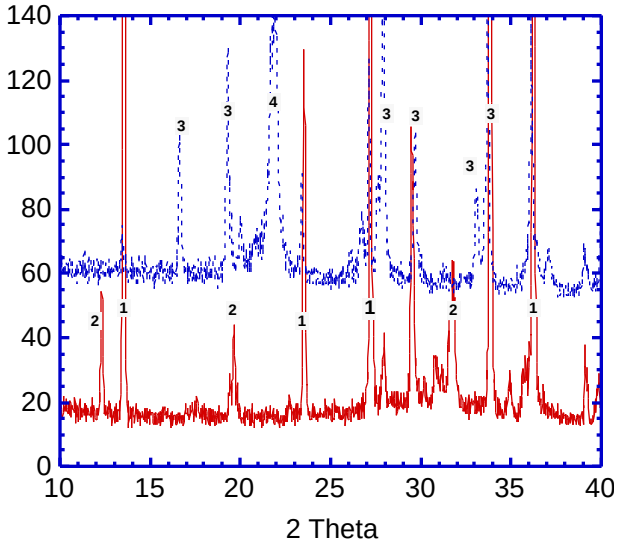


NDE

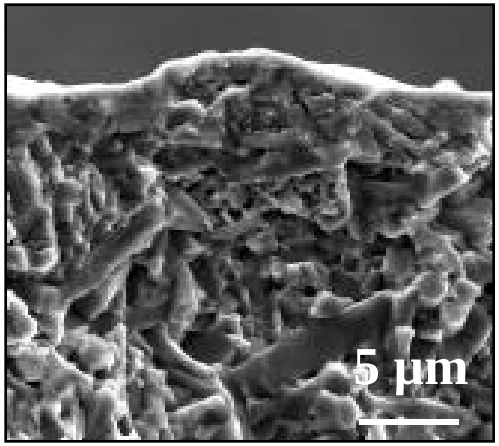
Surface Strength

SEM of Polished Cross Sections and Airfoil Surfaces



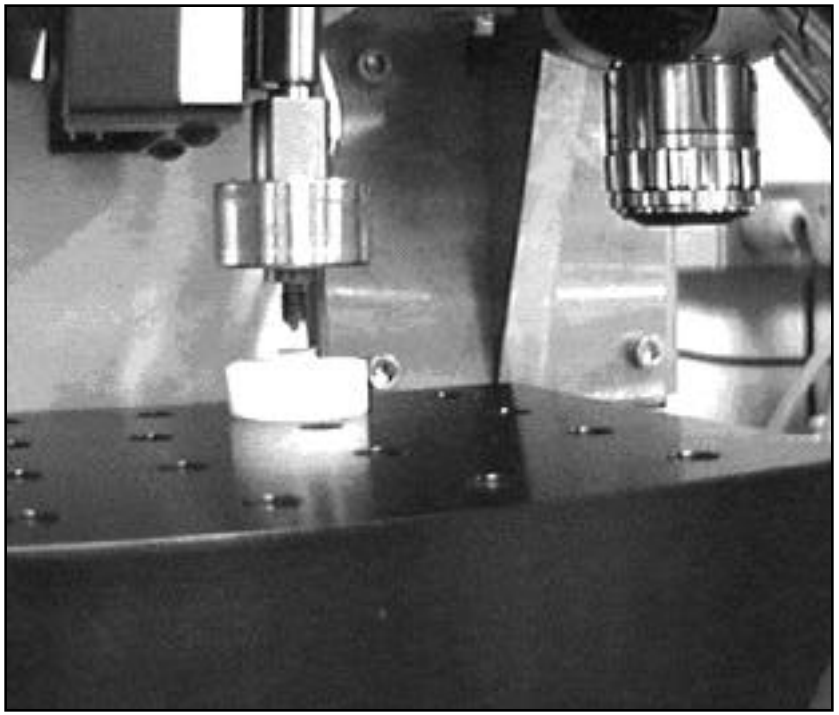


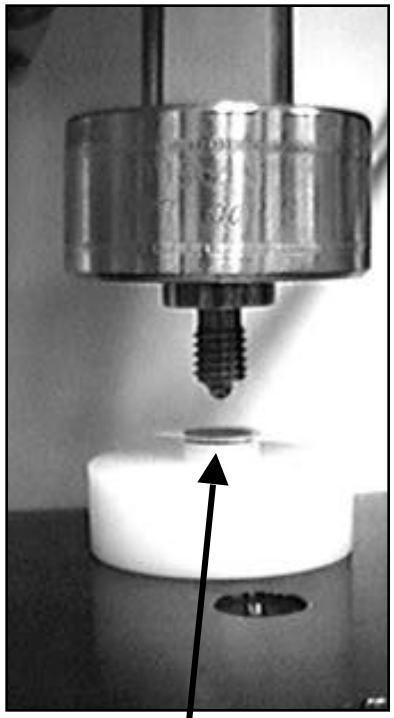
X-Ray Diffraction



SEM of Fracture Surfaces

Biaxial Disks Were Loaded to Failure Using a Computer Controlled X-Y-Z Micro-stepping Stage Assembly





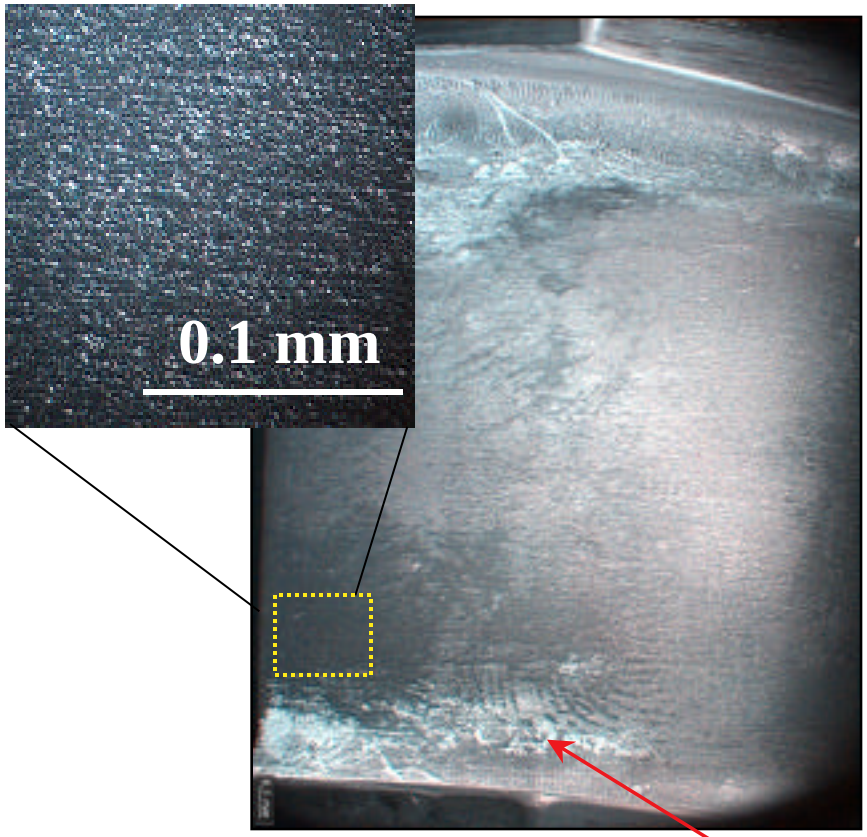
Ball-on-ring configuration

Exposed surfaces of biaxial disks from airfoils were tested under tension

Characterization Results of Uncoated Kyocera SN282 Si_3N_4 Vanes

Kyocera Industrial Ceramics Corporation

Light-Colored Phase Observed On SN282 Vane Airfoil Surfaces After Engine Field Test



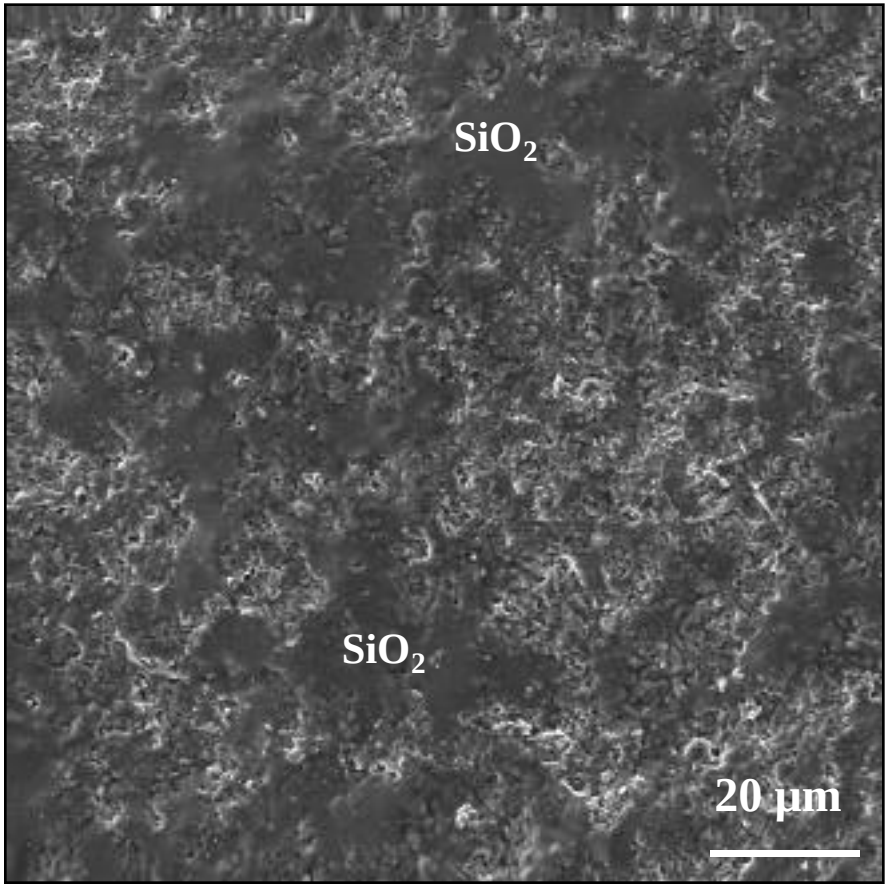
200 h
SN282 48

Light-colored phase

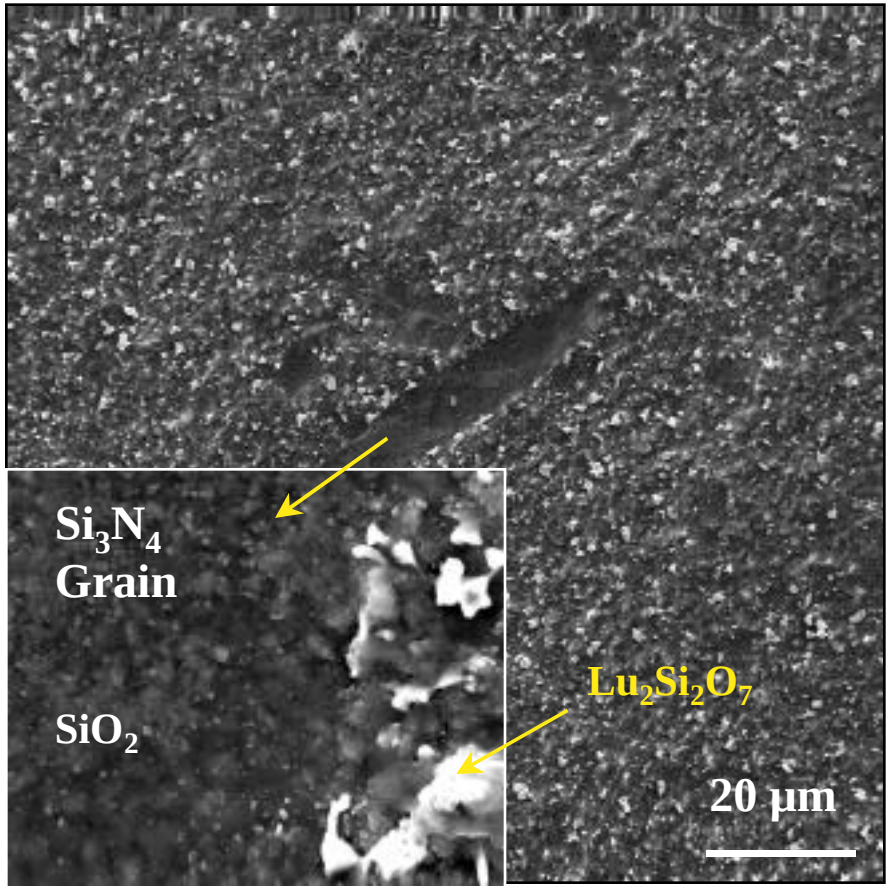
1148 h
SN282 47

Light-colored phase identified via X-ray to be *Lu-silicate*

Presence of Light-Colored Phase Arises From the Recession of Silicon Nitride Grains

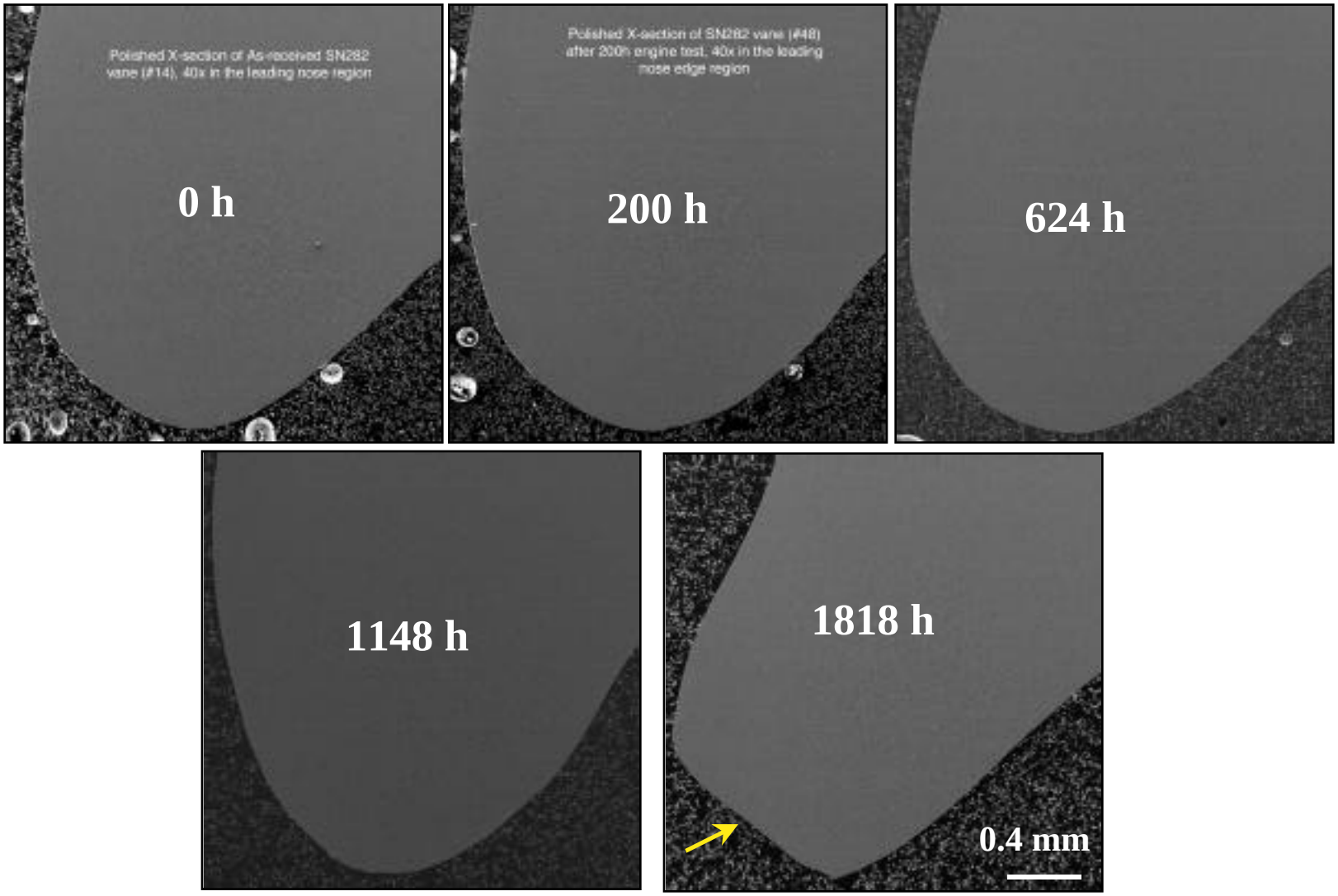


As-received (#14)

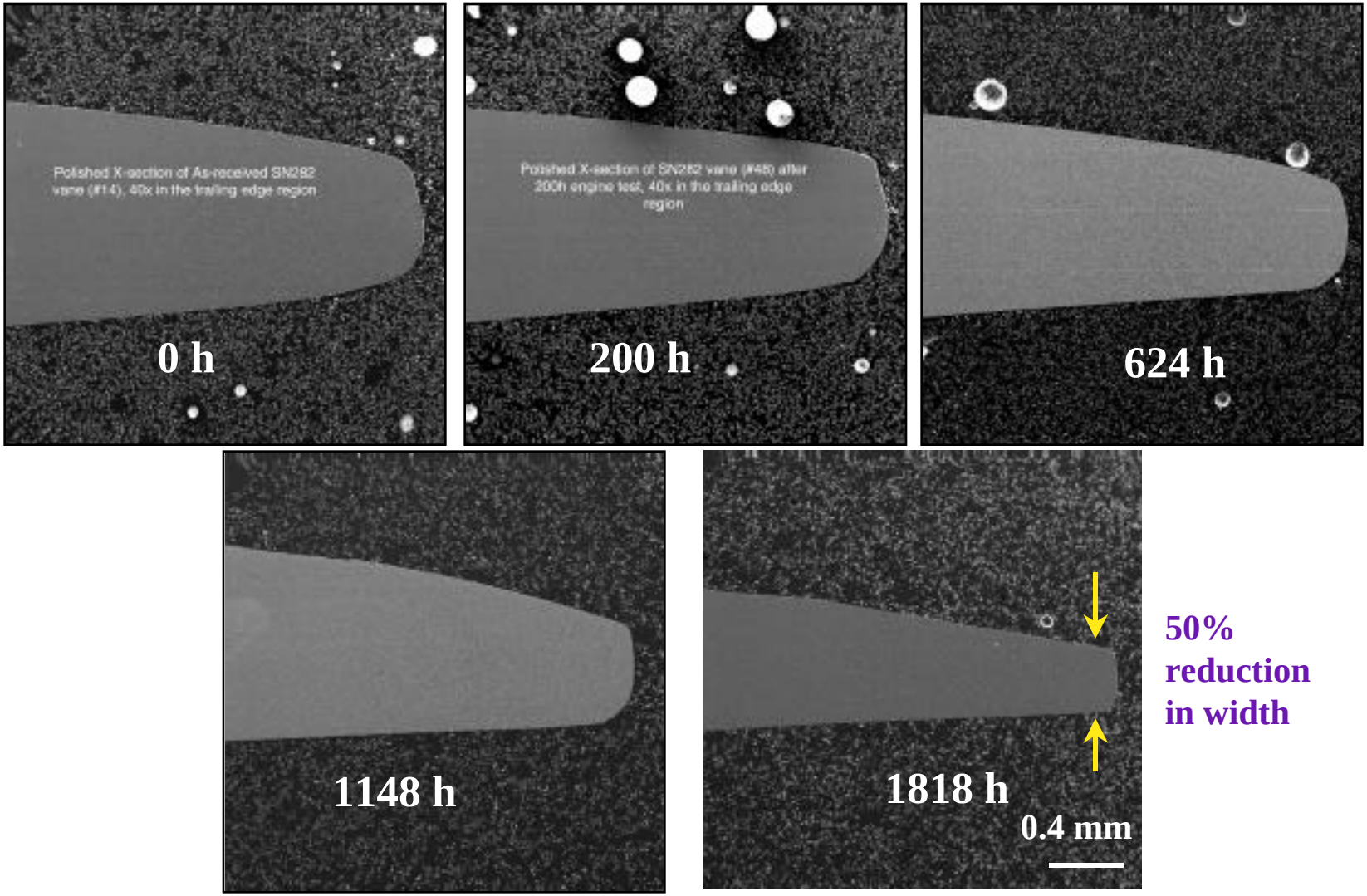


624h Test (#62)

Leading Edge Midspan Profiles of SN282 Vanes Significantly Changed With Exposure Time

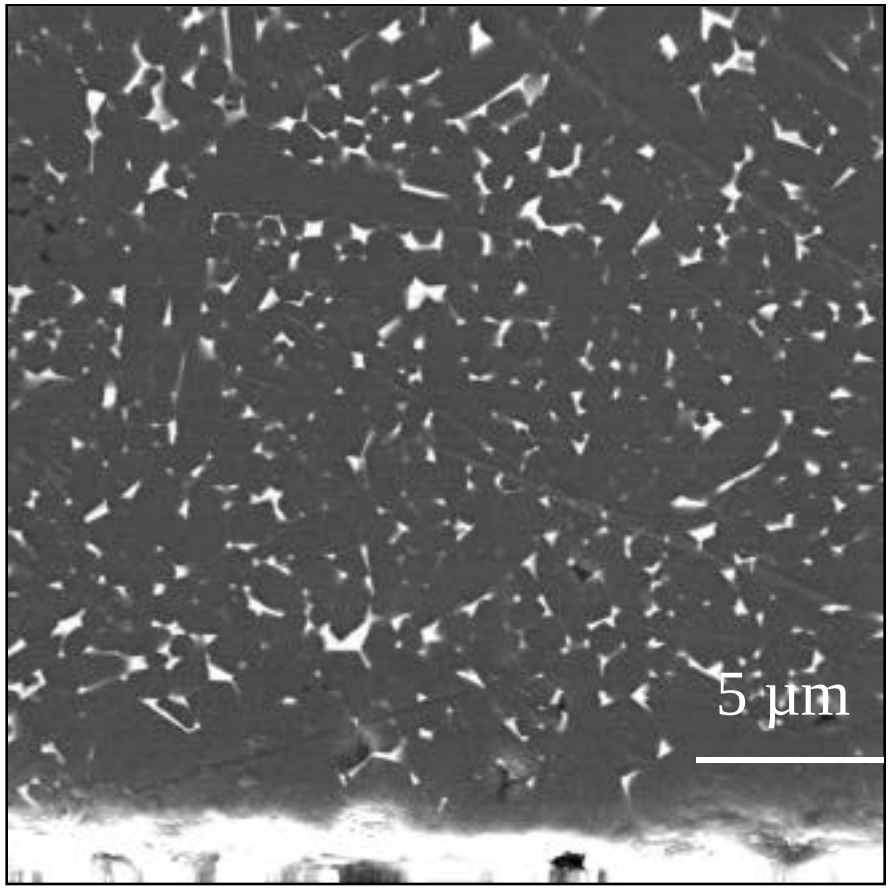


Similar Changes in Profiles Also Observed in Trailing Edge Midspan Region of SN282 Vanes

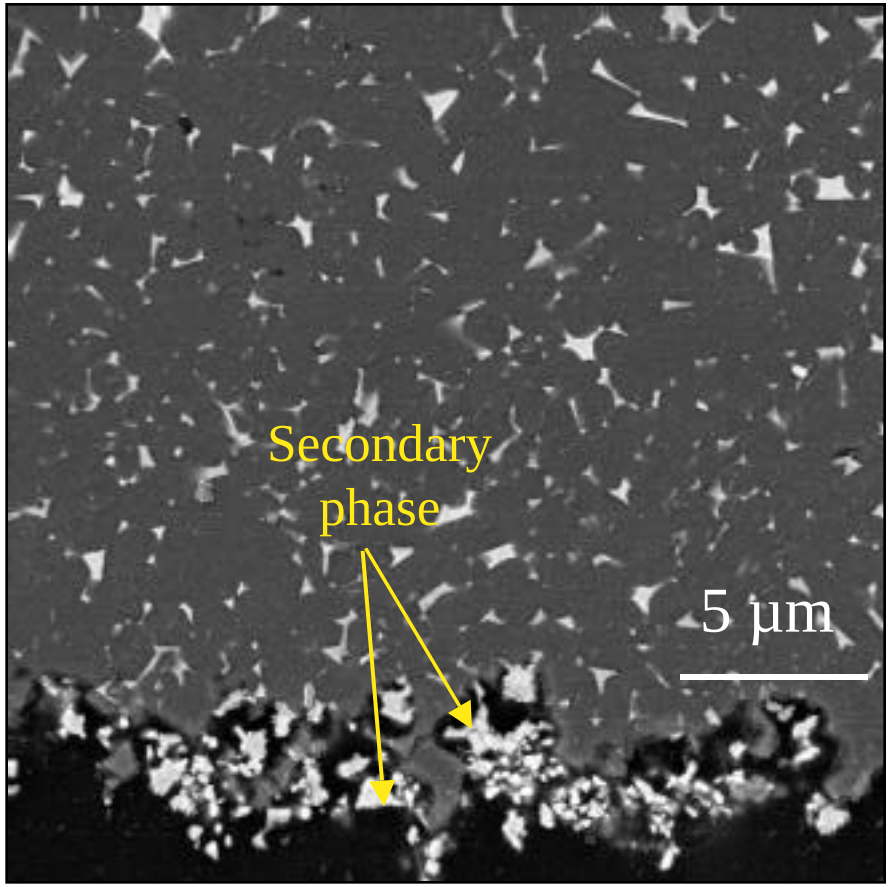


50% reduction in width

Accumulation of Secondary Phase Observed on Airfoil Surface of SN282 Vanes



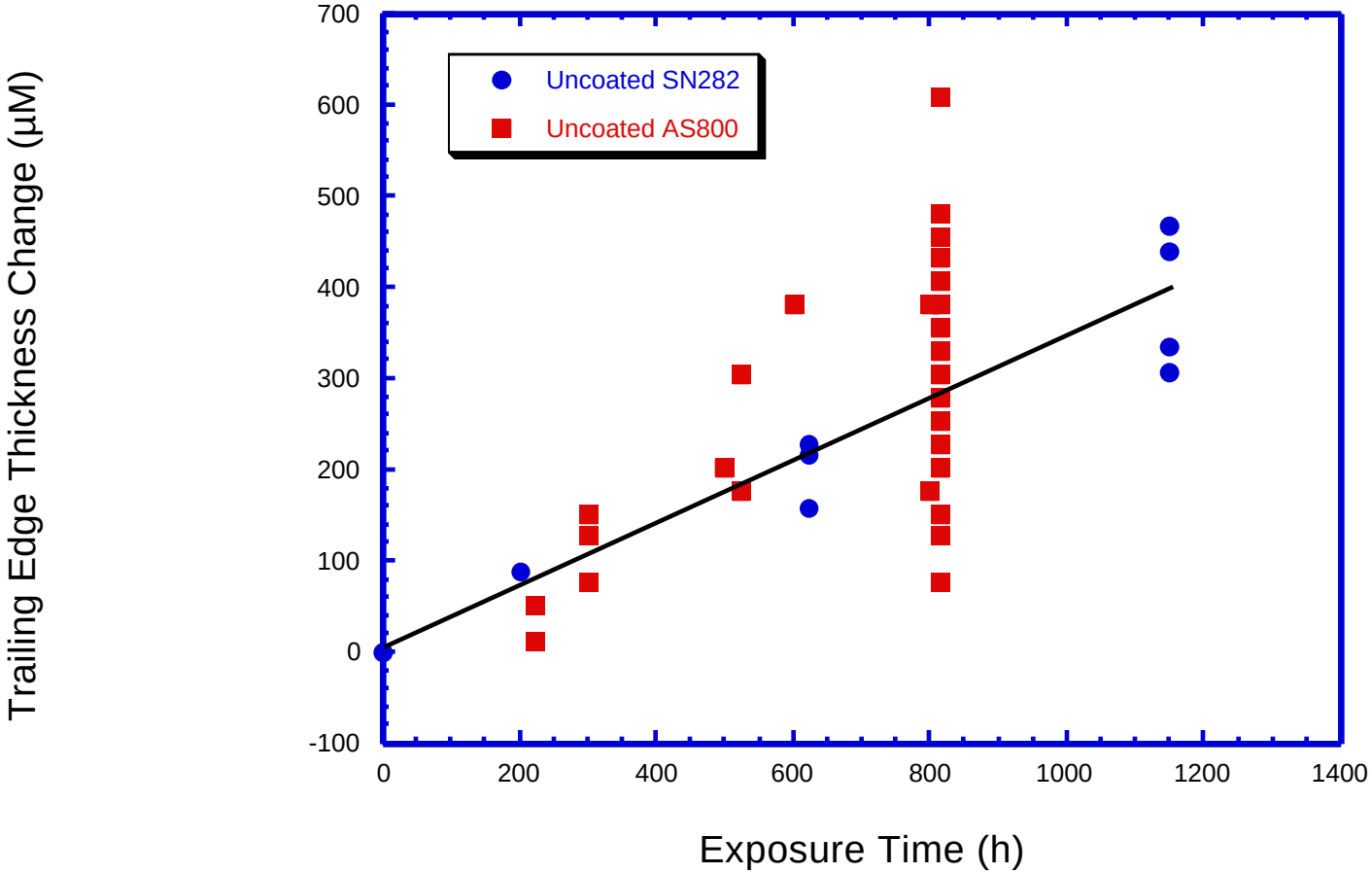
0 h
SN282 #14



1148 h
SN282 #47

"Secondary phase (*Lu-silicate*) is relative stable in gas turbine environments"

Uncoated SN282 Vanes Exhibited Similar Recession Behavior to Uncoated AS800 Vanes

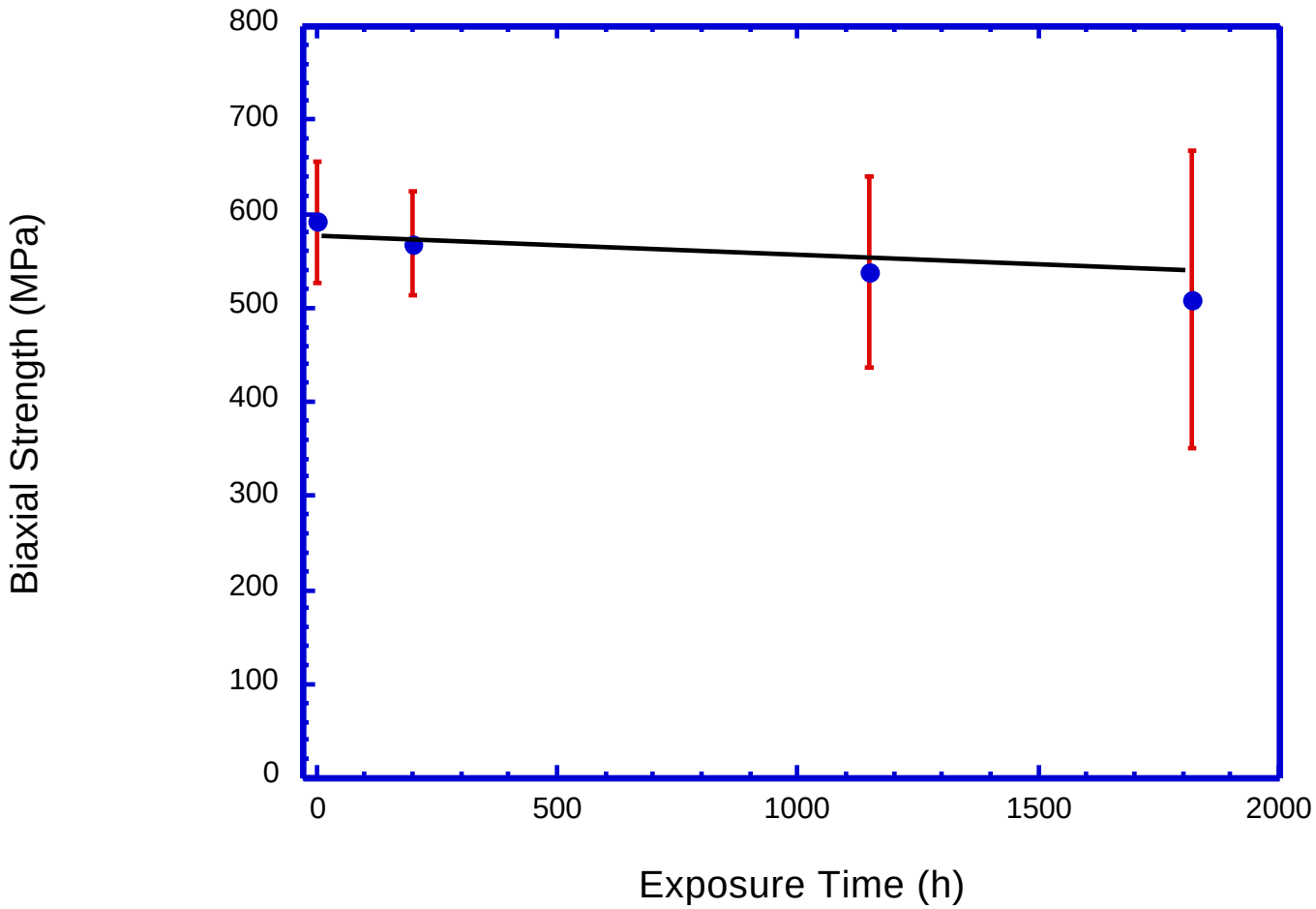


SN282 via CMC

AS800 via micrometer

"Similar recession processes (oxidation of Si_3N_4 and volatilization of SiO_2)"

Mechanical Strength of Uncoated SN282 Vanes Exhibited Minor Change With Exposure Time

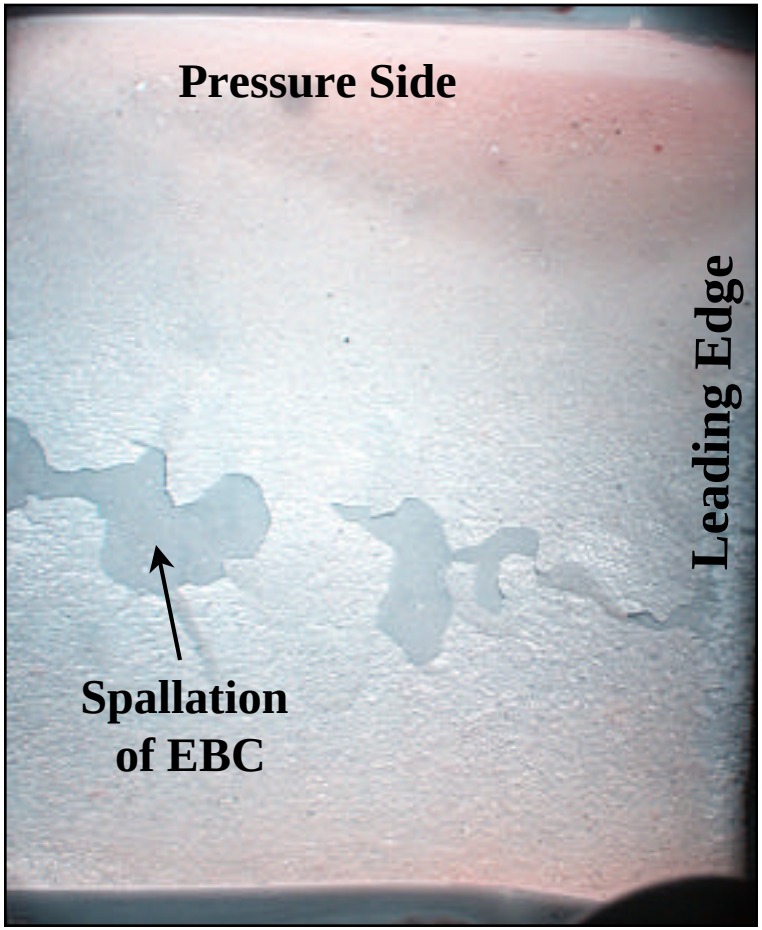


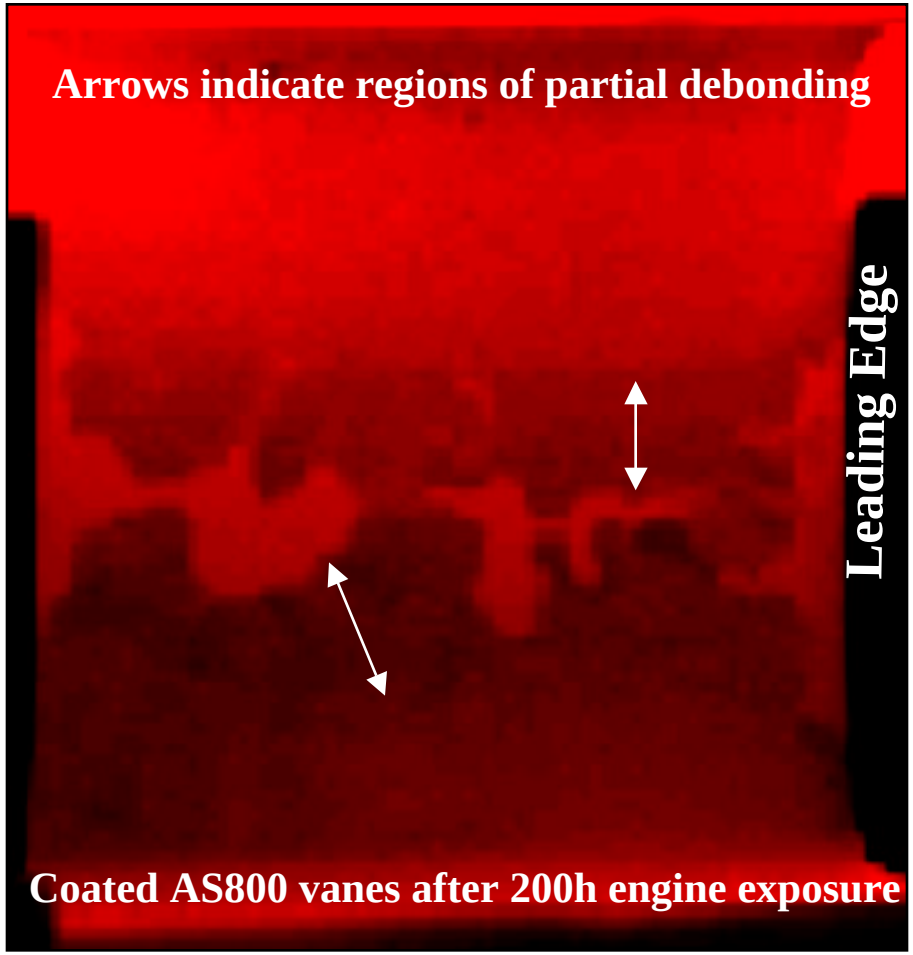
The observed trend in strength similar to uncoated AS800 vanes in Phase I

Characterization Results of Honeywell AS800 Si_3N_4 Vanes With Plasma-Sprayed Oxide-Based Coating

Honeywell Ceramic Components

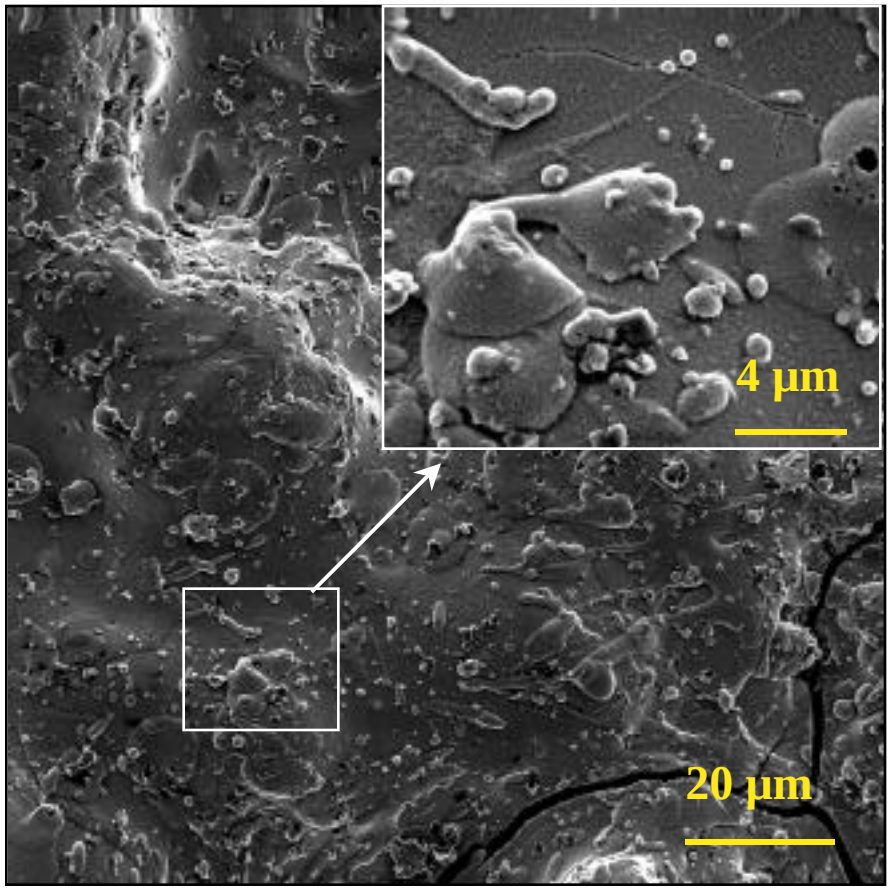
Infrared Image of Airfoil Surface Revealed Partial Debonding of Honeywell Experimental EBC



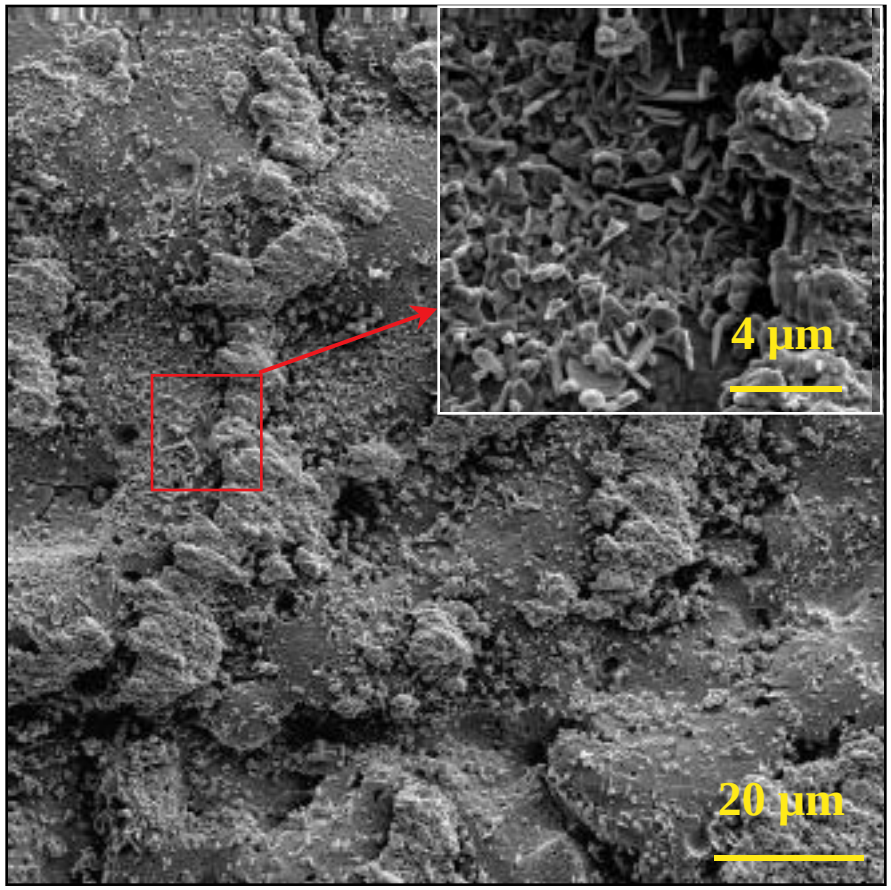


IR camera offers an useful means for NDE

Change in Microstructure Observed in Plasma-Sprayed Oxide-Based EBC After Engine Exposure

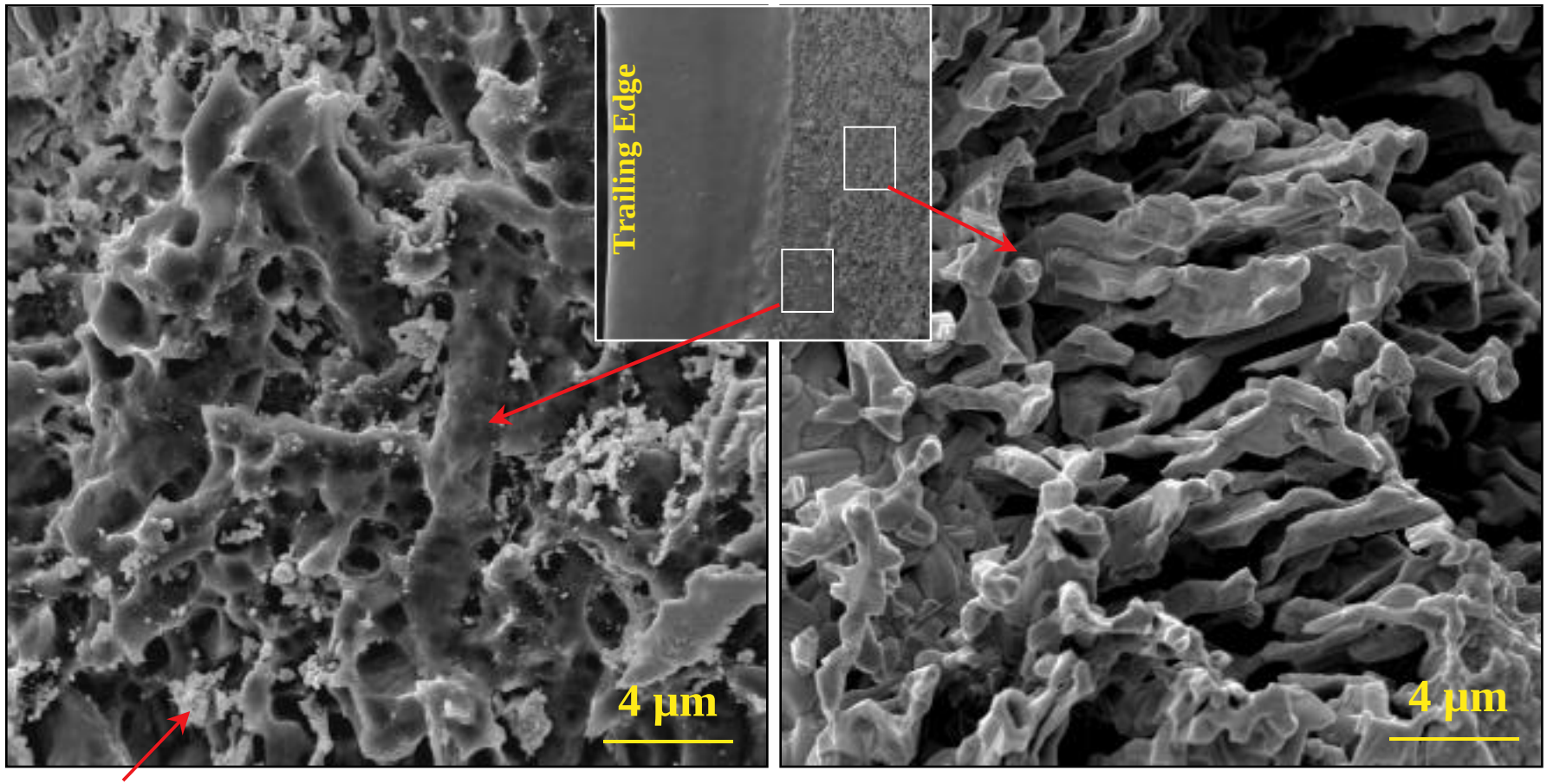


As-received (#126)



524h Test (#131)

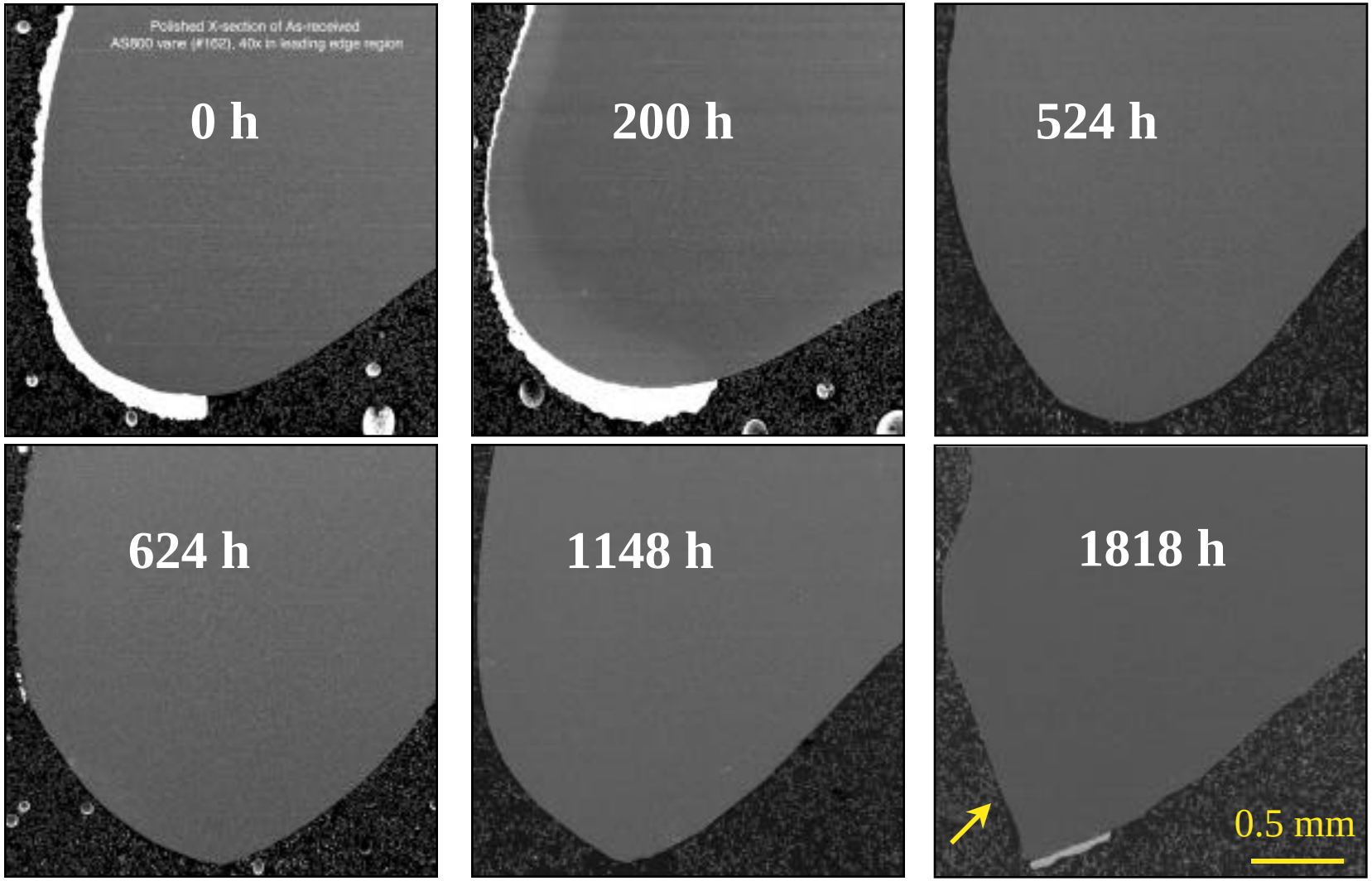
Severe Environmental Attack in Silicon Nitride Observed in Region With EBC Spallation



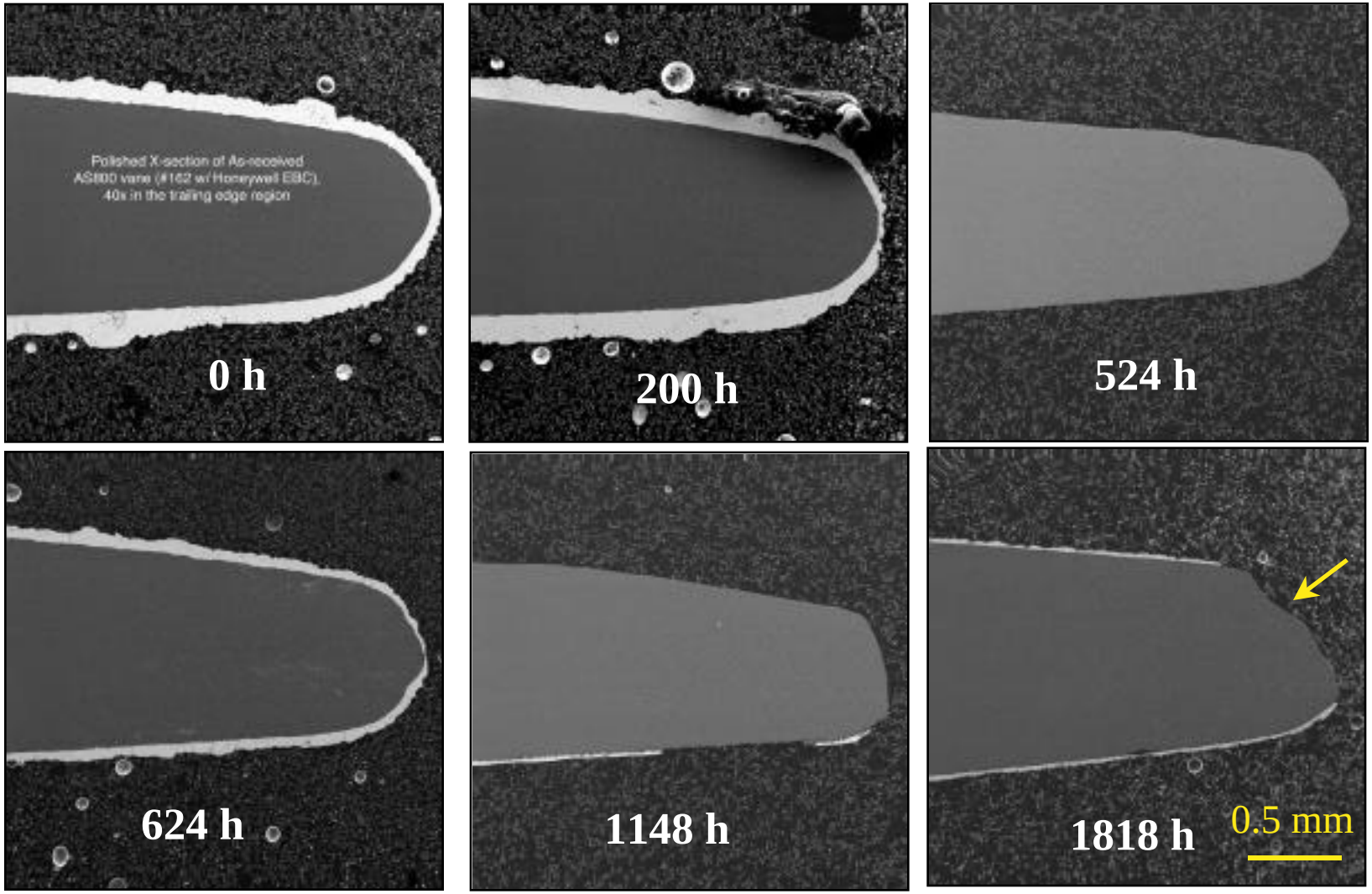
2nd phase

AS800 vane with oxide-based EBC (#137) after 624h test

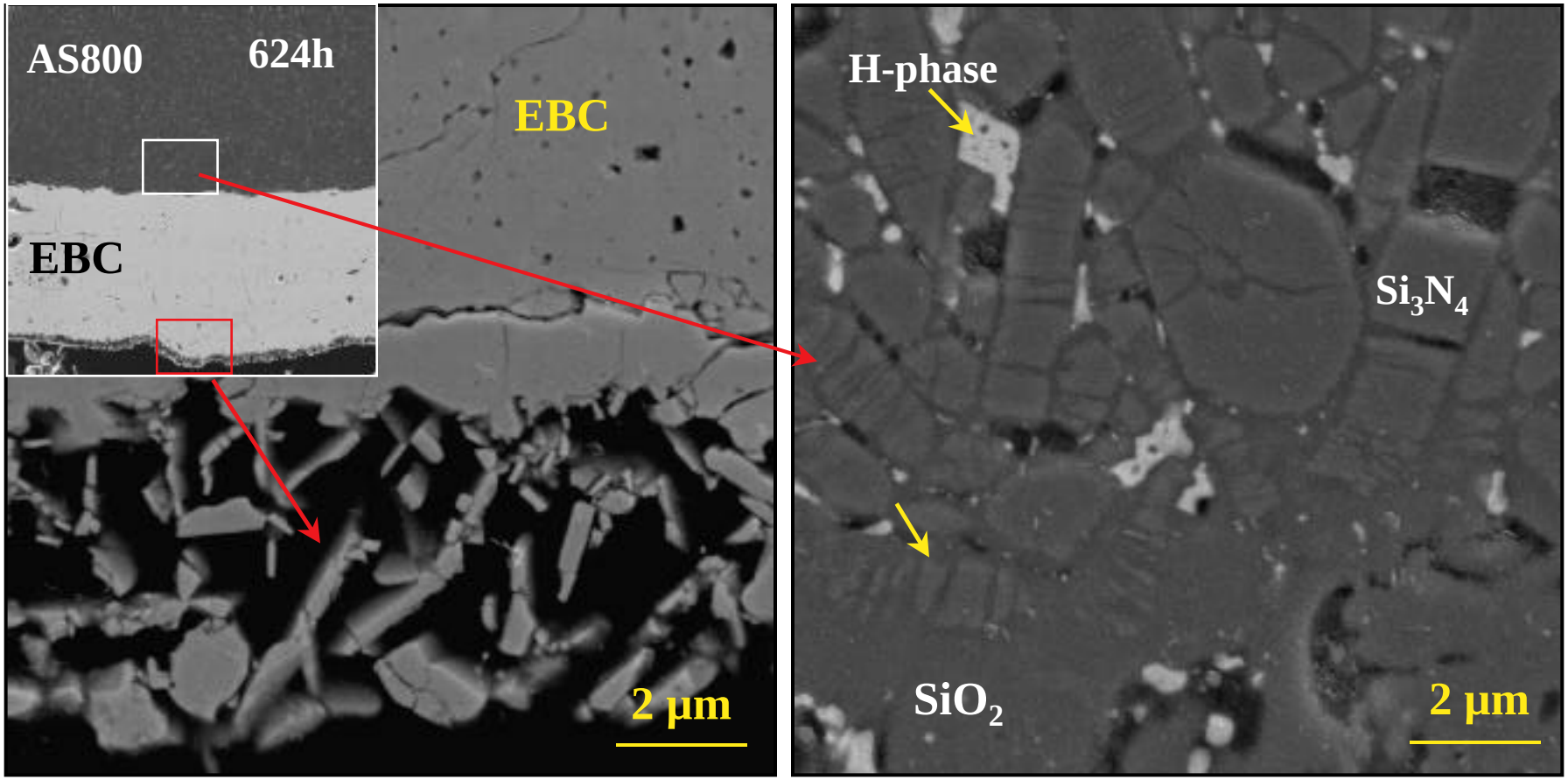
Leading Edge Midspan Profiles of EBC AS800 Vanes Significantly Changed With Exposure Time



Similar Changes Observed in Trailing Edge Midspan Profiles of EBC AS800 Vanes



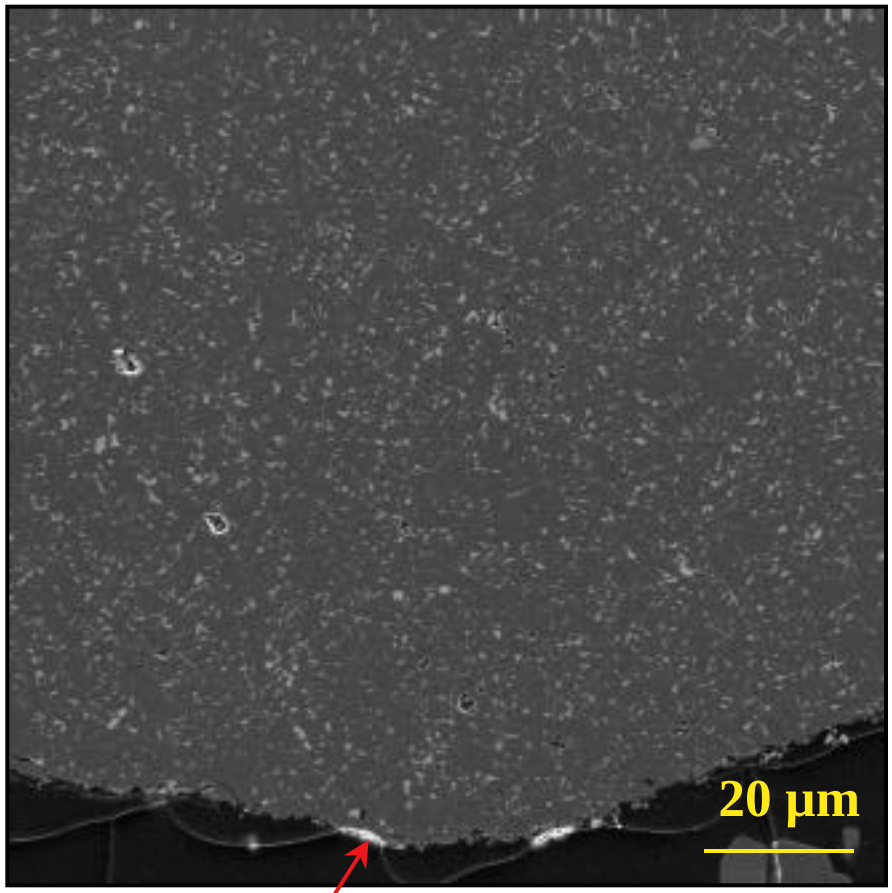
Environmentally Affected Zone (EAZ) Observed in AS800 Silicon Nitride Underneath The Oxide-Based EBC

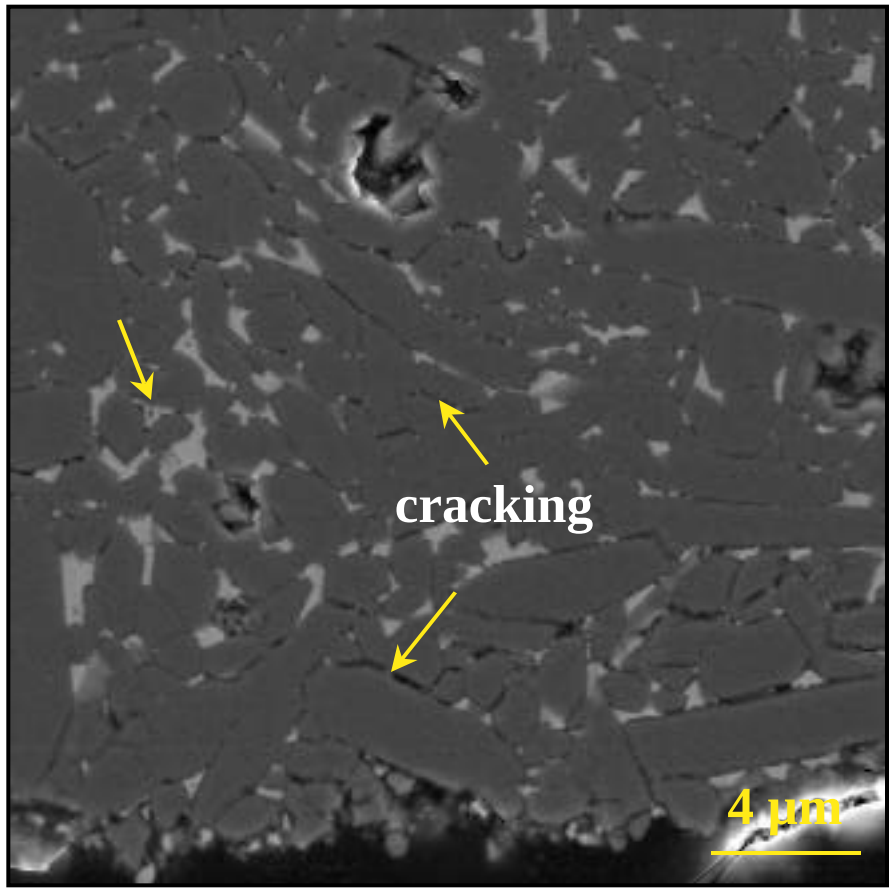


"The experimental EBC is not an effective diffusion barrier of water vapor"

But, it could inhibit the Si_3N_4 material from recession

Change in Microstructure (Intergranular Cracking and Pores) Observed in Region With EBC Spallation

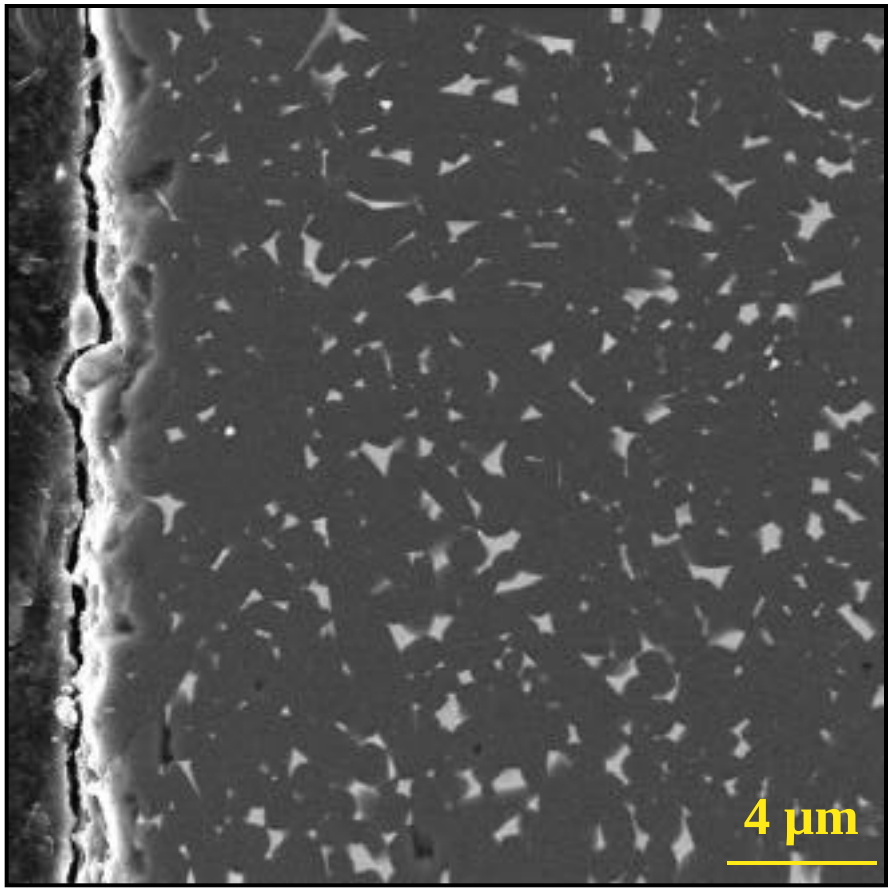




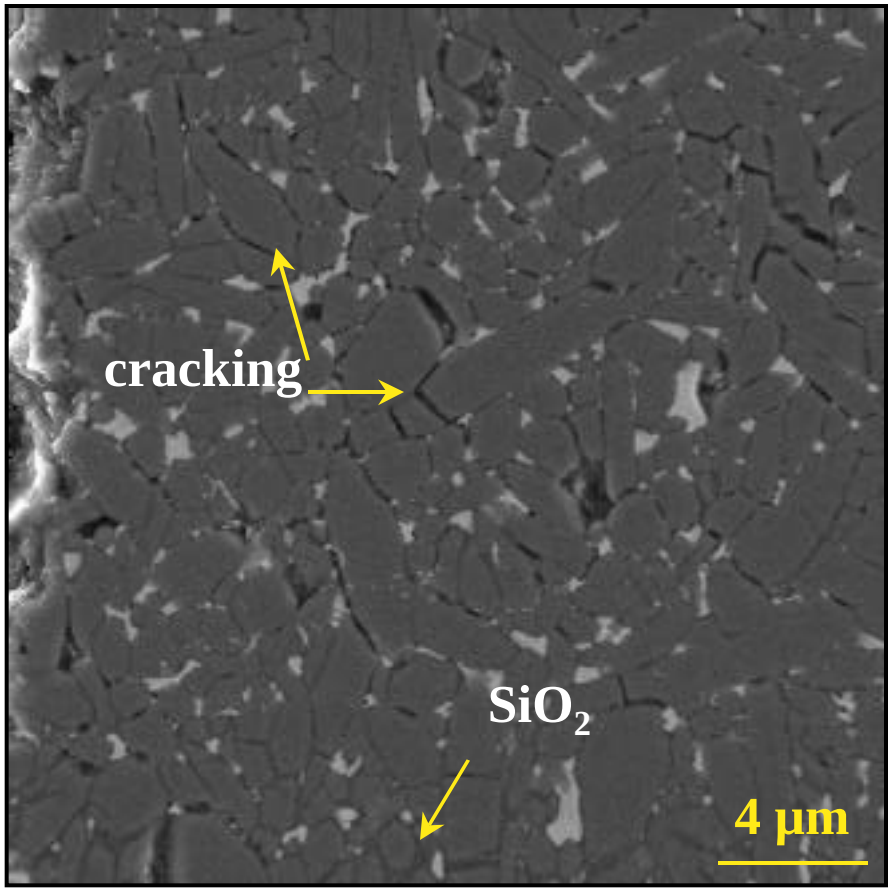
Leading edge region

A800 #86 after 1148h engine test

SN282 Exhibited a More Stable Microstructure Than AS800 in Gas Turbine Environment



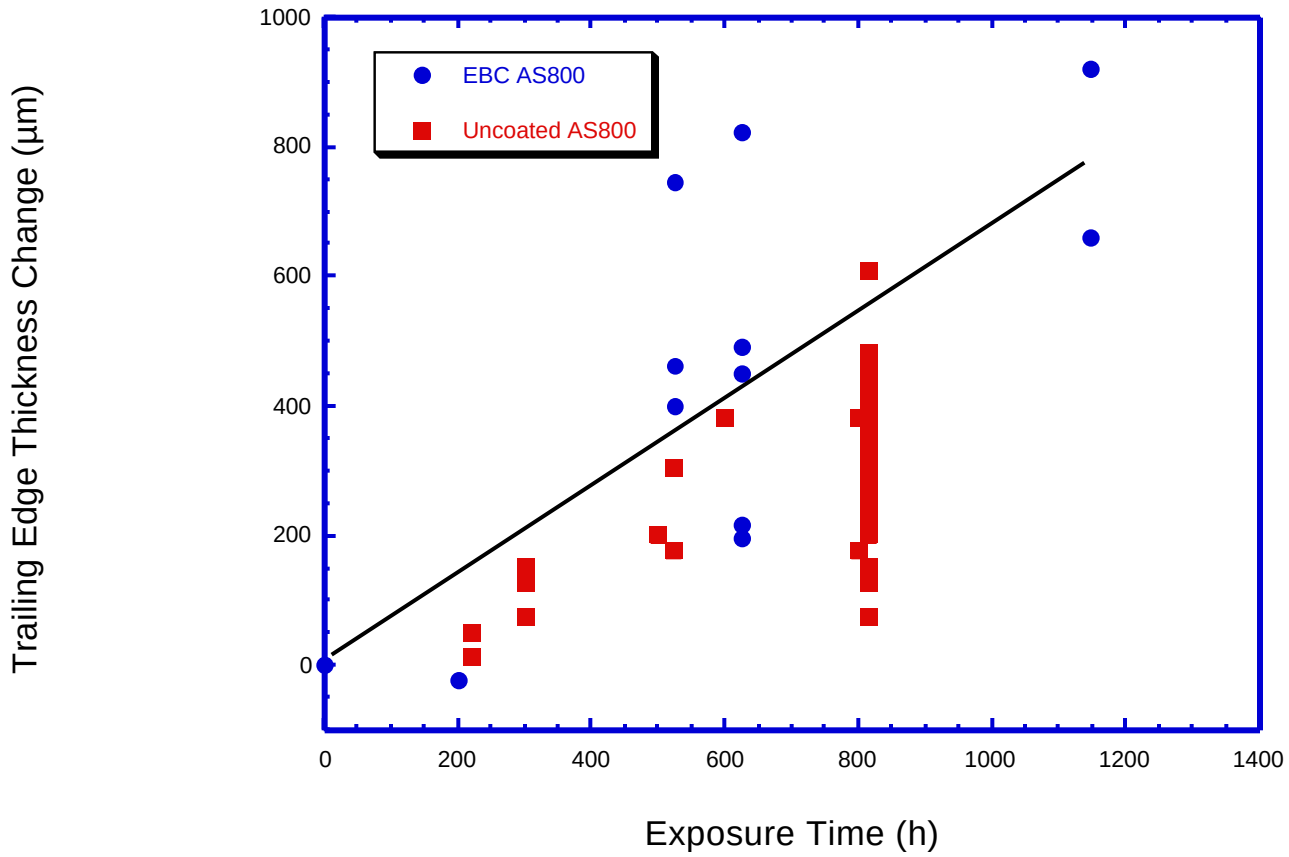
SN282 1818h test vane



AS800 1818h test vane

The relative more stable microstructure of SN282 is probably due to the Lu-silicate phase, which is more stable than H-phase in AS800

Thickness Change Measured in EBC AS800 Vanes is Grater Than the Uncoated Vanes in Phase I

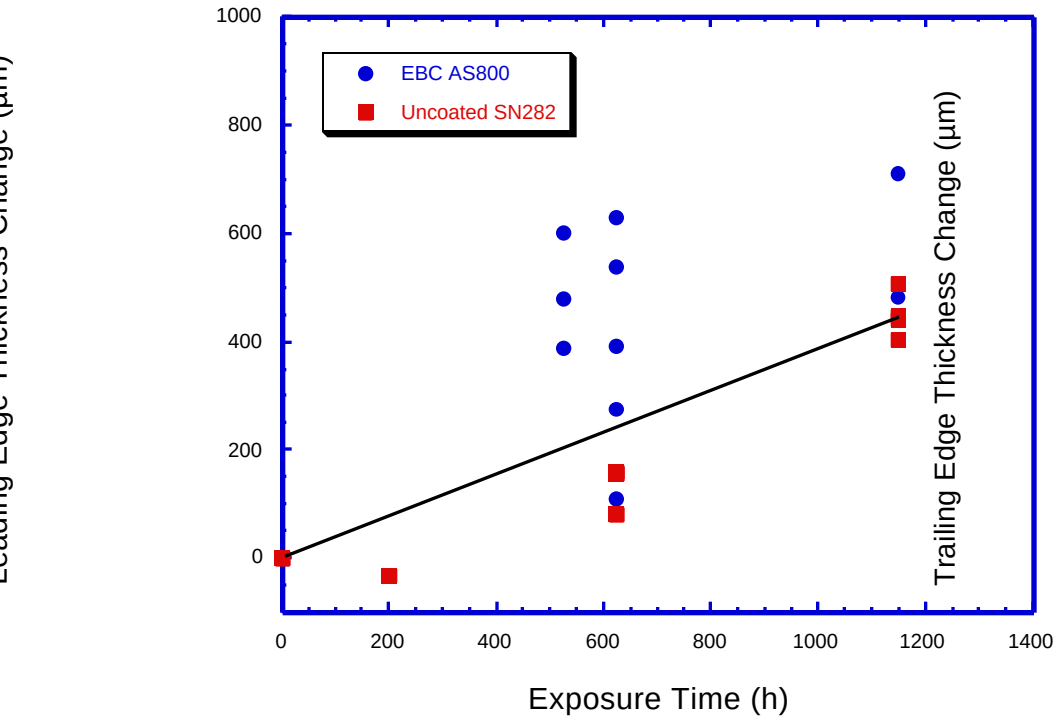


EBC AS800 via CMC

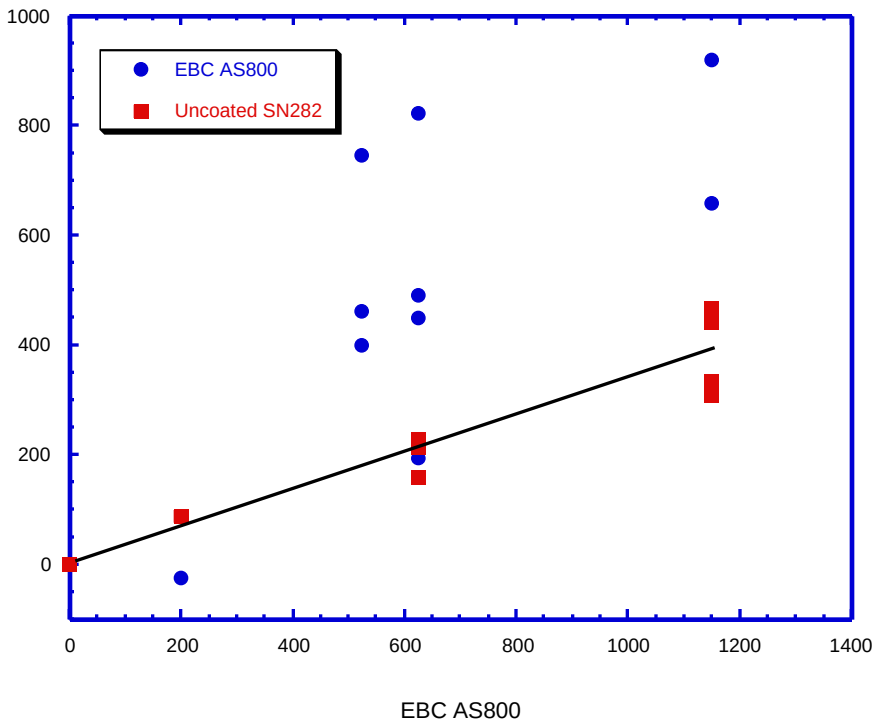
Uncoated AS800 via micrometer

Greater dimension change could be attributed to the material recession of oxide-based EBC

Thickness Change in EBC AS800 Vanes is Also Significantly Grater Than Uncoated SN282 Vanes

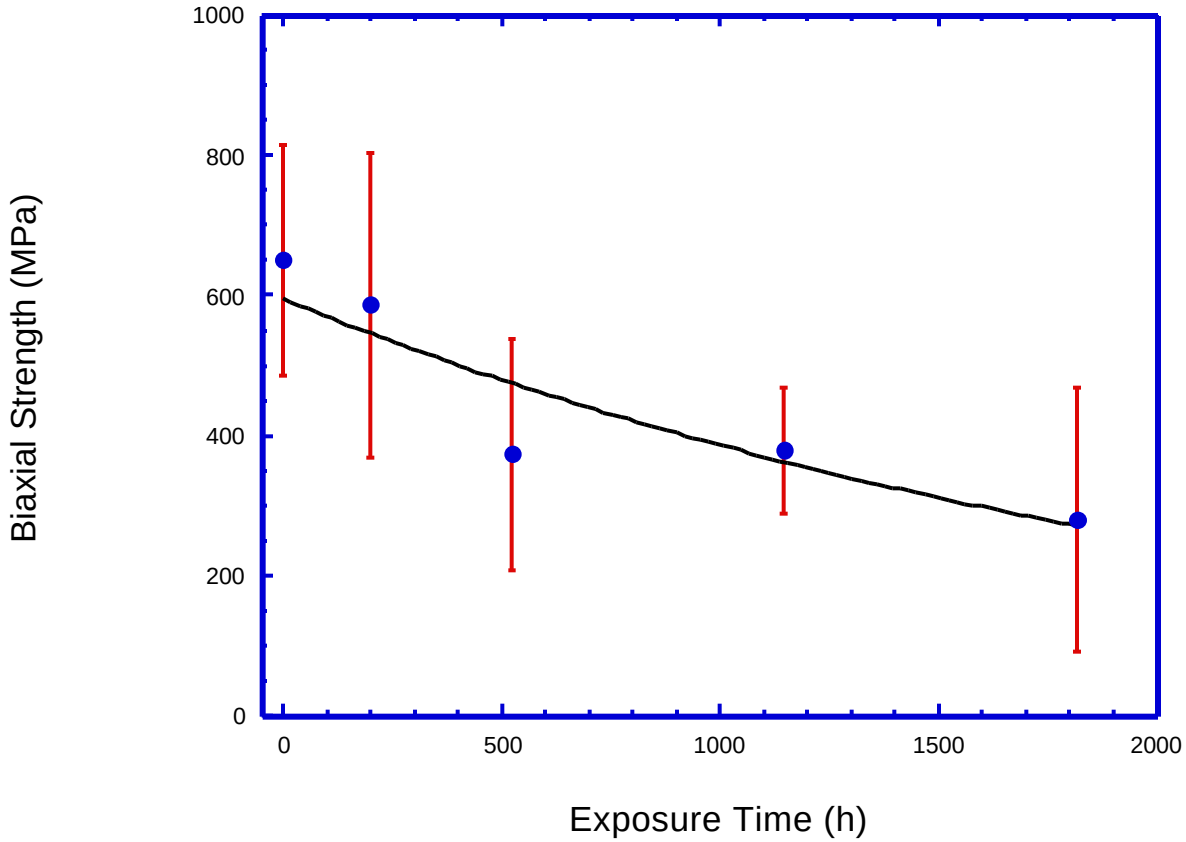


Leading edge region



Trailing edge region

Biaxial Strength of EBC AS800 Vanes Decreases With an Increase in Engine Exposure Time

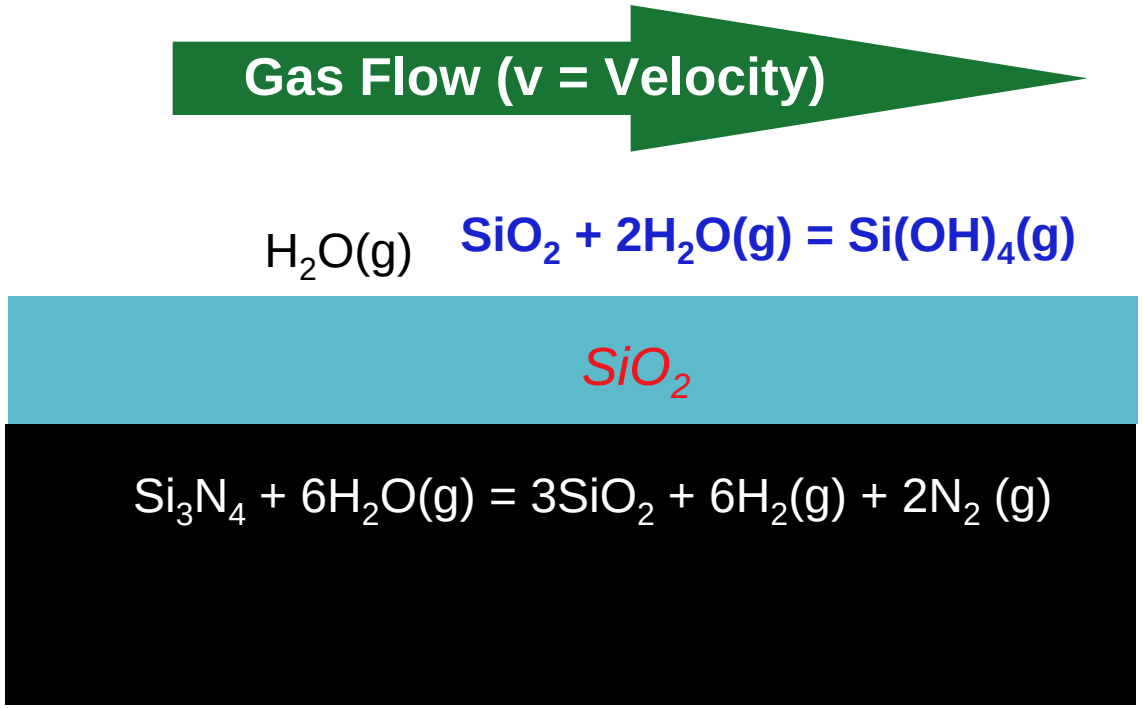


Strength decrease could be attributed to (1) increased surface roughness and (2) generation of subsurface damage zone

Recession of Silicon Nitride in Turbine Environment

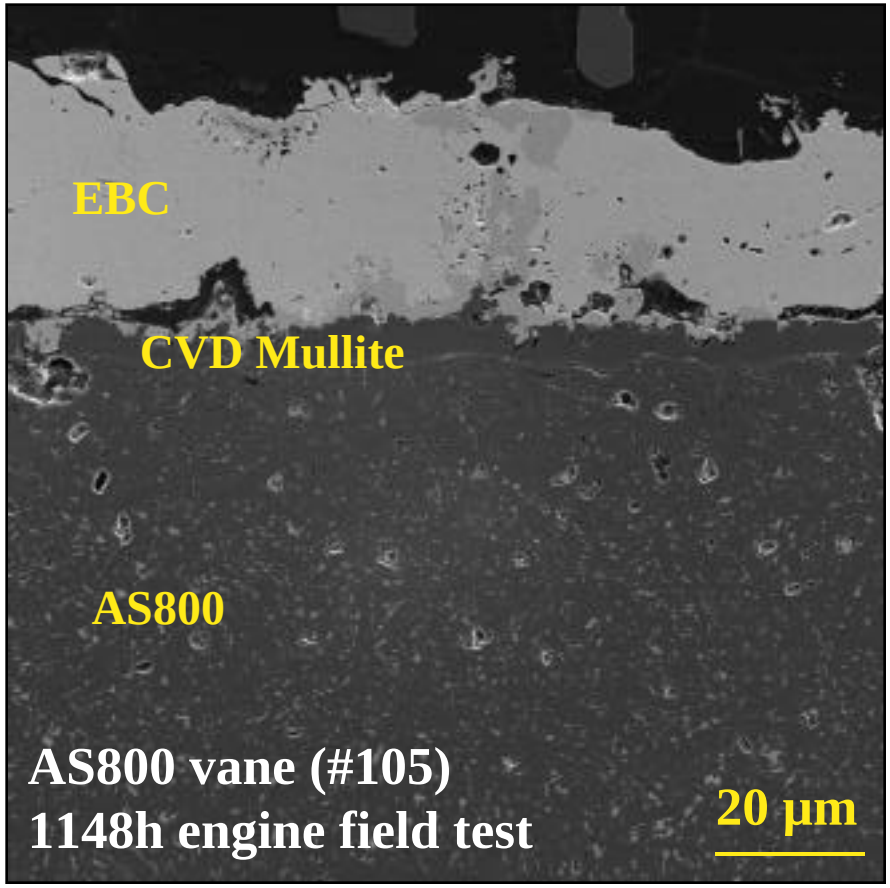
- **Silica forms in oxidizing environments**
- **Volatilization of the silica scale leads to paralinear oxidation**
  - **Effect is enhanced by the presence of water vapor and high gas velocities**
- **This results in continual loss of the underlying silicon nitride ceramic**

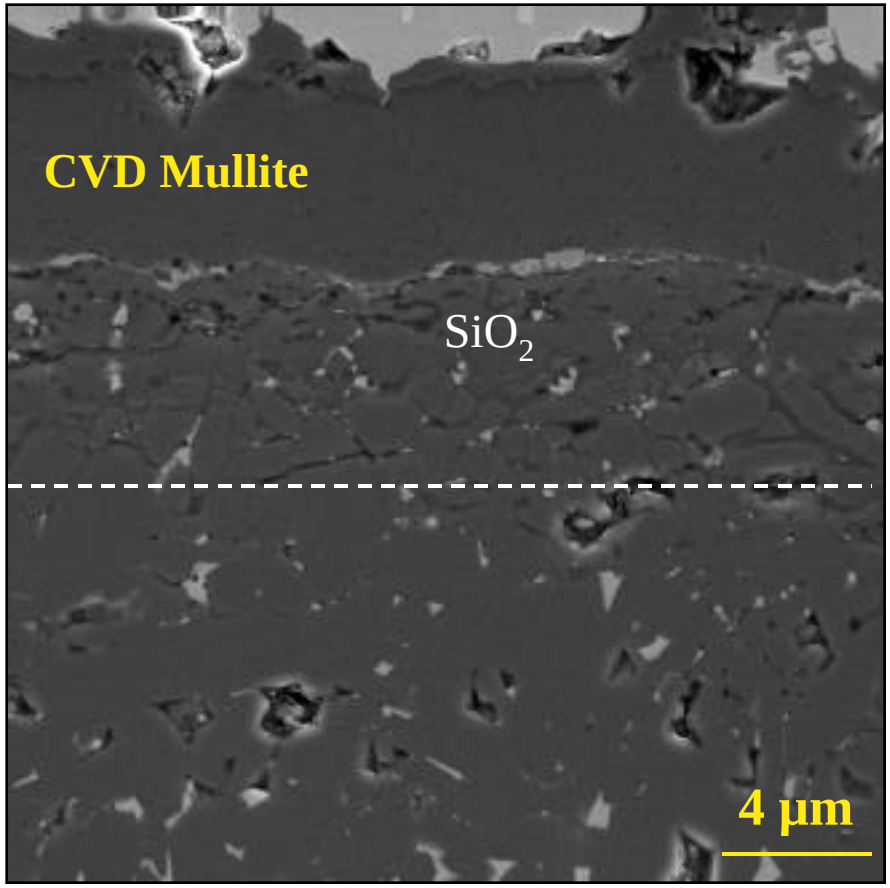
Volatilization Rate $v^{1/2}\ P(H_2O)^2/(P_{total})^{1/2}$,



Model has been verified by works at NASA (Opila *et al.*) and ORNL (More *et al.*)

Reduction in Environmental Effect Might be Achieved via Engineered Approaches





Subsurface damage zone substantially minimized

A collaborative effort is needed to develop an effective EBD system to protect Si_3N_4 components in combustion environments

Conclusions

- Both uncoated SN282 and coated AS800 vanes were successfully tested in a commercial turbine engine for up to 2000 h.

- However, both uncoated SN282 and coated AS800 vanes exhibited substantial material recession in turbine environments.

- The experimental plasma-sprayed oxide-based EBC developed by Honeywell is not an effective diffusion barrier to turbine environments.

- The mechanical properties of SN282 airfoil exhibited minor change with exposure time. However, the strength of AS800 airfoil decreased with an increase in exposure time.

- Alternative EBD systems need to be explored and developed to ensure long-term stability and performance in gas turbines.