Lessons From Gas Turbine Jet Engine Monitoring and Maintenance

Mike Maloney, Pratt & Whitney (retired)

Mike Maloney | LinkedIn

Logistics and Manufacturing under Attack
Virtual Workshop on June 2-4, 2021
National Academies of Sciences, Engineering and Medicine/DDMI

The Establishment of a Viable Digital Twin Infrastructure Could Prevent This Occurrence

<u>Impact on Operation</u>

- FAA Issued an Emergency Directive to Inspect Engines Before Further Flight
- Approximately 168 Aircraft Affected
- Selected Airlines Retire Planes from Service

(Hartford Courant)

(National Transportation and Safety Board

Currently, Assessment of Continued Use Based Upon Periodic Inspection

[FAA Statement on Pratt & Whitney Engine Emergency Airworthiness Directive]()
https://www.flightglobal.com/safety/ntsb-says-united-engine-failure-caused-by-metal-fatigue/142556.article

Typical Gas Turbine Engine Material Failure Modes

<u>Mechanical</u>

- Fracture
- Fatigue
- Creep
- Erosion
- Foreign Object Damage
- Domestic Object Damage

<u>Environmental</u>

- Oxidation
- Corrosion
- Ingested Material Induced Distress

} Will Use These Modes as Examples

Turbine Engine Health Monitoring for Digital Twin – Environmental Durability

What Data Needs to be Collected?

- Temperature (Possibly Temperature Ramp Rate, Thermal Transient Induced Damage)
- Time
- Pressure
- Ingested Gas Chemistry and Volume
- Ingested Particulate Chemistry and Mass

How Will the Data be Collected?

- Temperature Sensors
- Pressure Sensors
- Inlet Air Collection Sensors

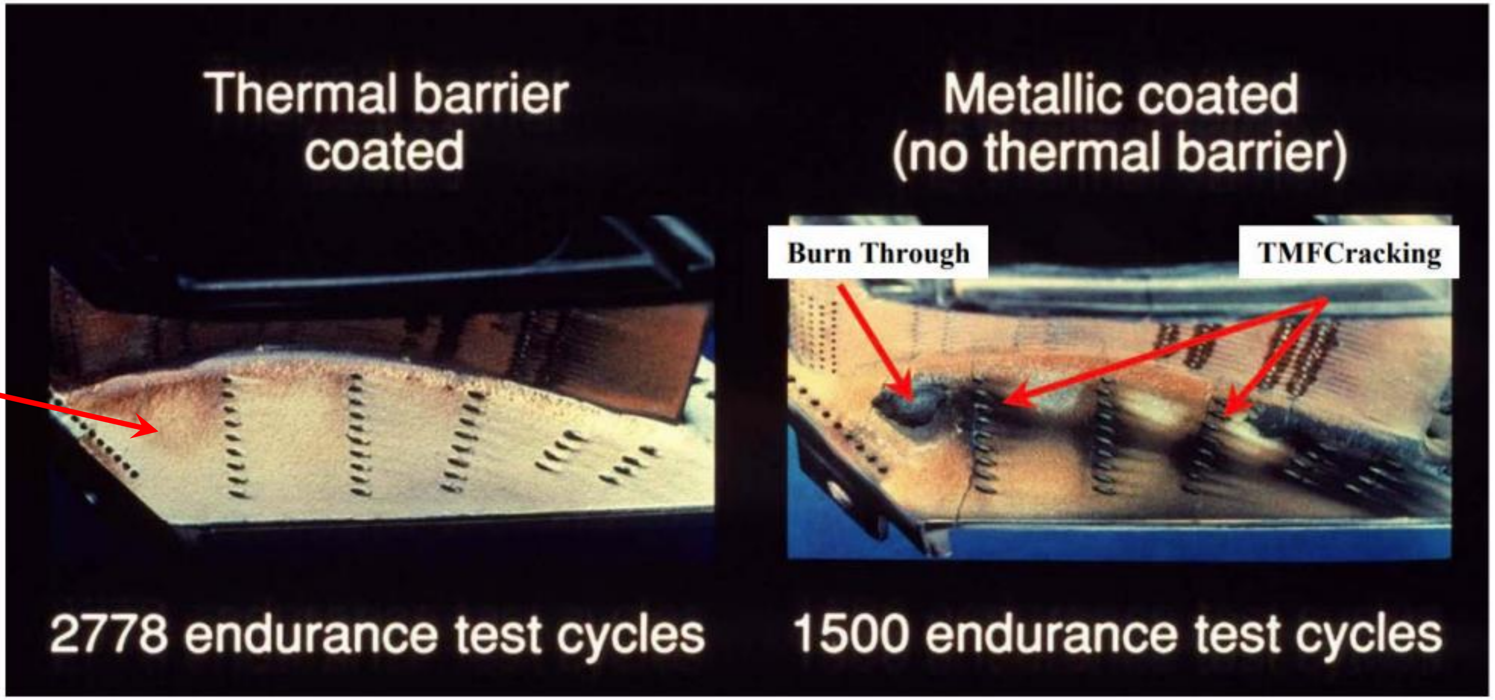
How Will the Data be Used?

- Physics-based Life Models for Oxidation
- Physics-based Life Models for Hot-corrosion
- Physics-based Life Models for Ingested Particulate Induced Distress

Improvement in Oxidation and Thermal Mechanical Fatigue Resistance by Application Of a Thermal Spray Ceramic Thermal Barrier Coating

1985, JT9D Engine Test

Thermal Spray Manufacturing Process Provides a Low Compliance "Splat" Ceramic Microstructure



S. Manning Meier, D.M. Nissley, and K.D. Sheffler, Status of Ceramic Thermal Barrier Thermal Barrier Coatings – Gas Turbine Applications and Life Prediction Method, Proceedings of the 1990 Coatings for Advanced Heat Engines Workshop, Aug. 6-9, Castine ME, II-57-65

- **Application of Thermal Spray TBC Eliminates Distress of Vane Platform**
- **Extended Service Life to 18,000 Hours**

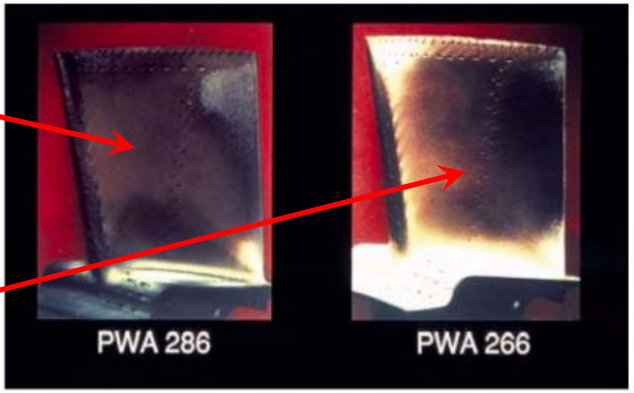
Cost of State of the Art Thermal Spray Coater is Approximately $1.5M

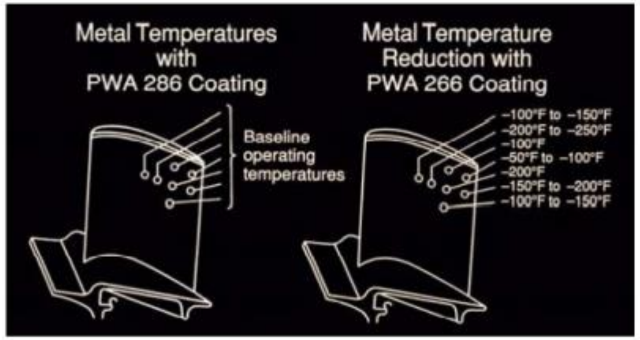
Improvement in Airfoil Durability with the Electron Beam Physical Vapor Deposition (EB-PVD) Coating Manufacturing Process

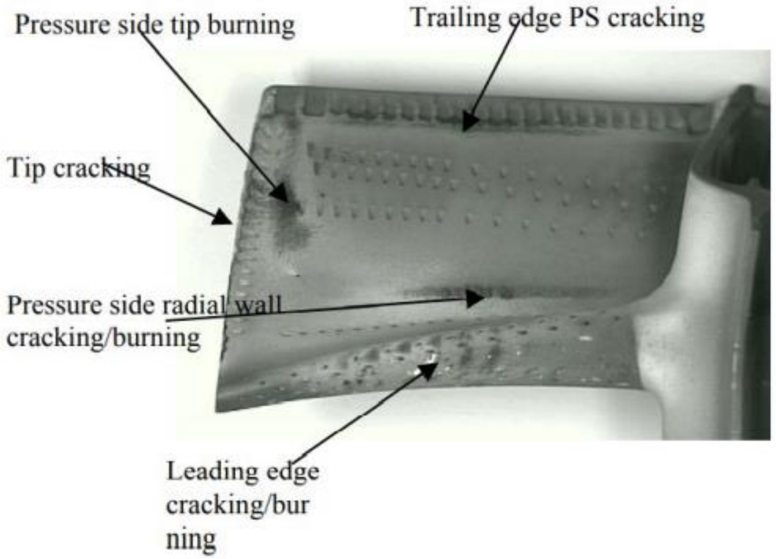
1987, Engine Test Quantifies EB-PVD Temperature Benefit as High as 250F

Oxidation Resistant NiCoCrAlHfSi Metallic Coating

EB-PVD Manufacturing Process Provides a High Compliance "Columnar" Ceramic Microstructure





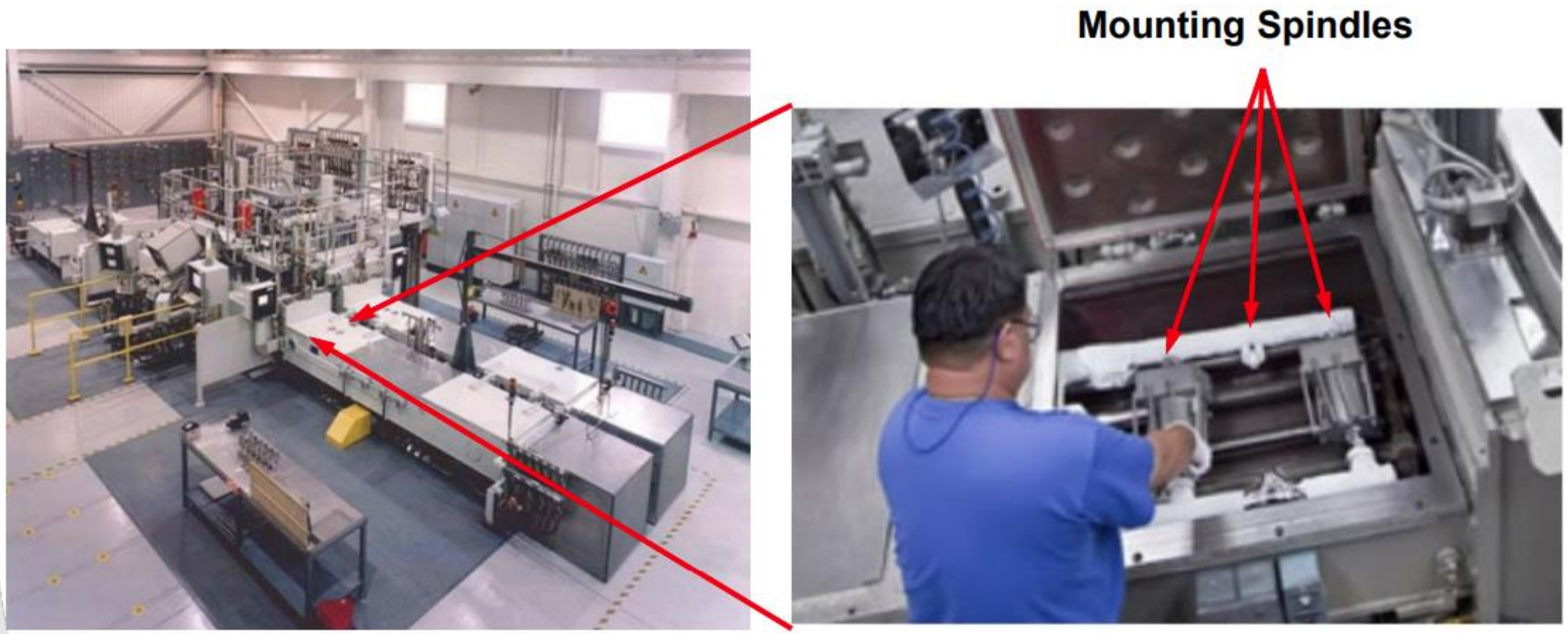


Presented at the International Gas Turbine and Aeroengine Congress and Exposition Cologne, Germany June 1-4, 1992

- **EB-PVD TBC PW2000 1st Blade to Address Field Shortfalls**
- **PW4056 1st P&W Engine with "Designed In" Blade TBC, 1992**

Cost of State of the Art EB-PVD Coater is Approximately $25M

Modern Electron Beam Physical Vapor Deposition (EB-PVD) Manufacturing Coater



Four Sting EB-PVD Coating Unit

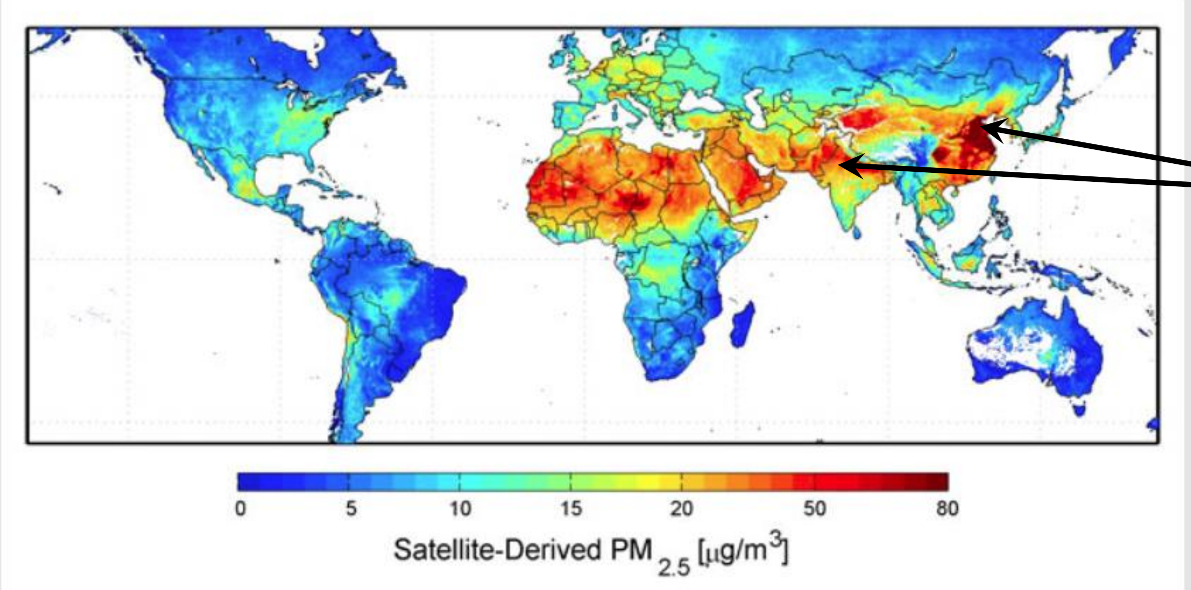
Loading Chamber

- EB-PVD TBC Coating Process used Primarily for Single Crystal Turbine Blades that Operate at Very High Temperatures in the High Pressure Turbine.
- Coating Deposition Typically Carried out at 2000 °F in a High Vacuum Environment
- Much More Involved Coating Process than Air Plasma Spray.

Some Engine Manufacturers Have Invested in Several $25M Coaters to Deploy Advanced Coatings and Improve Engine Fuel Burn and Performance and be Competitive

Ingested Atmospheric Gas Species and Suspend Particulate Matter Influences Gas Turbine Engine Durability

Fine particulate matter (PM2.5), are 2.5 micrometers or less in diameter



› View larger
Global satellite-derived map of $PM_{2.5}$ averaged over 2001-2006. Credit: Dalhousie University, Aaron van Donkelaar

Rapid Increase in Air Traffic

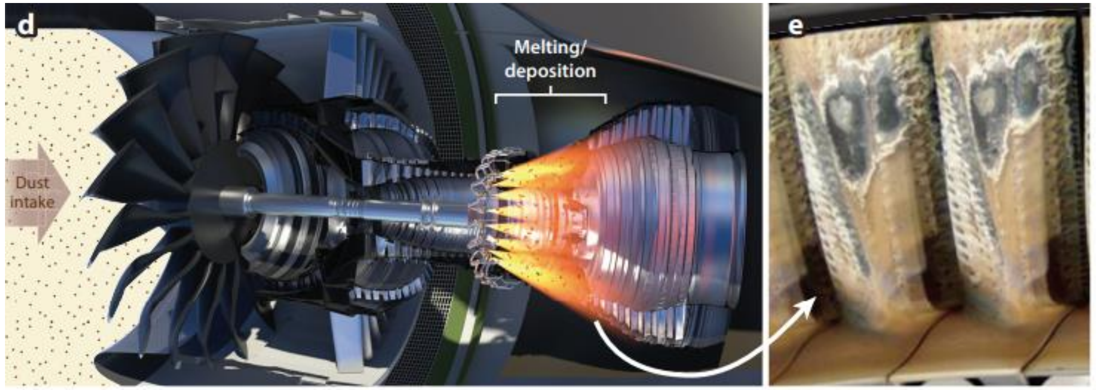
Regional Variability of Chemical Compounds that Contribute to Hot Corrosion

		Los Angeles	Beijing	Delhi
SO_2, ppm		0.002	0.055	0.007
PM	Concentration, μ mol./m³	0.006-0.02	0.12-0.41	0.38-0.64
Sulfate Salts*	Na_2SO_4, mol.%	48-52%	12-21%	32-56%
	K_2SO_4, mol.%	7-11%	9-28%	10-16%
	$MgSO_4$, mol.%	17%	10-12%	10-17
	$CaSO_4$, mol.%	24%	41-67%	18-42%

*Assumes that all measured Na^+, K^+, Mg^{2+} and Ca^{2+} in PM are present in the form of sulfate. Courtesy of Z. Tang and B. Gleeson, University of Pittsburgh

Ingested Particulate (CMAS) Induced Distress

W. S. Walsh, K. A. Thole, and C. Joe, "Effects of Sand Ingestion on the Blockage of Film-Cooling Holes," in *Volume 3: Heat Transfer, Parts A and B*, 2006, vol. 2006, pp. 81–90.



Annu. Rev. Mater. Res. 2017. 47:297–330

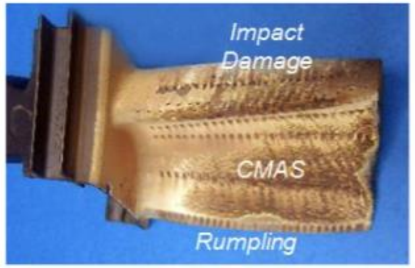
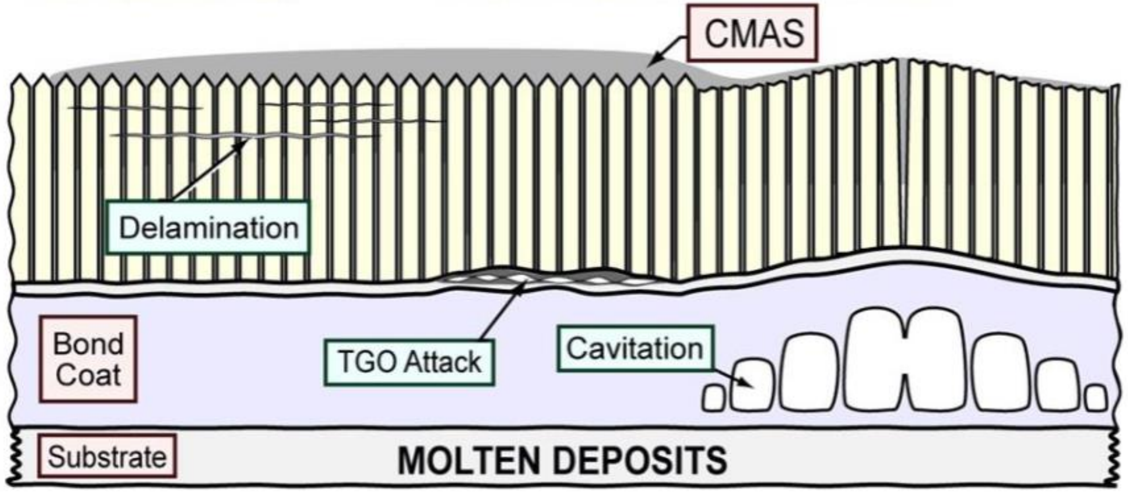


Image courtesy of GE Aviation

TBC Failure Mechanisms

- *Multiple variants of delamination mechanism directly related to CMAS attack*
- *Intrinsic mechanisms aggravated by higher bond coat temperatures in CMAS penetrated areas*

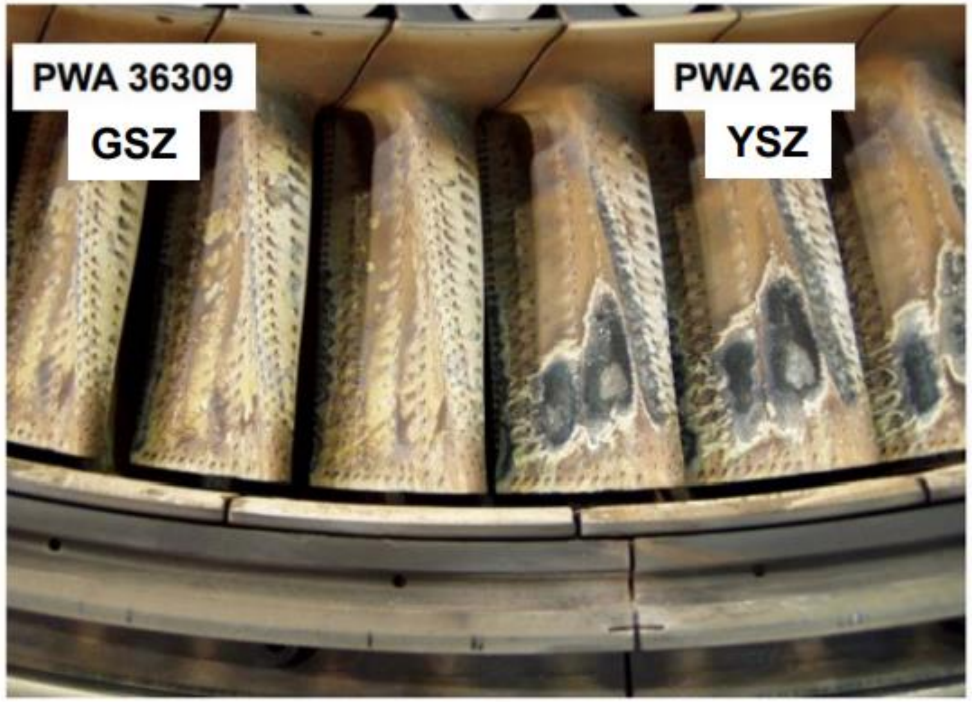


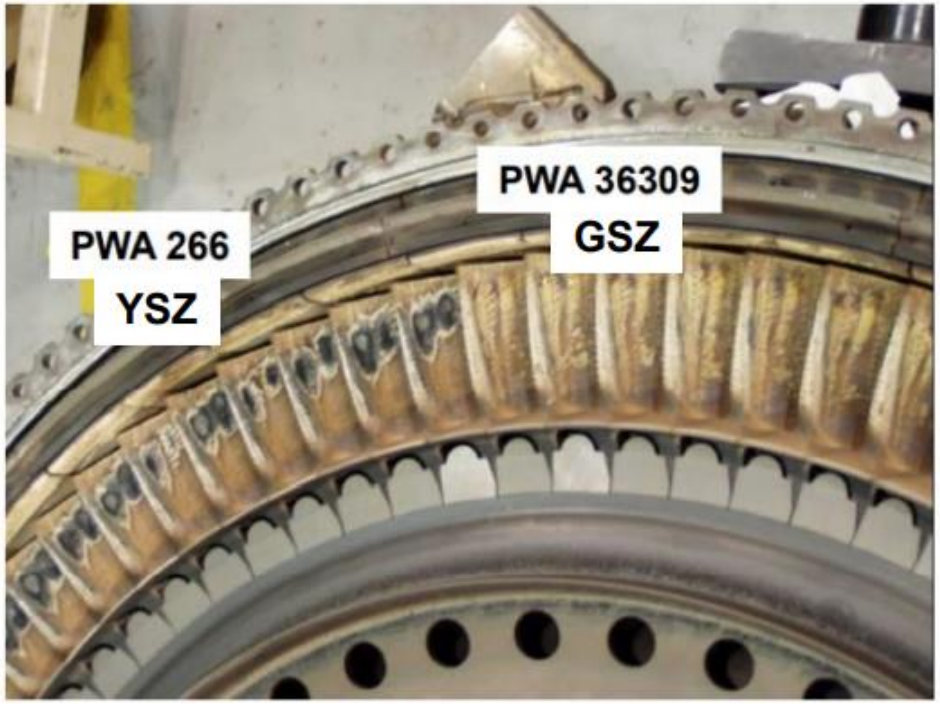
Levi et al., MRS Bulletin Issue on Thermal Barrier Coatings, October 2012; adapted from A.G. Evans et al., JECerS 2008

- **CMAS: Calcium, Magnesium Alumina, Silicate**
- **Ingested Primarily at Altitude and Melts onto and into Protective Coatings Leading to Spallation**

Increased Resistance to Particulate Matter Induced Distress By Ceramic Composition Substitution

Commercial Service Engine Test In Middle East, Three Year Duration





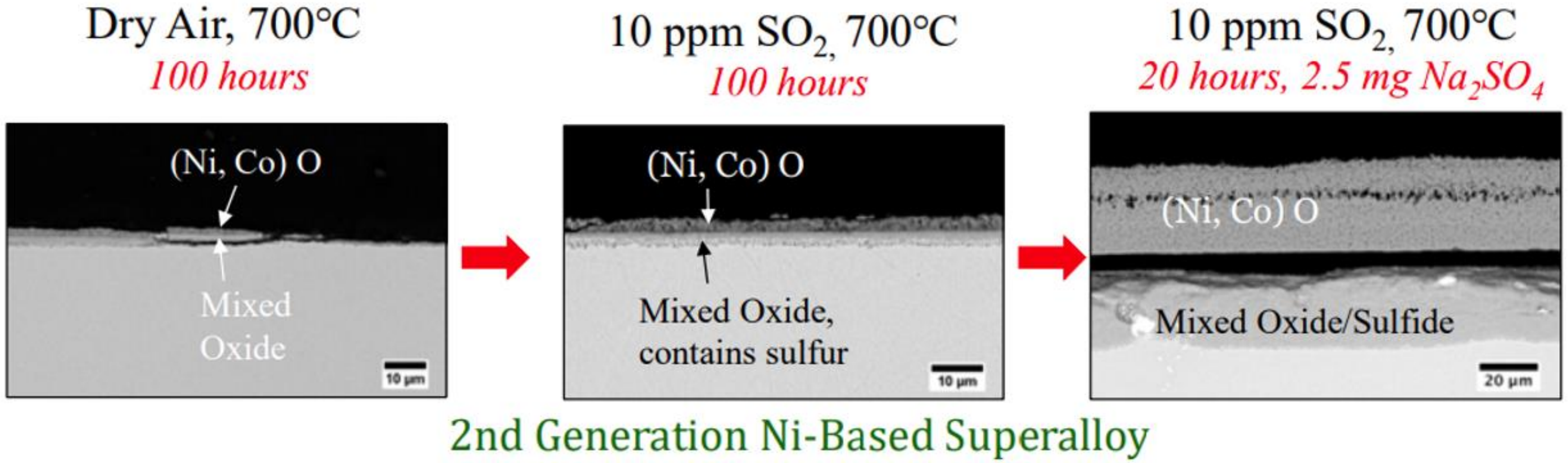
Patent No.: US 6,177,200 B1
Date of Patent: Jan. 23, 2001
Maloney

- **Durability Improvement Due to Lower Thermal Conductivity and Resistance to Molten Deposits.**
- **GSZ Dual-layer TBC Used in High Pressure Turbine of all New P&W Commercial and Military Engines.**

Turbine Forum 2006, April 26,2005, Nice Port St Laurent, France

Utilization of New Gadolinia-Zirconia Ceramic Factors in Patent Position, Manufacturing Robustness, Availability (China), and Raw Material and Manufacturing Cost.

Sulfate Deposit Induced Hot Corrosion



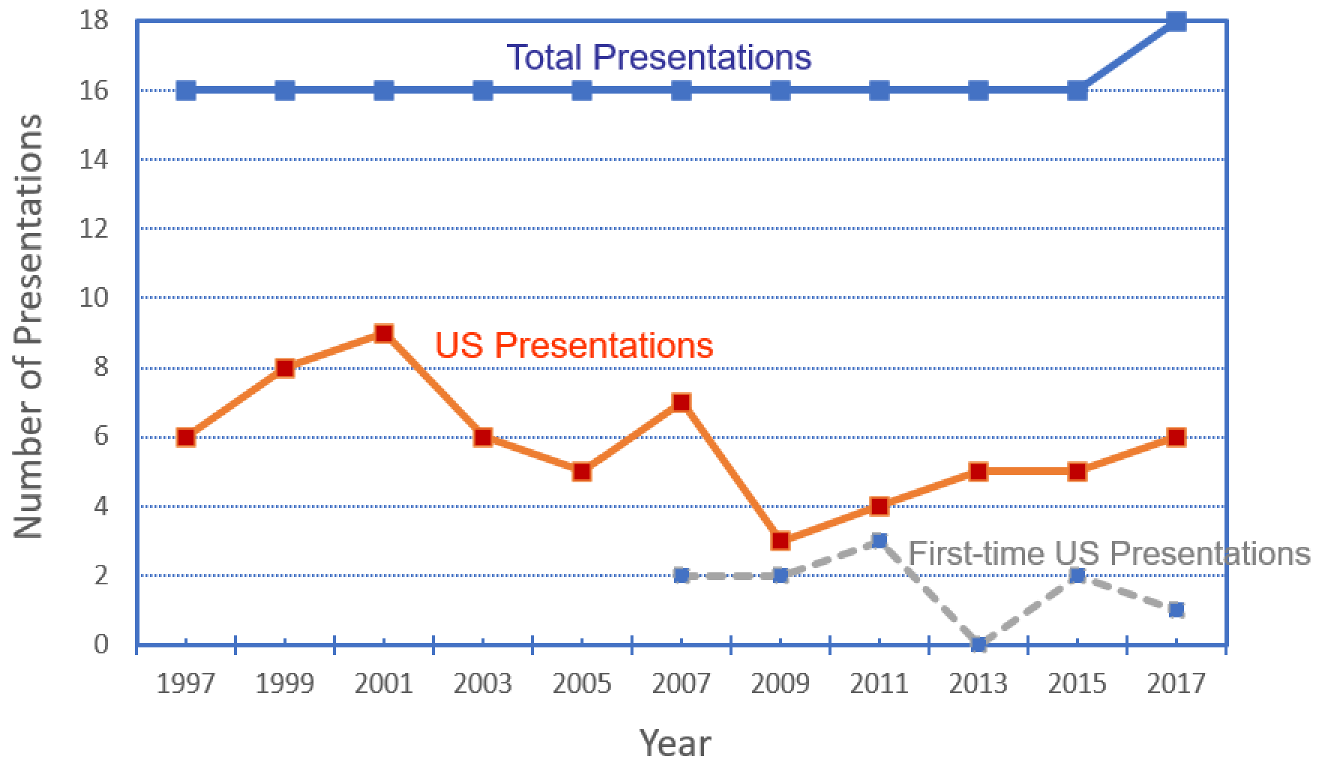
Brian Gleeson, University of Pittsburg, SAE E-41 Committee Meeting March 12, 2021

Compressor Turbine Blades

https://www.euravia.aero/news/what-is-sulphidation?locale=en

20 Year History of Gordon Research Conferences on High Temperature Corrosion

Premier Conference Held Once Every Two Years



➡ By all indicators, there has been are decline in high-temperature corrosion research in the US.

Brian Gleeson, University of Pittsburg, NAE Committee on Advanced Technologies for Gas Turbines Dec. 17, 2018

Sensors Technology: Temperature, Load, Pressure, Ingested Matter

Sensors are an integral part of the digital twin and digital thread, and they are essential for providing real-time data representing the condition of the physical asset and/or the environment in which it is operating. Research is needed to develop sensors that are
(1) capable of operating under the extreme conditions within a gas turbine,
(2) tailored to fit within the geometric constraints of the turbine, and
(3) able to monitor critical parameters.

NAE Website - Advanced Technologies for Gas Turbines

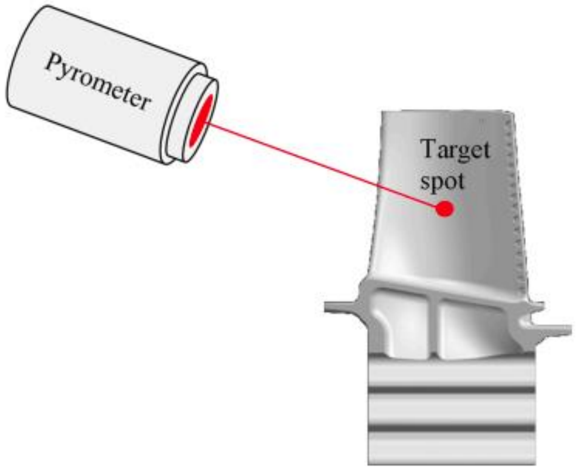


Figure 20. Principle pyrometry.

Temperature

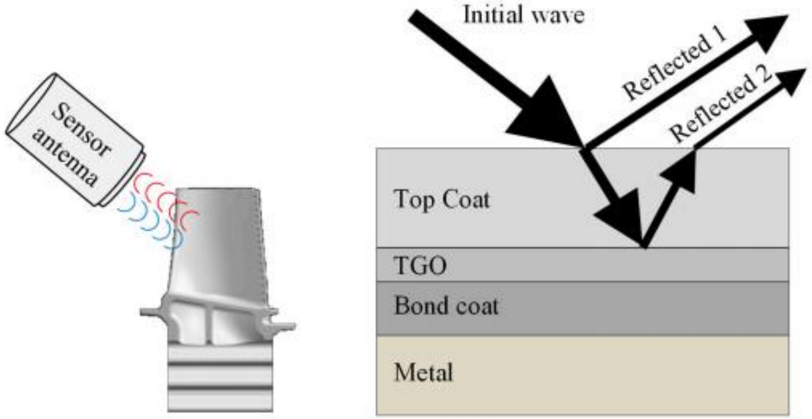


Figure 25. Principle of mm-wave propagation in TBC coating.

Coating Spallation

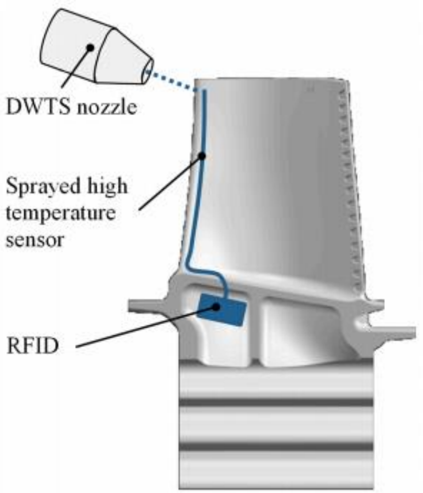


Figure 26. Principle DWTS on a turbine blade.

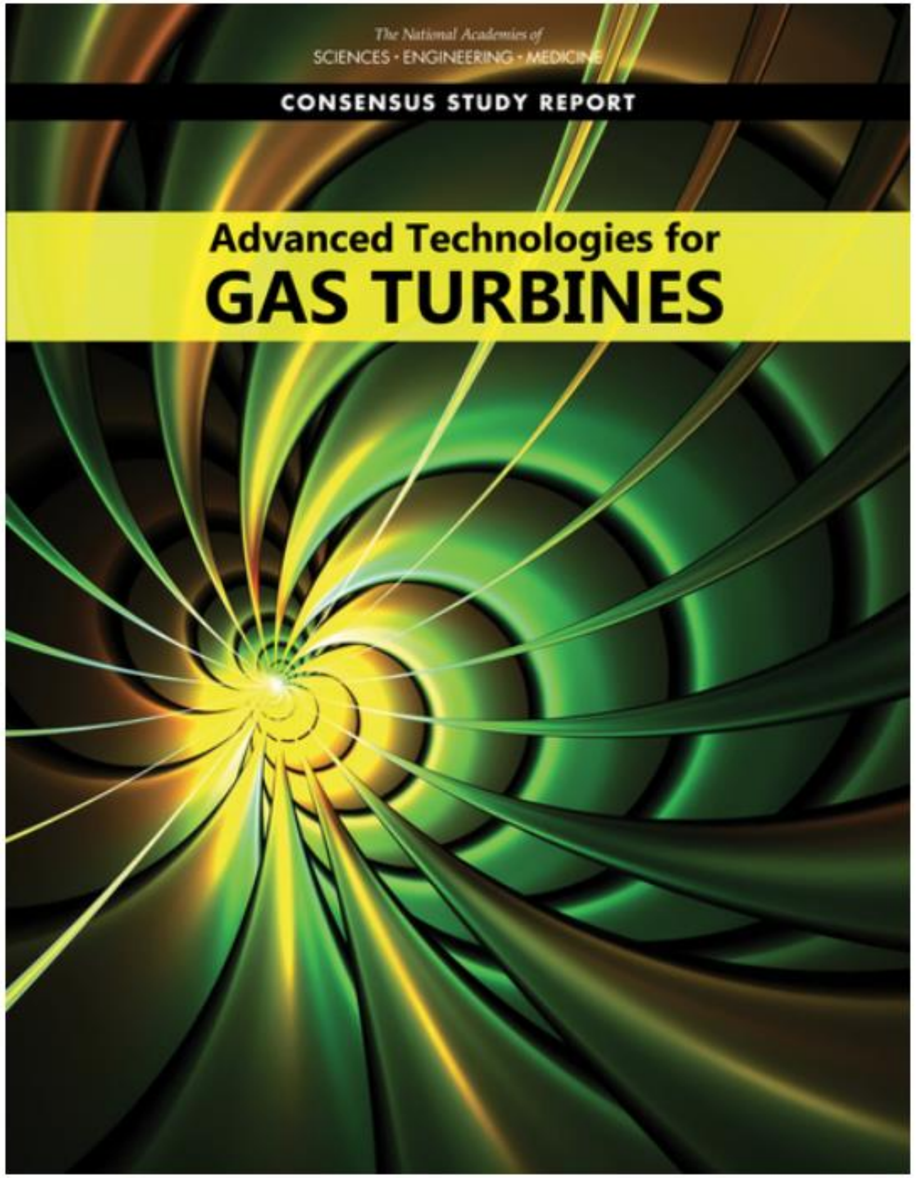
Strain

Sensors | Free Full-Text | A Review of NDT/Structural Health Monitoring Techniques for Hot Gas Components in Gas Turbines | HTML (mdpi.com)

Key Requirements (Gaps) in Establishing a Viable Digital Twin Infrastructure Relative to Environmental Distress Modes

- <u>**Turbine Engine Health Monitoring Sensors**</u>
  - **Temperature**
  - **Pressure**
  - **Ingested Gas Compounds**
  - **Ingested Particulate Matter**
- <u>**Physics-Based Life Models**</u>
  - **Oxidation**
  - **Hot Corrosion**
  - **Gaseous Compounds Induced Distress**
  - **Particulate Matter Induced Distress**

For Additional Information



[Advanced Technologies for Gas Turbines (2020)]

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NAE Website - Advanced Technologies for Gas Turbines

- Research Area 2: Structural Materials and Coatings, Page 46
- Research Area 8: Condition-Based Operations and Maintenance, Page 85
- Research Area 9: Digital Twins and Their Supporting Infrastructure, Page 90