NASA/TM—2009-215459

History of Thermal Barrier Coatings for Gas Turbine Engines

Emphasizing NASA's Role From 1942 to 1990

Robert A. Miller
Glenn Research Center, Cleveland, Ohio

March 2009

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Robert A. Miller
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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

March 2009

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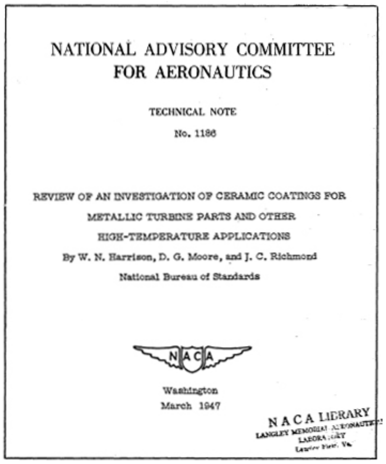
Outline

- **NBS/NACA role in frit coatings**
- **Thermal spray coatings for rocket applications**
- **Stecura-Liebert zirconia-yttria TBCs**
- **Identification of optimum t'-ZrO_2 composition**
- **Failure mechanisms and life prediction**
- **Brief synopsis of post 1990 efforts**

NACA's Earliest Turbine Blade-Oriented Ceramic Coatings Research was on NBS Frit Enamel Coatings 1942-1956

Probably the first aero ceramic coatings paper by Harrison & Moore, NBS – published as NACA TN in 1947



NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

TECHNICAL NOTE

No. 1186

REVIEW OF AN INVESTIGATION OF CERAMIC COATINGS FOR
METALLIC TURBINE PARTS AND OTHER
HIGH-TEMPERATURE APPLICATIONS

By W. N. Harrison, D. G. Moore, and J. C. Richmond

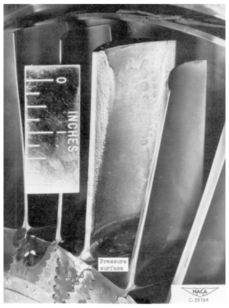
National Bureau of Standards

Washington
March 1947

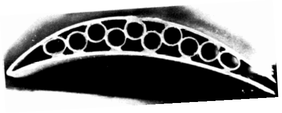
W.N. Harrison, D.G. Moore, and J.C. Richmond, "Review of an Investigation of Ceramic Coatings for Metallic Turbine Parts and Other High Temperature Applications," NACA TN-1186, National Advisory Committee for Aeronautics, 1947

The NBS Frit Coating was tested on Turbine Blades in an Engine as Early as 1948

Figure from 1953 engine test (Bartoo & Clure). Coating on one blade lasted 100 hrs



Top Edge of an Air-Cooled Blade



E.R. Bartoo and J.L. Clure, "Experimental Investigation of Air-Cooled Turbine Bladesin a Turbojet Engine, XIII. Performance Evaluation of Several Protective Coatings Applied to Turbine Blades of Nonstrategic Steels, NACA Research Memo E53E18, 1953

C.R. Morse, Comparison of National Bureau of Standards ceramic coatings L-7C and A-417 on turbine blades in a turbojet engine, NACA Research Memo E8120, 1948

F.G. Garrett and C.A. Gyorgak, "Adhesive and Protective Characteristics of Ceramic Coating A-417 and Its Effects on Engine Life of Forged Refractory-26 (AMS 5760) and Cast Satellite (AMS 5385) Turbine Blades," NACA RM-E52130, 1953

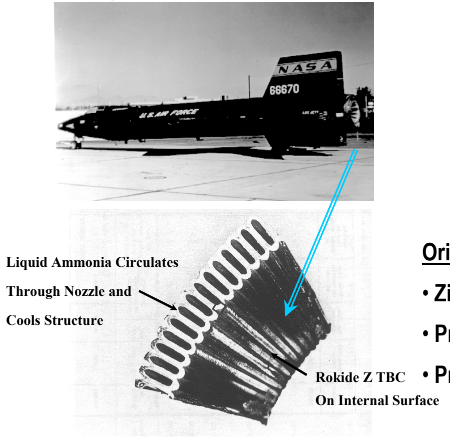
- ***Also, frit coating development led by Air Force in the 40s, 50s and 60s***

A.V. Levy, Ceramic Coating for Insulation, Met. Prog., Vol. 75, 1959, pp. 86–89

Durability questions followed all ceramic coatings for decades partly due to popular image of enameled kitchenware and possibly from negative Air Force results on engines in the 40s, 50s and 60s

Flame Sprayed Coatings were Used for Rocket Applications

The first and most visible was the use of Rokide™ Thermal Barrier Coatings on the XLR99 Rocket Engine Nozzles of the X-15, 1960



Brazed Stainless Steel Tube Structure

X-15 Flight in Early 60s

Originally Coated with Rokide Z TBC

- Zirconia Top Coat/Nickel Chrome Bond Coat
- Prevents Oxidation of Tube Assembly
- Prevents Boiling of Liquid Ammonia

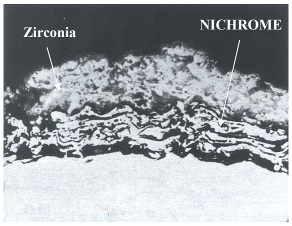
Rokide Torch

L.N. Hjelm and B.R. Bornhorst, “Development of Improved Ceramic Coatings to Increase the Life of XLR99 Thrust Chamber” Research-Airplane-Committee Report on Conference on the Progress of the X-15 Project. NASA Tech Memo x-57072, 1961, 227-253.

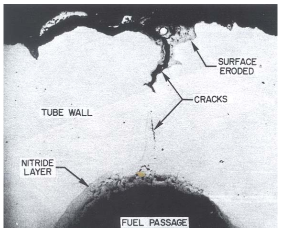
H. Davies, The Design and Development of the Thiokol XLR-99 Rocket Engine for the X-15 Aircraft, J Royal Aeroat Soc 67, 79-91, 196

The XLR-99 development was managed out of Wright Patterson – Air Force Base, Robert L. Wiswell , X-15 Propulsion System, AIAA-1997-2682 AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 33rd, Seattle, WA, July 6-9, 1997

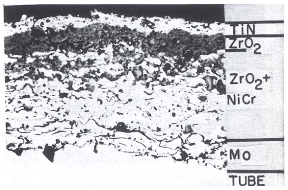
Graded Rokide™ Thermal Barrier Coating Prevented Premature Failure of X-15 Combustion Chamber



Rokide Z Coating, As Processed



Spalled Region After Test



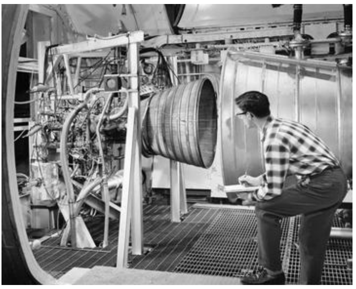
Graded Coating with Mo "Primer"

Use of Graded Coating Significantly Improved Nozzle Life

- **Grading Improved Coating Adhesion**
- **TiN Outer Layer Prevents Erosion (Chalking)**

TBCs Found Use in LH2/LOX Rocket Engine Development

- Development by NACA/NASA with Industrial Partners began in 1956



C. Leibert reported to me (personal communication ca. 1984) that TBCs were first used to extend life past one second!

Was a crucial step towards LH2/LOX rocket engine development

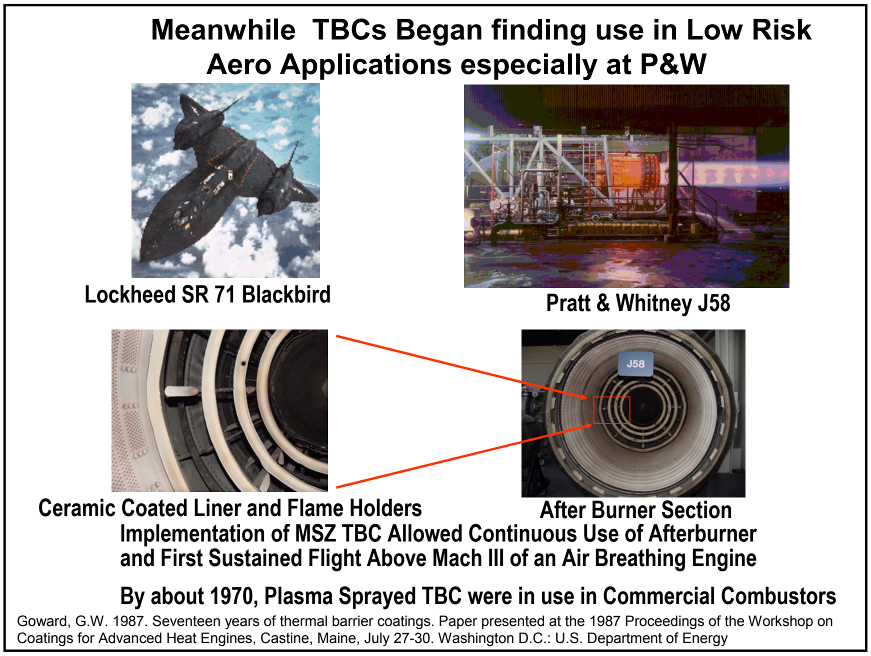
NASA in Cleveland had a rocket-TBC group into the 1990s

H.G. Price Jr., R.L. Schacht, and R.J. Quentmeyer," Reliability of Effective Thermal Conductivity of Three Metallic-Ceramic Composite Insulating Coatings on Cooled Hydrogen-Oxygen Rockets," NASA TN D-7392, 1973

Materials-Oriented Thermal Spray Research in the 60s and Early 70s - Sal Grisaffe

- Sal conducted basic thermal spray research in 60s
- Alumina, Zirconia (Calcia and possibly Yttria stabilized) and Hafnia coatings for nuclear rocket applications in the early 70s
- He founded and headed the first coating’s group in the 60s
  - I joined the coatings group in 1978

S.G. Grisaffe, Simplified Guide to Thermal-Spray Coatings, Mach. Des., Vol. 39, 1967, pp. 174–181
A.N. Curren, S.G. Grisaffe, and K.C. Wycoff, “Hydrogen Plasma Tests of Some Insulating Coating Systems for the Nuclear Rocket Thrust Chamber,” NASA TM X-2461, National Aeronautics and Space Ad- ministration, 1972



Meanwhile TBCs Began finding use in Low Risk Aero Applications especially at P&W

Lockheed SR 71 Blackbird

Pratt & Whitney J58

Ceramic Coated Liner and Flame Holders

After Burner Section

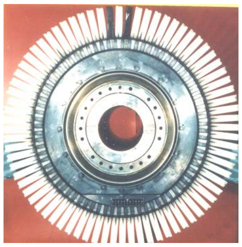
Implementation of MSZ TBC Allowed Continuous Use of Afterburner and First Sustained Flight Above Mach III of an Air Breathing Engine

By about 1970, Plasma Sprayed TBC were in use in Commercial Combustors

Goward, G.W. 1987. Seventeen years of thermal barrier coatings. Paper presented at the 1987 Proceedings of the Workshop on Coatings for Advanced Heat Engines, Castine, Maine, July 27-30. Washington D.C.: U.S. Department of Energy

Mid 70s, Development of "Modern" Thermal Spray Coatings

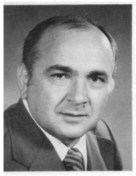
TBC of zirconia-12%yttria on NiCrAlY survived J-75 engine test



Key Accomplishments

- **Use of Yttria as Zirconia Stabilizer**
- **Use of MCrAlY Type Bond Coat**
- **First demonstration that Blade TBCs were feasible**
- **Demonstrated that graded region was not required**

Jack Brown



Stecura

Liebert

S. Stecura, "Two-Layer Thermal Barrier Coating for Turbine Airfoils— Furnace and Burner Rig Test Results," NASA TM X-3425, National Aeronautics and Space Administration, 1976

C.H. Liebert and F.S. Stepka, Potential Use of Ceramic Coating as a Thermal Insulation on Cooled Turbine Hardware, NASA TM X-3352, 1976

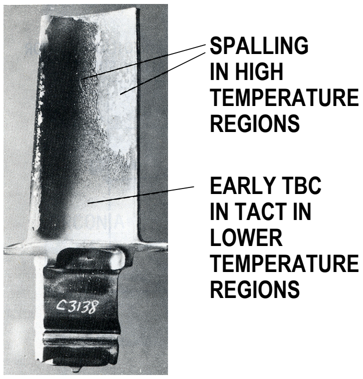
Comment from G.W. Goward

-- then of Turbine Components Corp., formerly of Pratt & Whitney

> *"Although the engine was run at relatively low pressures, the gas turbine engine community was sufficiently impressed to prompt an explosive increase in development funds and programs to attempt to achieve practical utilization of the coatings on turbine airfoils"*

Goward, G.W. 1987. Seventeen years of thermal barrier coatings. Paper presented at the 1987 Proceedings of the Workshop on Coatings for Advanced Heat Engines, Castine, Maine, July 27-30. Washington D.C.: U.S. Department of Energy.

The NASA TBC was Tested with Mixed Results in a More Advanced JT9D at P&W, 1977



Sevcik and Stoner/P&W, 1977:
Failure correlated better with regions of high temperature than regions of highest compressive stress.

This suggested that mechanisms associated with high temperature must be occurring

Tom Strangman was involved in the above discussion

W.R. Sevcik and B.L. Stoner, NASA Contractor Report CR-135360, 1978 (Pratt & Whitney Aircraft)

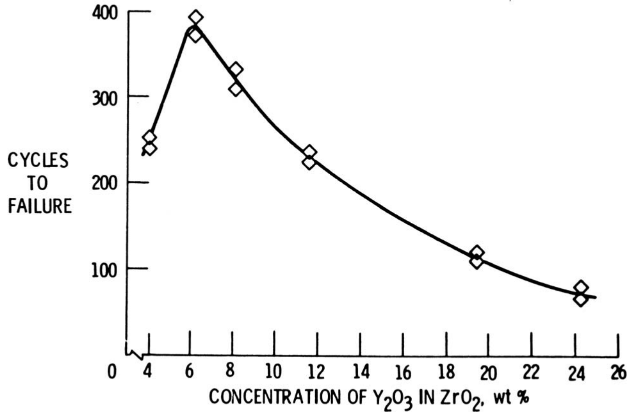
Comment from Goward, 1987:

“The results (of the JT9D test of the NASA TBC) indicated that while the coatings had considerable promise, further development would be required”

Goward, G.W. 1987. Seventeen years of thermal barrier coatings. Paper presented at the 1987 Proceedings of the Workshop on Coatings for Advanced Heat Engines, Castine, Maine, July 27-30. Washington D.C.: U.S. Department of Energy

Stecura Reported Optimum Zirconia-Yttria TBC Composition in 1978 – Still the State-of-the-Art!

- Stecura conducted furnace, natural gas torch, and burner rig tests

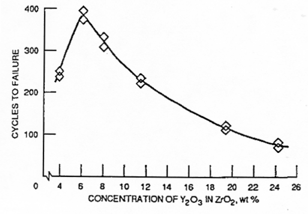


S. Stecura, “Effects of Compositional Changes on the Performance of a Thermal Barrier Coating System,” NASA TM-78976, National Aeronautics and Space Administration, 1978

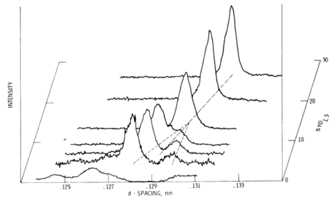
Compositions Having Optimum Life Were Correlated With Phase Distribution

(Miller, Smialek, Garlick 1981,1983)

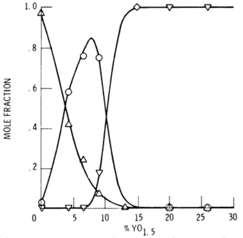
Stecura optimum from 1978



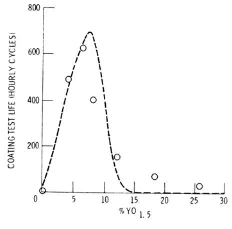
Xray evidence of tetragonal phase



Phase distribution in early TBC



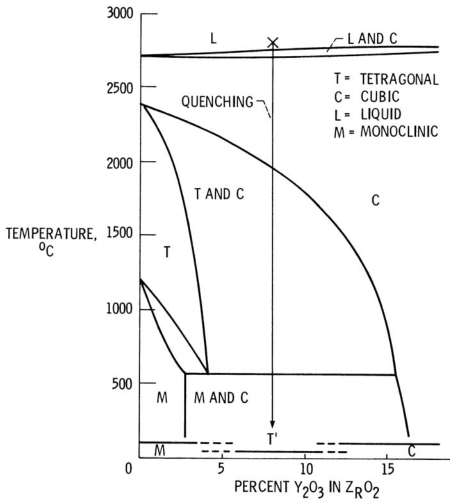
Tetragonal Correlated with Life



R.A. Miller, R.G. Garlick, and J.L. Smialek, Ceram. Soc. Bull., Vol. 62, 1983, pp. 1355–1358

Optimum Phase was t'-ZrO_2 Phase First Reported by Scott

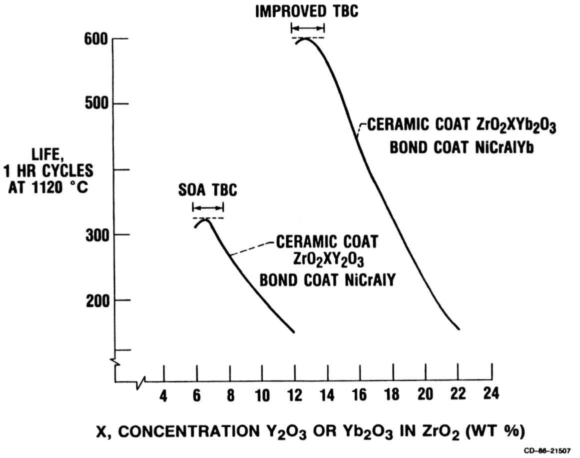
(Miller, Smialek, Garlick 1981, 1983)



H.G. Scott, J. Mater. Sci, 10, 1527-1535 (1975)

Stecura's Later Work Reported 2X Life for Ytterbia-Stabilized Zirconia on a Yb-Containing Bond Coat

IMPROVED TBC SYSTEM YIELDS ≅2X LIFE IN LAB TESTS COMPARED TO CURRENT SOA TBC'S



S. Stecura, New ZrO2-Yb2O3 Plasma-Sprayed Coatings for Thermal Barrier Applications, Thin Solid Films, Vol. 150, 1987, pp. 15–40

In addition to favoring 6-8YSZ, Stecura also Recommended Bond Coats with Lower CTE’s

- His eventual favorite MCrAlY was
  Ni – 35Cr – 6Al – Yb (or Y)

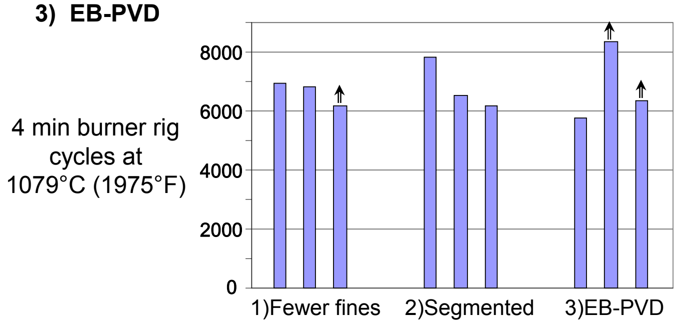
This is a more ductile bond coat due to low aluminum and it has lower expansion due to an α-Cr

S. Stecura, Advanced Thermal Barrier System Bond Coatings for Use on Ni-, Co-, and Fe-Base Alloy Substrates, NASA TM 87062, July 1985

NASA-Sponsored Pratt & Whitney Development Effort Identified Three Optimum 6YSZ TBC Microstructures

Task II Optimums:

1. **Conventionally plasma sprayed with fewer fines (55% -325 mesh)***
2. **Segmented plasma sprayed structure from 1” stand-off distance**
3. **EB-PVD**



Segmented TBC had thermal conductivity 1.9X conventional optimum
*Note that NASA at that time typically used 15% -325mesh)

N.P. Anderson and K.D. Sheffler, Development of Strain Tolerant Thermal Barrier Coating Systems, Tasks I-III, NASA-CR-168251, PWA-5777-29, September 1983.

Arguments Persisted in early 80s over Role of Heat Flux vs. Thermal Expansion Mismatch and Environmental Effects -- even for Burner Rig Testing

- In the early 1980s some believed that failure occurred due to stresses encountered on heating
  - Those believing heat flux effects caused failure calculated max stress at 2 seconds into heating in burner rig.
- We conducted a series of short- and longer-cycle burner rig experiments and concluded the following:
  - Cracks link up at the interface prior to visible surface cracking or spalling, due primarily to thermal expansion mismatch between ceramic/metal
  - A few cycles after the cracks link up to form a delaminated region (visible as a hot-spot on heating), the rapidly heated unattached portion of the coating spalls on heating
  - Failure is influenced by bond coat plasticity and oxidation at the irregular bond coat/ceramic interface
  - Also, coating life was time and cycle dependent

R. A. Miller and C. E. Lowell, Thin Solid Films 95, 265 (1982)

Paul Siemers of GE CR&D was another researcher to recognize the importance of bond coat oxidation and plasticity

> *“The durability of thermal barrier coatings is limited by degradation of adhesion by environmental interactions rather than by mechanical stress per se.”*

P.A. Siemens and W.B. Hillig, “Thermal-Barrier-Coated Turbine Blade Study,” NASA CR-165351, National Aeronautics and Space Administration, 1981

Other NASA Efforts in the 1980s

Abradable seals
  P&W, NASA Bob Bill
    - First discussion of TBC creep (Firestone, U Illinois)
    - This non-textbook use of the term “creep” was controversial!
  Later led to thick diesel TBC program

Dirty fuels
- In-house and DOE and EPRI funding
- Many parallels with CMAS
  - For example Sodium Sulfate does not react with Zirconia-Yttria
    - Rather, when the dew point is less than the coating temperature and the melting point is also less, then liquid Sodium Sulfate wicks into the pores and micro-cracks of the coating leading to a loss of strain tolerance
  - Other impurities such as Vanadium salts also react

RF Firestone, WR Logan, JW Adams - NASA CR-167868, 1982
RA Miller, Ceramic Thermal Barrier Coatings for Electric Utility Gas Turbine Engines, NASA Tech Memo 87288, Jan 1986
RA Miller Analysis of the response of a thermal barrier coating to sodium and vanadium doped combustion gases NASA Tech Memo 79205, 1979

Other NASA Efforts in the 1980s

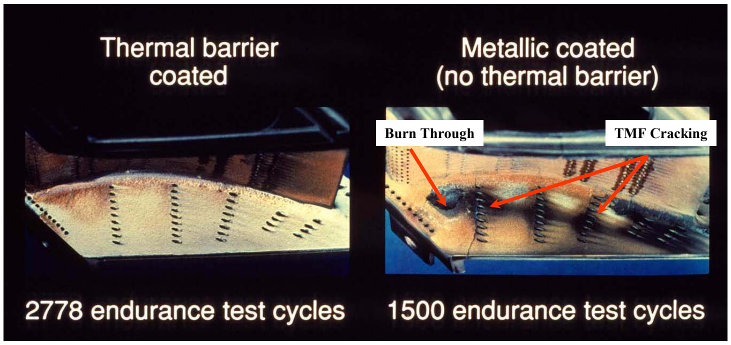
Industry trials
- via coatings group and Liebert’s turbine cooling branch
  - many different applications

TBCs were in 2 Major NASA projects
- Energy Efficient Engine with GE
- Engine Component Improvement with P&W
- Both contracts involved analytical assessment of the value of TBCs

C.H. Liebert and F.S. Stepka, Industry Tests of NASA Ceramic Thermal Barrier Coating” NASA Technical Paper 1425, June 1979
C.H. Liebert and R.A. Miller, Ceramic Thermal Barrier Coatings, I&EC Product Research abd Devel., Sept. 1984, 344-349
E.C. Duderstadt and P. Agarwal, “Energy Efficient Engine. High Pressure Turbine Thermal Barrier Coating Support Technology Report,” NASA CR-168037, National Aeronautics and Space Administration, 1983

In 1985 Pratt & Whitney used Zirconia-Yttria TBC to Fix a Vane Platform Endurance Issue

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



- P&W shared these results with NASA leading to TBC task in Hot Section Technology (HOST) Life Prediction Program

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

S. Manning Meier and D.K. Gupta, The evolution of thermal barrier coatings in gas turbine engine applications Journal of Engineering for Gas Turbines and Power; Vol. 116, 250-257, 1994

This slide and the next 14 that follow are from a 1987 presentation on progress under the Hot Section Technology (HOST) TBC life prediction program. They are repeated here as history

HOST TBC LIFE PREDICTION

NASA
C. STEARNS
R. MILLER
J. NESBITT
S. LEVINE
J. MERUTKA

GE
R. HILLERY
B. PILSNER
R. McKNIGHT

PRATT & WHITNEY
K. SHEFFLER
J. DeMASI (Marcin)
S. MANNING (Meier)
M. ORTIZ
D. NISSLEY*

SOUTHWEST RESEARCH INSTITUTE
T. CRUSE
A. NAGY

GARRETT TURBINE ENGINE CO.
T. STRANGMAN
J. NEUMAN
A. LIU

CSU
G. CHANG
W. PHUCHAROEN

CD-87-29053

*Added to ackowledge post 1987 contribution

R. A. Miller, J. Eng. Gas Turbines Power 109, 448 (1987)

APPROACH TO TBC LIFE MODEL DEVELOPMENT

- INITIAL LABORATORY MODEL (NASA)
  - UNDERSTAND FAILURE MECHANISMS
  - FORMULATE MECHANISM MATHEMATICALLY
  - COLLECT LABORATORY LIFE DATA
  - FIT MODEL TO LIVES
- ENGINE CAPABLE MODELS (PWA, GTEC, GE CONTRACTS)
  - FURTHER UNDERSTANDING
  - FORMULATE MATHEMATICALLY
  - COLLECT LIFE DATA OVER MANY CONDITIONS ON BOM SYSTEM
  - MEASURE MATERIALS PROPERTIES
  - FIT MODEL TO LIVES
  - EXTRAPOLATE TO ENGINE MISSIONS
- DETAILED FINITE ELEMENT σ-ε ANALYSIS (CSU, NASA)

CD-87-29050

UNDERSTANDING OF FAILURE MECHANISMS SUFFICIENT TO ALLOW MODELING

FAILURE BY CRACKING/DELAMINATION IN CERAMIC NEAR INTERFACE
- ■ PROGRESSIVE CRACKING OBSERVED
- ■ σ, ε MODELED

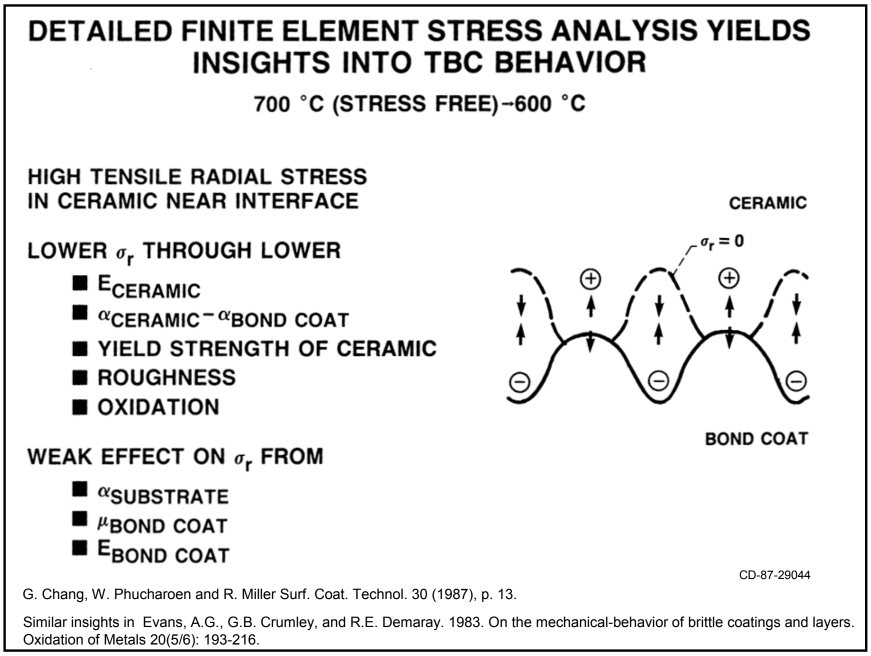
EMPIRICAL OBSERVATIONS

CYCLIC COMPONENT TO FAILURE
- ■ THERMAL EXPANSION MISMATCH[a]
- ■ HEATING TRANSIENTS

TIME-AT-TEMPERATURE COMPONENT
- ■ OXIDATION[a]
- ■ PHASE CHANGES
- ■ SINTERING
- ■ DIFFUSION
- ■ CREEP

[a] KEY FACTORS INCLUDED IN PRELIMINARY NASA MODEL

CD-87-29052



DETAILED FINITE ELEMENT STRESS ANALYSIS YIELDS INSIGHTS INTO TBC BEHAVIOR

700 °C (STRESS FREE)→600 °C

HIGH TENSILE RADIAL STRESS IN CERAMIC NEAR INTERFACE

LOWER σ_r THROUGH LOWER

- $E_{CERAMIC}$
- $\alpha_{CERAMIC} - \alpha_{BOND\ COAT}$
- YIELD STRENGTH OF CERAMIC
- ROUGHNESS
- OXIDATION

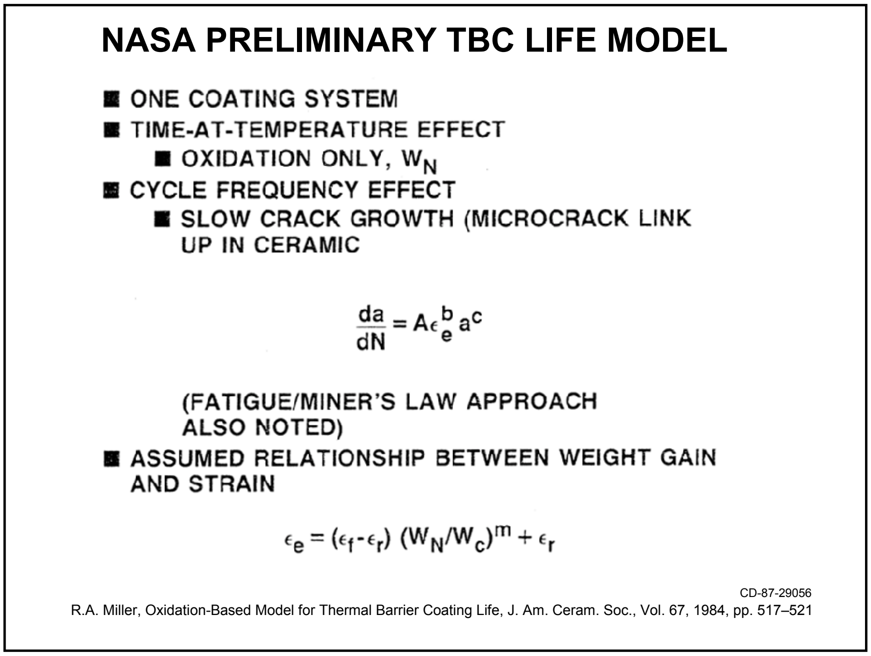
WEAK EFFECT ON σ_r FROM

- $\alpha_{SUBSTRATE}$
- $\mu_{BOND\ COAT}$
- $E_{BOND\ COAT}$

CD-87-29044

G. Chang, W. Phucharoen and R. Miller Surf. Coat. Technol. 30 (1987), p. 13.

Similar insights in Evans, A.G., G.B. Crumley, and R.E. Demaray. 1983. On the mechanical-behavior of brittle coatings and layers. Oxidation of Metals 20(5/6): 193-216.



NASA PRELIMINARY TBC LIFE MODEL

- ONE COATING SYSTEM
- TIME-AT-TEMPERATURE EFFECT
  - OXIDATION ONLY, W_N
- CYCLE FREQUENCY EFFECT
  - SLOW CRACK GROWTH (MICROCRACK LINK UP IN CERAMIC

$$\frac{da}{dN} = A\epsilon_e^b a^c$$

(FATIGUE/MINER'S LAW APPROACH ALSO NOTED)

- ASSUMED RELATIONSHIP BETWEEN WEIGHT GAIN AND STRAIN

$$\epsilon_e = (\epsilon_f - \epsilon_r)\ (W_N/W_c)^m + \epsilon_r$$

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R.A. Miller, Oxidation-Based Model for Thermal Barrier Coating Life, J. Am. Ceram. Soc., Vol. 67, 1984, pp. 517–521

NASA PRELIMINARY TBC LIFE MODEL CONTINUED

- RESULTING MODEL

$$\sum_{N=1}^{N_f}\left[(1-\epsilon_r/\epsilon_f)\,(W_N/W_c)^m+\epsilon_r/\epsilon_f\right]^b$$

- ALTERNATIVE ASSUMPTION OF STRENGTH DEGRADATION FROM ϵ_{f_0} TO ϵ_r

$$\epsilon_f/\epsilon_r=(1-\epsilon_{f_0}/\epsilon_r)\,(W_N/W_c)^m+\epsilon_{f_0}/\epsilon_r$$

- RESULTING ALTERNATIVE MODEL

$$\sum_{N=1}^{N_f}\left[(1-\epsilon_{f_0}/\epsilon_r)\,(W_N/W_c)^m+\epsilon_{f_0}/\epsilon_r\right]^{-b}=1$$

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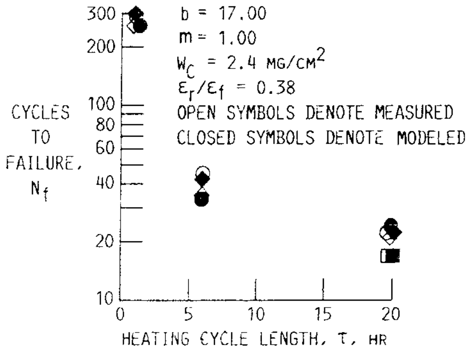
PRELIMINARY MODEL YIELDS GOOD AGREEMENT BETWEEN EXPERIMENTAL AND CALCULATED TBC LIVES

$$\text{MODEL: }\sum_{N=1}^{N_f}\left[\left(1-\frac{\varepsilon_r}{\varepsilon_f}\right)\left(\frac{W_N}{W_C}\right)^m+\frac{\varepsilon_r}{\varepsilon_f}\right]^b=1$$



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P&W HOST ACCOMPLISHMENTS

DEGRADATION MODES IDENTIFIED

- **Mechanical (major mode)**
  - **Near interfacial ceramic cracking**
  - **Apparent near-interface ceramic weakening**
- **Oxidation (major mode)**
  - **Oxidation effect phenomenologically characterized**
  - **Complex oxide scale characterized**
  - **Interaction mechanism not understood**
- **Hot corrosion (minor mode)**
  - **Not observed in flight service**
  - **Threshold corrodant level identified in lab**
- **Erosion (minor mode)**
  - **Isolated occurrence in flight service**
  - **Limited lab characterization needed**
- **F/BMOD (minor model)**
  - **Not identified in flight service**
  - **Experimental engines exhibit high –resistance**

P&W HOST ACCOMPLISHMENTS

MAJOR MODE CORRELATIVE LIFE MODEL PROPOSED

- **Fatigue based model**
- **Reversed ceramic plastic strain is primary driving force**
- **Oxidation acts to "weaken" ceramic**
- **Preliminary correlation coefficient 0.89 (90 experimental data points)**
- **Upgraded analysis in progress**
- **Incorporates improved ceramic behavior model**
- **Oxidation contribution improved by use of NASA data**

Thermal Barrier Coating Life Prediction Model Development: Phase I-Final Report, NASA CR 182230
J.T. DeMasi, K.D. Sheffler, M. Ortiz - National Aeronautics and Space Administration, Washington DC, 1989
Thermal barrier coating life prediction model development—phase II
S.M. Meier, D.M. Nissley, K.D. Sheffler - NASA CR-18911, July, 1991

PWA/SwRI TBC LIFE MODEL

- BILL-OF-MATERIAL COATING SYSTEM
- TIME-AT-TEMPERATURE EFFECT
  - OXIDATION ONLY, δ
  - ARRHENIUS LAW
- CYCLE FREQUENCY EFFECT
  - INELASTIC FATIGUE MODEL

$$N_f = (\Delta\epsilon_i / \Delta\epsilon_f)^b$$

$$\Delta\epsilon_i = \Delta\alpha\ \Delta T + \Delta\epsilon_h + \Delta\epsilon_c - 2\,\frac{\sigma_{ys}}{E}$$

ASSUMED STRENGTH DEGRADATION DUE TO OXIDATION

$$\Delta\epsilon_f = \Delta\epsilon_{f0}\ (1 - \delta/\delta_c)^c + \Delta\epsilon_i\ (\delta/\delta_c)^d$$

- MINERS RULE

$$\sum_{N=1}^{N_f} \frac{1}{N} \geq 1$$

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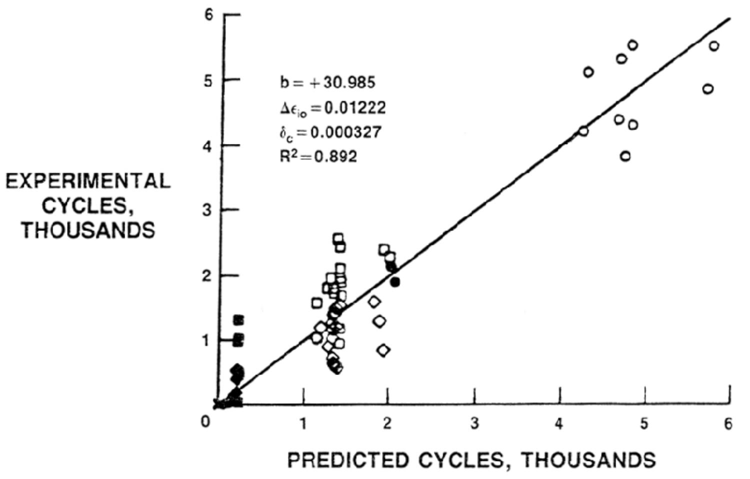
CORRELATION BETWEEN MEASURED AND MODELED LIVES (PRELIMINARY PRATT & WHITNEY DATA)



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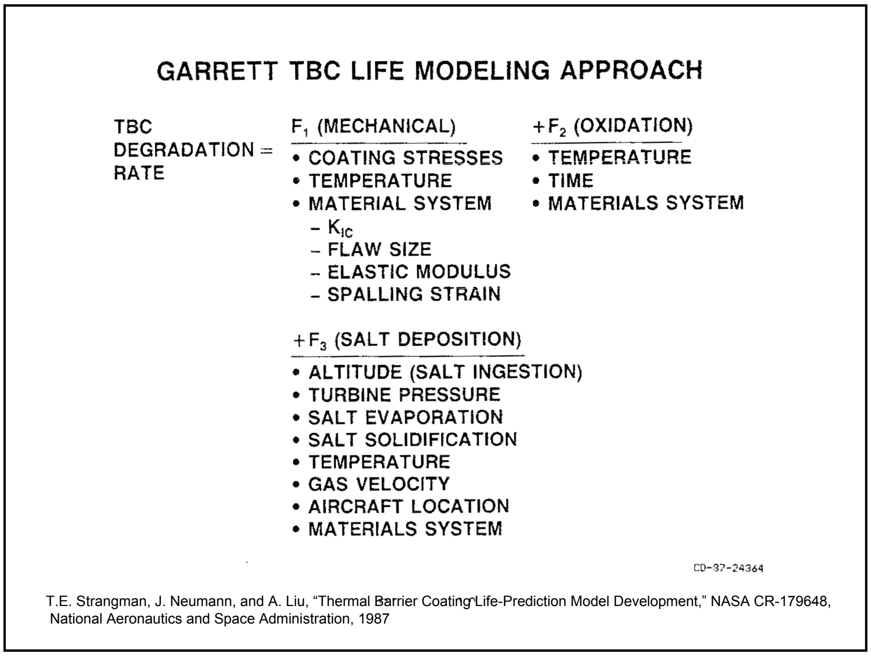

GARRETT TBC LIFE MODELING APPROACH

TBC DEGRADATION RATE = F_1 (MECHANICAL) + F_2 (OXIDATION) + F_3 (SALT DEPOSITION)

F_1 (MECHANICAL)
- COATING STRESSES
- TEMPERATURE
- MATERIAL SYSTEM
  - K_{IC}
  - FLAW SIZE
  - ELASTIC MODULUS
  - SPALLING STRAIN

+F_2 (OXIDATION)
- TEMPERATURE
- TIME
- MATERIALS SYSTEM

+F_3 (SALT DEPOSITION)
- ALTITUDE (SALT INGESTION)
- TURBINE PRESSURE
- SALT EVAPORATION
- SALT SOLIDIFICATION
- TEMPERATURE
- GAS VELOCITY
- AIRCRAFT LOCATION
- MATERIALS SYSTEM

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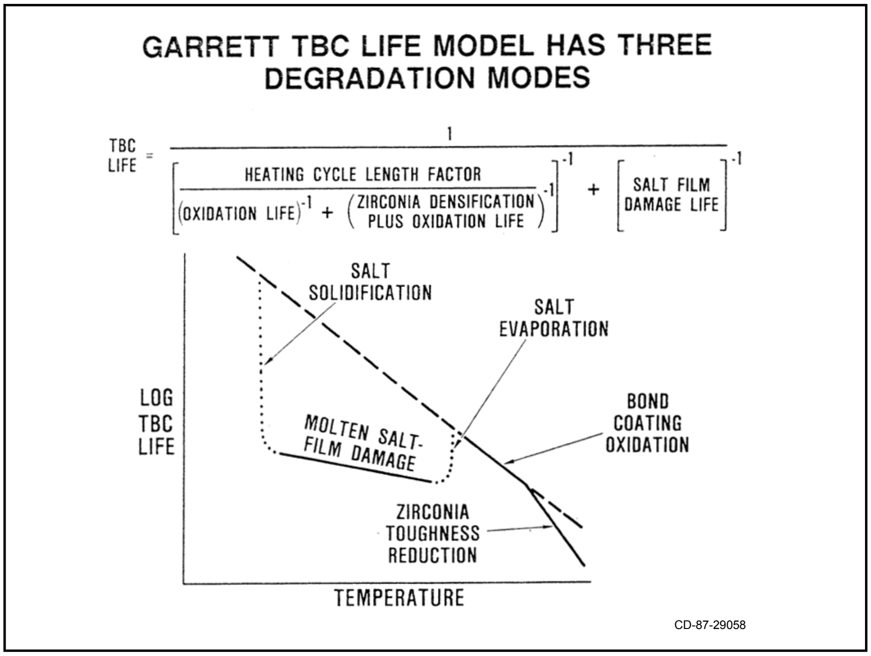
T.E. Strangman, J. Neumann, and A. Liu, “Thermal Barrier Coating Life-Prediction Model Development,” NASA CR-179648, National Aeronautics and Space Administration, 1987



GARRETT TBC LIFE MODEL HAS THREE DEGRADATION MODES

$$\text{TBC LIFE} = \frac{1}{\left[\dfrac{\text{HEATING CYCLE LENGTH FACTOR}}{(\text{OXIDATION LIFE})^{-1} + \left(\begin{matrix}\text{ZIRCONIA DENSIFICATION}\\ \text{PLUS OXIDATION LIFE}\end{matrix}\right)^{-1}}\right]^{-1} + \left[\begin{matrix}\text{SALT FILM}\\ \text{DAMAGE LIFE}\end{matrix}\right]^{-1}}$$

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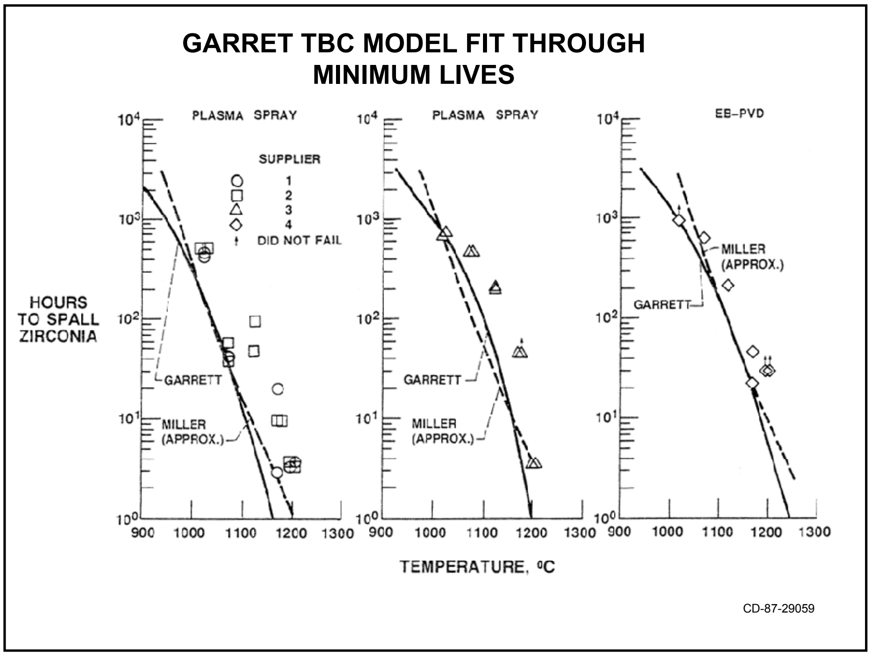

GARRET TBC MODEL FIT THROUGH MINIMUM LIVES

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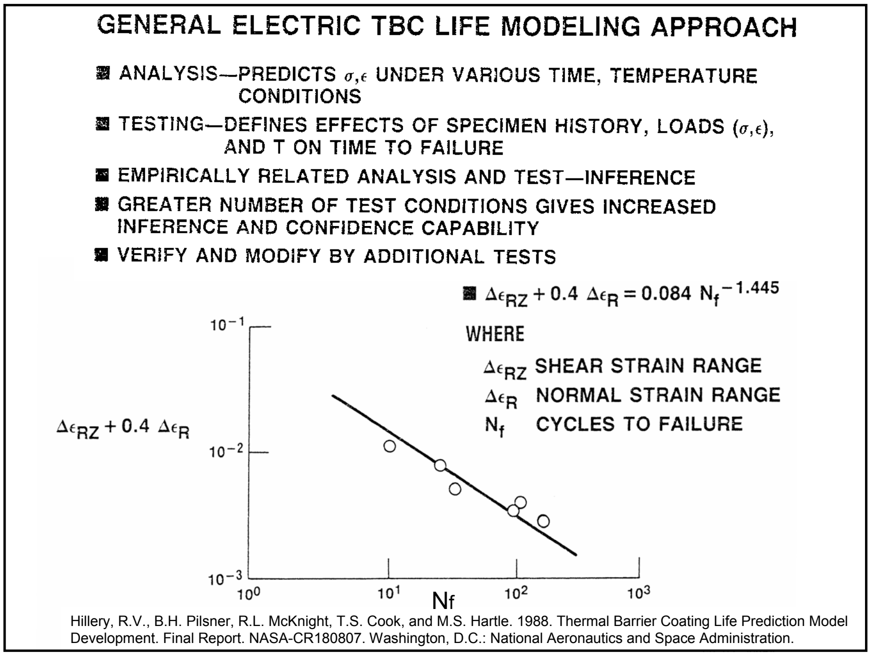


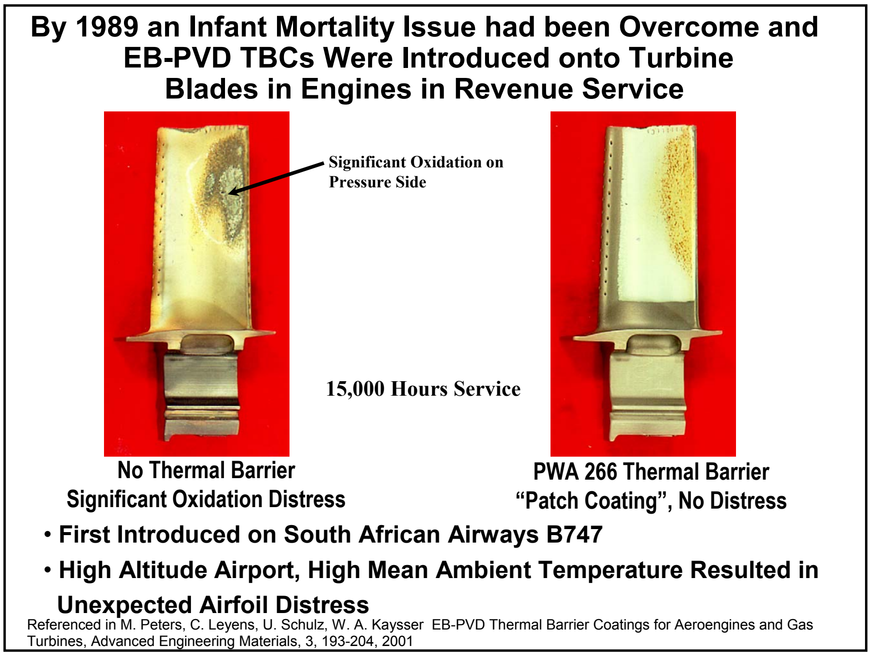
GENERAL ELECTRIC TBC LIFE MODELING APPROACH

- ANALYSIS—PREDICTS σ,ϵ UNDER VARIOUS TIME, TEMPERATURE CONDITIONS
- TESTING—DEFINES EFFECTS OF SPECIMEN HISTORY, LOADS (σ,ϵ), AND T ON TIME TO FAILURE
- EMPIRICALLY RELATED ANALYSIS AND TEST—INFERENCE
- GREATER NUMBER OF TEST CONDITIONS GIVES INCREASED INFERENCE AND CONFIDENCE CAPABILITY
- VERIFY AND MODIFY BY ADDITIONAL TESTS
- $\Delta\epsilon_{RZ} + 0.4\ \Delta\epsilon_R = 0.084\ N_f^{-1.445}$

WHERE

$\Delta\epsilon_{RZ}$ SHEAR STRAIN RANGE
$\Delta\epsilon_R$ NORMAL STRAIN RANGE
N_f CYCLES TO FAILURE

Hillery, R.V., B.H. Pilsner, R.L. McKnight, T.S. Cook, and M.S. Hartle. 1988. Thermal Barrier Coating Life Prediction Model Development. Final Report. NASA-CR180807. Washington, D.C.: National Aeronautics and Space Administration.



By 1989 an Infant Mortality Issue had been Overcome and EB-PVD TBCs Were Introduced onto Turbine Blades in Engines in Revenue Service

Significant Oxidation on Pressure Side

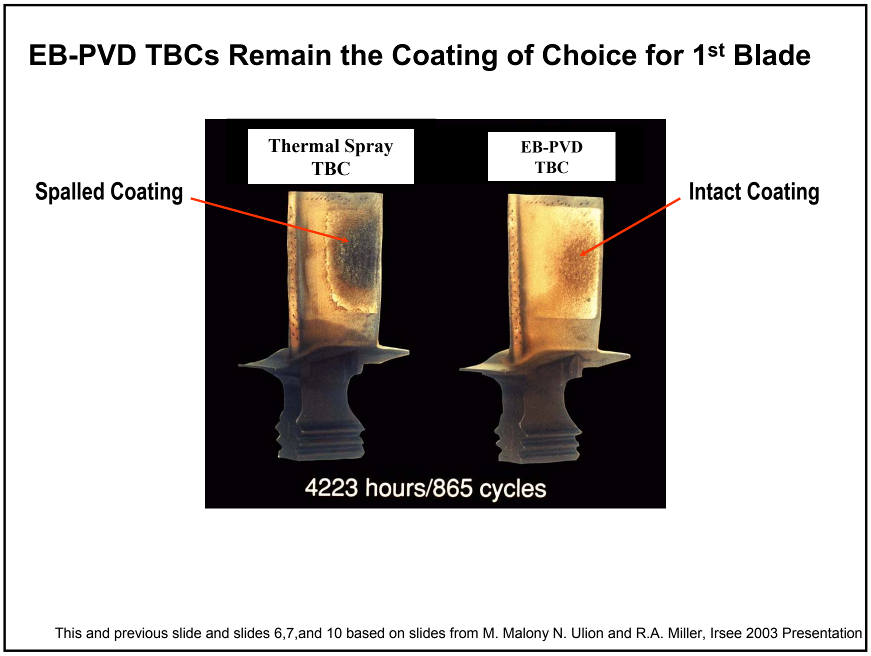
15,000 Hours Service

No Thermal Barrier
Significant Oxidation Distress

PWA 266 Thermal Barrier
“Patch Coating”, No Distress

- First Introduced on South African Airways B747
- High Altitude Airport, High Mean Ambient Temperature Resulted in Unexpected Airfoil Distress

Referenced in M. Peters, C. Leyens, U. Schulz, W. A. Kaysser EB-PVD Thermal Barrier Coatings for Aeroengines and Gas Turbines, Advanced Engineering Materials, 3, 193-204, 2001



EB-PVD TBCs Remain the Coating of Choice for 1st Blade

Thermal Spray
TBC

EB-PVD
TBC

Spalled Coating

Intact Coating

4223 hours/865 cycles

This and previous slide and slides 6,7,and 10 based on slides from M. Malony N. Ulion and R.A. Miller, Irsee 2003 Presentation

Concluding Remarks -- NASA had Substantial Involvement in Early TBC Research and TBC Research Continued through the 90s and 00s …

1990s:

Thick Diesel
- With the Army Research Lab at NASA and Caterpillar
- Built on thick shroud work
- Dongming Zhu joined NASA team

EBCs
- Built on initial Solar Turbines Research

High Speed Research
- NASA/GE/P&W
- Began a period of strong interaction with industry
  - A useful reality check!

2000s:

Ultra Efficient Engine Technology
- Low k TBC / High heat flux laser rig testing
- EBCs

D. Zhu and R.A. Miller, Investigation of Thermal High Cycle and Low Cycle Fatigue Mechanisms of Thick Thermal Barrier Coatings, Materials Science and Engineer. Vol. A245, pp. 212-223, 1998
K.N. Lee, R.A. Miller, and N.S. Jacobson, New generation of plasma-sprayed mullite coatings on silicon-carbide. J. Am. Ceram. Soc. 78 3 (1995), pp. 705–710
D. Zhu and R.A. Miller, Development of Advanced Low Conductivity Thermal Barrier Coatings, Int. J. Appl. Ceram. Technol., Vol. 1, 86-94, 2004

Concluding Remarks --

… and TBC Research Continues Today

Fundamental Aeronautics Program
- Erosion
  - Rotorcraft oriented; first blade EB-PVD
  - Burner rig has been modified for particle injection
- Damping
  - High force/high frequency/high temperature capability
- TBC Lifing
  - Small program aimed at Supersonic mission
- EBCs
  - Current task is also aimed at Supersonics

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

NASA has played a central role in the development of thermal barrier coatings (TBCs) for gas turbine applications. This report discuses the history of TBCs emphasizing the role NASA has played beginning with (1) frit coatings in the 1940s and 1950s; (2) thermally sprayes coatings for rocket application in the 1960s and early 1970s; (3) the beginnings of the modern era of turbine section coatings in the mid 1970s; and (4) failure mechanism and life prediction studies in the 1980s and 1990s. More recent efforts are also briefly discussed.

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Thermal barrier coatings; Gas turbine engines; History

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