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
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Space Administration

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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'-ZrO₂ 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


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


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


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

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

X-15 Flight in Early 60s

Brazed Stainless Steel Tube Structure


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

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

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

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

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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

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”

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

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”
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


Compositions having optimum life were correlated with phase distribution

(Miller, Smialek, Garlick 1981, 1983)

Stecura optimum from 1978

X-ray evidence of tetragonal phase

Phase distribution in early TBC

Tetragonal correlated with life

Optimum Phase was $t'$-ZrO$_2$ Phase First Reported by Scott (Miller, Smialek, Garlick 1981, 1983)


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

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 87002, 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

4 min burner rig cycles at 1079°C (1975°F)

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

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


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.”

Other NASA Efforts in the 1980s

Abreadable 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

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

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


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

<table>
<thead>
<tr>
<th>NASA</th>
<th>GE</th>
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<tbody>
<tr>
<td>C. STEARNS</td>
<td>R. HILLERY</td>
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<td>R. MILLER</td>
<td>B. PILSNER</td>
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<td>J. NESBITT</td>
<td>R. MCKNIGHT</td>
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<td>S. LEVINE</td>
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<tr>
<th>PRATT &amp; WHITNEY</th>
<th>SOUTHWEST RESEARCH</th>
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<tr>
<td>K. SHEFFLER</td>
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<tr>
<td>J. DeMASI (Marcin)</td>
<td>T. CRUSE</td>
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<td>S. MANNING (Meier)</td>
<td>A. NAGY</td>
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<td>M. ORTIZ</td>
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<td>D. NISSLEY*</td>
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<thead>
<tr>
<th>GARRETT TURBINE ENGINE CO.</th>
<th>CSU</th>
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<tr>
<td>T. STRANGMAN</td>
<td>G. CHANG</td>
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<tr>
<td>J. NEUMAN</td>
<td>W. PHUCHAROEN</td>
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<td>A. LIU</td>
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*Added to acknowledge post 1987 contribution
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 $\sigma$-$\varepsilon$ ANALYSIS (CSU, NASA)

UNDERSTANDING OF FAILURE MECHANISMS
SUFFICIENT TO ALLOW MODELING

FAILURE BY CRACKING/DELAMINATION IN CERAMIC NEAR INTERFACE
- PROGRESSIVE CRACKING OBSERVED
- $\sigma$, $\varepsilon$ 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
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 \( \sigma_r \) through lower
- \( E_{CERAMIC} \)
- \( \sigma_{CERAMIC} - \sigma_{BOND\ COAT} \)
- Yield strength of ceramic
- Roughness
- Oxidation

Weak effect on \( \sigma_r \) from
- \( \sigma_{SUBSTRATE} \)
- \( \rho_{BOND\ COAT} \)
- \( E_{BOND\ COAT} \)

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)

\[
\frac{da}{cN} = A e^{b} \sigma^{c} \\
(CFATIGUE/MINER’S LAW APPROACH ALSO NOTED)
\]

- Assumed relationship between weight gain and strain

\[
e_{G} = (e_{1} - e_{2}) \left( \frac{W_{C}}{W_{G}} \right)^{m} + e_{f}
\]


NASA PRELIMINARY TBC LIFE MODEL CONTINUED

**RESULTING MODEL**

\[ \sum_{N=1}^{N_f} \left[ (1 - \epsilon_f/\epsilon_r) \left( \frac{W_N}{W_0} \right)^m + \epsilon_f/\epsilon_r \right]^b = 1 \]

**ALTERNATIVE ASSUMPTION OF STRENGTH DEGRADATION FROM \( \epsilon_{t0} \) TO \( \epsilon_r \)**

\[ \epsilon_f/\epsilon_r = (1 - \epsilon_{t0}/\epsilon_r) \left( \frac{W_N}{W_0} \right)^m + \epsilon_{t0}/\epsilon_r \]

**RESULTING ALTERNATIVE MODEL**

\[ \sum_{N=1}^{N_f} \left[ (1 - \epsilon_{t0}/\epsilon_r) \left( \frac{W_N}{W_0} \right)^m + \epsilon_{t0}/\epsilon_r \right]^{-b} = 1 \]

PRELIMINARY MODEL YIELDS GOOD AGREEMENT BETWEEN EXPERIMENTAL AND CALCULATED TBC LIVES

MODEL:

\[ \sum_{N=1}^{N_f} \left[ (1 - \frac{E_f}{E_r}) \left( \frac{W_N}{W_0} \right)^m + \frac{E_f}{E_r} \right]^b = 1 \]

- \( b = 17.00 \)
- \( m = 1.00 \)
- \( W_0 = 2.4 \text{ mg/cm}^2 \)
- \( E_f/E_r = 0.38 \)

Cycles to Failure:

- Open symbols denote measured
- Closed symbols denote modeled

Heating Cycle Length, T. HR

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \]
<table>
<thead>
<tr>
<th>P&amp;W HOST ACCOMPLISHMENTS</th>
<th>DEGRADATION MODES IDENTIFIED</th>
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<tbody>
<tr>
<td>• Mechanical (major mode)</td>
<td>- Near interfacial ceramic cracking</td>
</tr>
<tr>
<td></td>
<td>- Apparent near-interface ceramic weakening</td>
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<tr>
<td>• Oxidation (major mode)</td>
<td>- Oxidation effect phenomenologically characterized</td>
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<tr>
<td></td>
<td>- Complex oxide scale characterized</td>
</tr>
<tr>
<td></td>
<td>- Interaction mechanism not understood</td>
</tr>
<tr>
<td>• Hot corrosion (minor mode)</td>
<td>- Not observed in flight service</td>
</tr>
<tr>
<td></td>
<td>- Threshold corrodatant level identified in lab</td>
</tr>
<tr>
<td>• Erosion (minor mode)</td>
<td>- Isolated occurrence in flight service</td>
</tr>
<tr>
<td></td>
<td>- Limited lab characterization needed</td>
</tr>
<tr>
<td>• F/BMOD (minor model)</td>
<td>- Not identified in flight service</td>
</tr>
<tr>
<td></td>
<td>- Experimental engines exhibit high –resistance</td>
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<table>
<thead>
<tr>
<th>P&amp;W HOST ACCOMPLISHMENTS</th>
<th>MAJOR MODE CORRELATIVE LIFE MODEL PROPOSED</th>
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<tr>
<td>• Fatigue based model</td>
<td></td>
</tr>
<tr>
<td>• Reversed ceramic plastic strain is primary driving force</td>
<td></td>
</tr>
<tr>
<td>• Oxidation acts to &quot;weaken&quot; ceramic</td>
<td></td>
</tr>
<tr>
<td>• Preliminary correlation coefficient 0.89</td>
<td>(90 experimental data points)</td>
</tr>
<tr>
<td>• Upgraded analysis in progress</td>
<td></td>
</tr>
<tr>
<td>• Incorporates improved ceramic behavior model</td>
<td></td>
</tr>
<tr>
<td>• Oxidation contribution improved by use of NASA data</td>
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</tbody>
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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
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

\[ N_f = \left( \frac{\Delta t_c}{\Delta t_{c0}} \right)^b \]
\[ \Delta t_f = \Delta t_0 + \Delta t_n + \Delta t_e - 2 \frac{E}{\psi} \]

ASSUMED STRENGTH DEGRADATION DUE TO OXIDATION

\[ \Delta t_f = \Delta t_{c0} \left( 1 - \delta \delta_{c} \right)^c + \Delta t_{f0} \left( \delta \delta_{c} \right)^d \]

- MINERS RULE

\[ \sum_{k=1}^{N} \frac{1}{N} \geq 1 \]

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

- Experimental cycles, thousands
- Predicted cycles, thousands

- \( b = 30.985 \)
- \( \Delta t_{c0} = 0.01222 \)
- \( \delta_{c} = 0.000327 \)
- \( R^2 = 0.882 \)
GARRETT TBC LIFE MODELING APPROACH

\[ TBC \text{ DEGRADATION RATE} = \frac{F_1 (MECHANICAL)}{+F_2 (OXIDATION)} \]

- COATING STRESSES
- TEMPERATURE
- MATERIAL SYSTEM
  - \( K_f \)
  - FLAW SIZE
  - ELASTIC MODULUS
  - SPALLING STRAIN

+ F₂ (SALT DEPOSITION)

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


GARRETT TBC LIFE MODEL HAS THREE DEGRADATION MODES

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

SALT SOLIDIFICATION

SALT EVAPORATION

BOND COATING OXIDATION

MOLTEN SALT FILM DAMAGE
GARRET TBC MODEL FIT THROUGH MINIMUM LIVES

GENERAL ELECTRIC TBC LIFE MODELING APPROACH

- ANALYSIS—PREDICTS $\sigma, \varepsilon$ UNDER VARIOUS TIME, TEMPERATURE CONDITIONS
- TESTING—DEFINES EFFECTS OF SPECIMENT HISTORY, LOADS ($\sigma, \varepsilon$),
  AND $T$ ON TIME TO FAILURE
- EMPIRICALLY RELATION ANALYSIS AND TEST—INFERENCE
- GREATER NUMBER OF TEST CONDITIONS GIVES INCREASED
  INFERENCE AND CONFIDENCE CAPABILITY
- VERIFY AND MODIFY BY ADDITIONAL TESTS

WHERE

\[ \Delta \varepsilon_{RZ} + 0.4 \Delta \varepsilon_R = 0.084 N_t^{-1.44} \]

- $\Delta \varepsilon_{RZ}$ SHEAR STRAIN RANGE
- $\Delta \varepsilon_R$ NORMAL STRAIN RANGE
- $N_t$ CYCLES TO FAILURE

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

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

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

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


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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14. ABSTRACT

NASA has played a central role in the development of thermal barrier coatings (TBCs) for gas turbine applications. This report discusses 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.

15. SUBJECT TERMS

Thermal barrier coatings; Gas turbine engines; History

16. SECURITY CLASSIFICATION OF:

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