National Aeronautics and Space Administration

Progress in Developing Luminescence-Based Diagnostics for Turbine Engine Coatings

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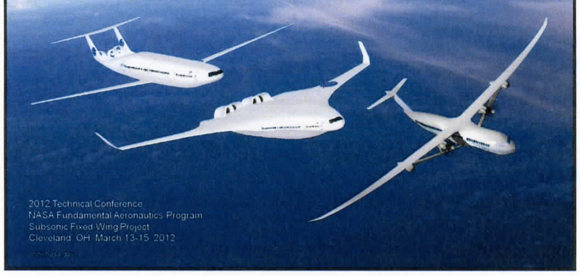


2012 Technical Conference
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH March 13-15, 2012

SFW.47.06.01
Luminescence-Based TBC/EBC Diagnostic Capabilities

- Objective
  - Develop and demonstrate luminescence-based mapping of temperature & damage progression for thermal and environmental barrier coatings used to protect turbine engine components.
- Motivation
  - Enabling technology for adoption of higher turbine inlet temperatures needed to meet EPP technical challenge of reducing thrust-specific energy consumption.
  - Higher temperature metallic or ceramic components will require protective coatings.
  - Protective coatings will require self-diagnostic capabilities because premature coating failure will be unacceptable.

SFW Strategic Thrusts & Technical Challenges

Energy Efficiency Thrust *(with emphasis on N+3)*
Develop economically practical approaches to improve aircraft efficiency

Environmental Compatibility Thrust *(with emphasis on N+3)*
Develop economically practical approaches to minimize environmental impact

Cross-Cutting Challenge *(pervasive across generations)*

*TC1 - **Reduce aircraft drag** with minimal impact on weight (aerodynamic efficiency)* — Drag

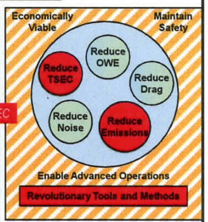
*TC2 - **Reduce aircraft operating empty weight** with minimal impact on drag (structural efficiency)* — Weight

*TC3 - **Reduce thrust-specific energy consumption** while minimizing cross-disciplinary impacts (propulsion efficiency)* — TSEC

*TC4 - **Reduce harmful emissions** attributable to aircraft energy consumption* — Clean

*TC5 - **Reduce perceived community noise** attributable to aircraft with minimal impact on weight and performance* — Noise

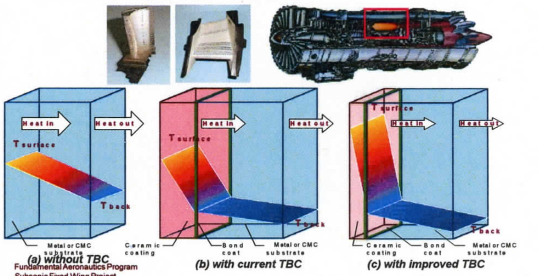
*TC6 - **Revolutionary tools and methods** enabling practical design, analysis, optimization, & validation of technology solutions for vehicle system energy efficiency & environmental compatibility* — Tools



Thermal Barrier Coatings (TBCs) Provide Thermal Protection for Gas Turbine Engine Components

— ***Ceramic oxide TBCs, e.g., yttria-stabilized zirconia, can increase engine temperatures, reduce cooling, lower emission, and improve engine efficiency and reliability.***

— ***TBCs provide thermal protection by sustaining a thermal gradient between the TBC surface and underlying metal component.***



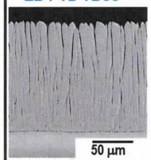
Outline

I. Luminescence-based monitoring of TBC delamination progression.
   I. Furnace cycling
   II. Effect of high heat-flux on TBC life
   III. Effect of cooling holes on TBC life

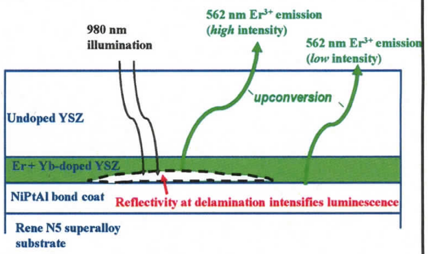
II. Luminescence-based temperature-sensing spin-off efforts
   I. Participation in phosphor-based temperature sensing demonstration in operating engine. (AFRL/VAATE)
   II. Development of optical thermometer and 2D temperature mapping. (ARMD seedling)

Detecting TBC Delamination by Reflectance-Enhanced Luminescence

EB-PVD TBCs*

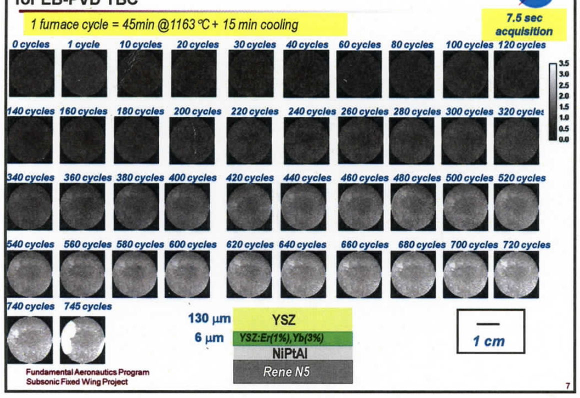


**Produced at Penn State.*

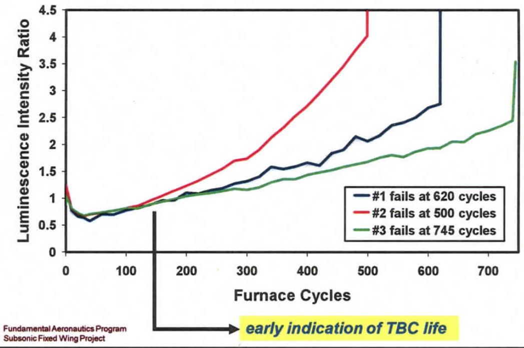


- Er^{3+} produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.
- Yb^{3+} absorbs 980 nm excitation and excites luminescence in Er^{3+} by energy transfer.
- Delamination contrast achieved because of increased reflection of excitation & emission at TBC/crack interface.

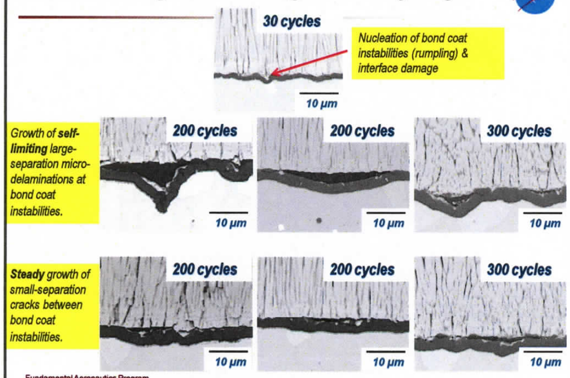
Upconversion Luminescence During Interrupted Furnace Cycling for EB-PVD TBC



Change in Upconversion Luminescence Intensity with Furnace Cycling to TBC Failure



TBC Failure Progression During Furnace Cycling



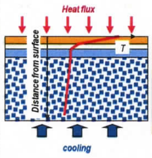
Effect of Heat Flux on TBC Life

Dongming Zhu, NASA GRC

- Extend luminescence-based delamination monitoring to TBCs subjected to high heat flux.
  - Thermal gradients present in high-heat-flux engine environment contribute additional driving forces for TBC delamination and may alter delamination progression pathway.
  - Valid diagnostics for predicting TBC remaining life must be based on measurements of TBCs exposed to engine-like high-heat-flux conditions.

Approach

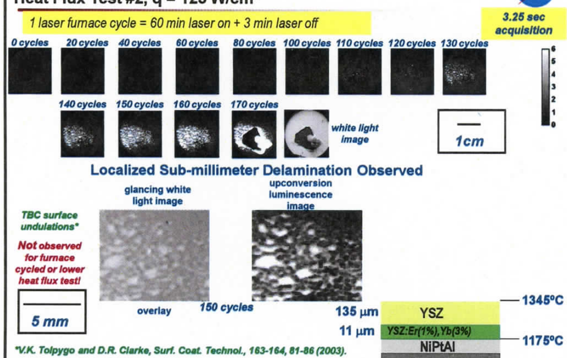
- Perform upconversion luminescence imaging during interrupted high-heat-flux laser testing.



•CO_2 laser heating

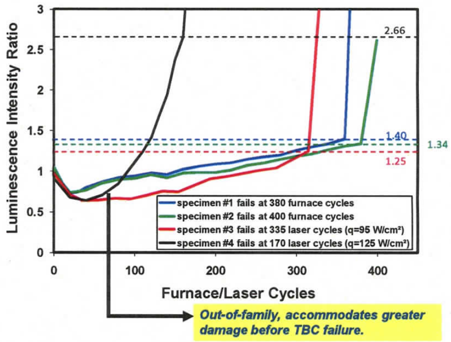
• High power CO_2 laser high-heat-flux rig

Upconversion Luminescence During Interrupted Laser Cycling Heat Flux Test #2, q = 125 W/cm²



*V.K. Tolpygo and D.R. Clarke, Surf. Coat. Technol., 163-164, 81-86 (2003).

Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling



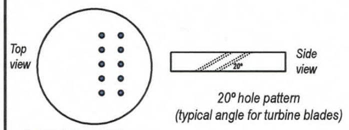
Observations from Luminescence Imaging of Laser-Cycled Specimens

Effect of Heat Flux on TBC Life:

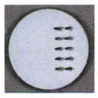
- High-heat-flux conditions produce TBC debond progression that accelerates (relative to isothermal conditions).
- High-heat-flux conditions change path of TBC debond propagation (exhibits interfacial rumpling).
- Diagnostic life prediction based on damage evolution occurring during isothermal exposures will grossly mispredict TBC remaining life under high heat flux conditions.

Monitoring TBC Delamination Around Laser-Drilled Cooling Holes

- **Problem:** Cooling holes in turbine blades and vanes can act as stress-concentrating failure initiation sites for surrounding TBC. Potential severity of these effects are unknown.
- **Objective**: Determine the severity of the effect of laser-drilled cooling holes on the lifetime of surrounding TBC using upconversion luminescence imaging.
- **Approach**: Performed luminescence imaging during interrupted furnace cycling of TBC-coated specimens with arrays of 0.020" diameter laser-drilled cooling holes. Monitored TBC delamination revealed by increased luminescence intensity.



20° hole pattern (typical angle for turbine blades)

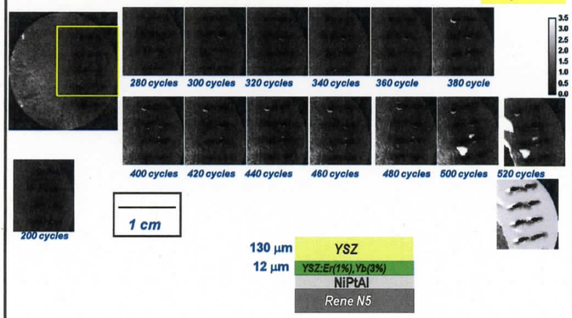


TBC-coated specimen with 0.020" diam laser-drilled cooling holes at 20°.

Monitoring Delamination Around Laser-Drilled Cooling Holes by Upconversion Luminescence Imaging During Furnace Cycling

1 furnace cycle = 45min @1163 °C + 15 min cooling

7.5 sec acquisition



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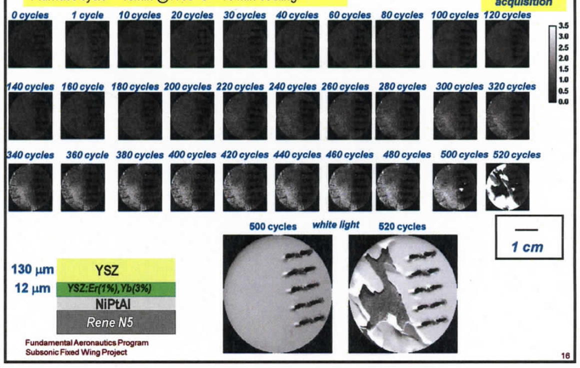
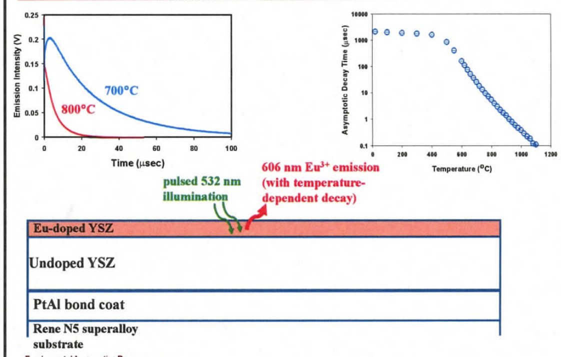


Effect of Cooling Holes on TBC Life

- Luminescence imaging easily detects delamination around cooling holes.
- Local delamination ***does*** initiate around cooling holes but exhibits very limited, stable growth.
- The unstable delamination propagation that leads to TBC failure actually AVOIDS vicinity of cooling holes.
- **Significance:** Cooling holes in turbine blades and vanes do not shorten TBC life and their behavior as debond initiation sites can be tolerated safely.

Luminescence-Based Remote Temperature Monitoring Using Temperature-Indicating TBCs

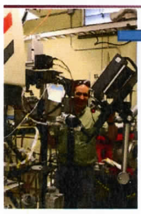


Temperature-Sensing Spin-Off Efforts

AFRL Versatile Affordable Advanced Turbine Engines (VAATE) Project

- Government/Industry team coordinated by PIWG/OAI.
- NASA GRC participation under SAA with AFRL, contributing Subsonic Fixed Wing expertise.
- ***Access to engine testing!***
- Objectives
  - Demonstrate thermographic phosphor (TP) based temperature measurements to 1300ºC on TP/TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.
  - Sufficiently mature capability that could be subsequently transferred to F135 and/or F136 engine.

VAATE Stepping Stone Approach to Engine Testing



NASA GRC High-Heat-Flux Laser Facility
•Proof-of-concept with easy optical access, no radiative background, no probe heating issues.
•Demonstrate TP capability to desired temperature limits & resolution.

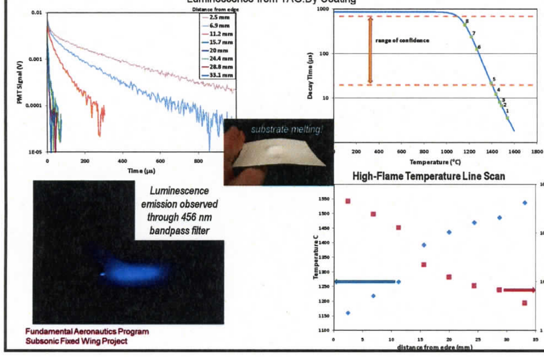
Williams International Combustor Burner Rig
•Demonstrate feasibility in post-combustion aggressive (but open) environment.
• burner flame
• high velocity gas
•Address probe/TP survivability & ability to "see" through flame.

AEDC J85-GE-5
•Probe/translate through afterburner flame.
•Opportunity to test excitation/collection integrated probe.

Honeywell TECH7000
•Final demonstration.
•Probe engineered for engine insertion.

Temperature Line Scan Across Hot Spot During Combustor Burner Heating

Traversing ***High-Flame*** Hot-Spot
Luminescence from YAG:Dy Coating



Luminescence emission observed through 456 nm bandpass filter

Temperature-Sensing Spin-Off Efforts

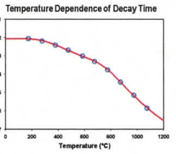
ARMD Seedling Fund: Luminescence-Based Temperature Mapping at Turbine Engine Temperatures Using Breakthrough Cr-Doped $GdAlO_3$ Broadband Luminescence

- Objectives
  - Demonstrate optical thermometer measurements up to 1300ºC.
  - 2D temperature-mapping of thermal gradients surrounding cooling holes.

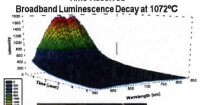
Demonstrated:
•Unprecedented luminescence intensity at high temperatures.
•Optical Thermometer to over 1000ºC.
•Patent filed.

Planned: 2D Temperature Mapping around Cooling Holes*
*with Tim Bencic & Dongming Zhu

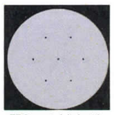
Temperature Dependence of Decay Time



Time-Resolved
Broadband Luminescence Decay at 1072ºC



Optical Thermometer



TBC-coated disk with array of 0.020" diam cooling holes.

Summary

- Luminescence-based mapping of damage accumulation in TBCs
  - Successfully tracks nucleation, growth, & coalescence stages of delamination crack progression.
  - Demonstrated predictive capability for remaining TBC life.
  - Presence of heat flux strongly affects TBC damage progression.
  - Cooling holes in turbine blades and vanes do not shorten TBC life and behavior as debond initiation sites can be tolerated safely.
- Luminescence-based temperature sensing spin-offs grow from SFW effort:
  - NASA joins VAATE team multi-stage effort leading to engine testing, contributing SFW-developed expertise.
  - Optical thermometer and 2D temperature mapping being developed in ARMD Seedling Project uses SFW discovery of breakthrough thermographic phosphor.

Contributors

NASA Glenn

- Dongming Zhu – high heat flux testing
- Tim Bencic – 2D temperature mapping
- Mike Cuy – furnace cycling
- Joy Buehler - metallography

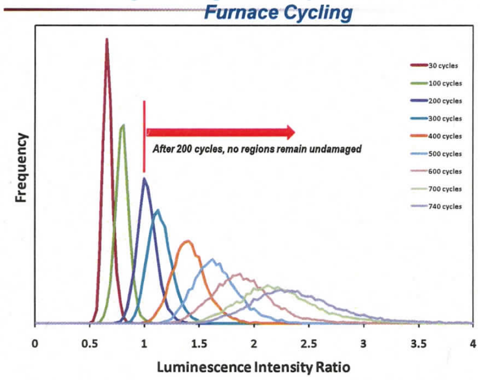
Penn State University

- Doug Wolfe – EB-PVD

VAATE Testing at Williams International

- Steve Allison/ORNL
- Tom Jenkins/Metrolaser
- Support staff at Williams International

Change in Image Intensity Distribution with Furnace Cycling



Combustor Burner Test Conditions

- Average exhaust temperature estimated at between 1670ºC and 1950ºC.
- Average exhaust velocity ~ 2050 ft/s for all tests.
- Fuel flow was adjusted for two different settings
  - "Low" & "High"
- Combustor rig run to near stoichiometric condition.