GAS TURBINE MATERIALS LIFE ASSESSMENT AND NONDESTRUCTIVE EVALUATION

J.G. Sun[1], K. Natesan[1], Z. Zeng[1], N. Tao[2], and A. Kulkarni[3]

[1]Argonne National Laboratory, Argonne, IL, USA

[2]Capital Normal University, Beijing, China

[3]Siemens Corporation, Charlotte, NC, USA

2015 NETL Crosscutting Research Review Meeting
Pittsburgh, PA
April 27-30, 2015

Work supported by U.S. Department of Energy,
Office of Fossil Energy, Crosscutting Research Program

Project Overview

- Team member: Siemens Corp. and Argonne National Lab
- Research focus: gas turbine materials
  - For higher-temperature engine operations to improve efficiency and reduce emissions
  - For the use of unconventional fuels with more corrosion species
- Project tasks:
  - Task 1: develop predictive models for deposition, corrosion and component life assessment
  - Task 2: develop/demonstrate NDE technologies for coatings
- Project started in FY2015

Task 1: Corrosion Test - Purpose

- To evaluate the corrosion effects on turbine materials for syngas and steam/CO_2 environments.
- The investigation involves testing of materials in support of H_2 Turbine and Zero Emission Power Plant (ZEPP) program being conducted at Siemens.
- This project builds on existing gas turbine technology and product developments, and will develop, validate, and prototype test the necessary turbine related technologies and sub-systems needed to demonstrate the ability to meet the DOE turbine program goals.

Task 1: Approach

Alloys and coatings on alloys will be tested in simulated environments in laboratory set ups.

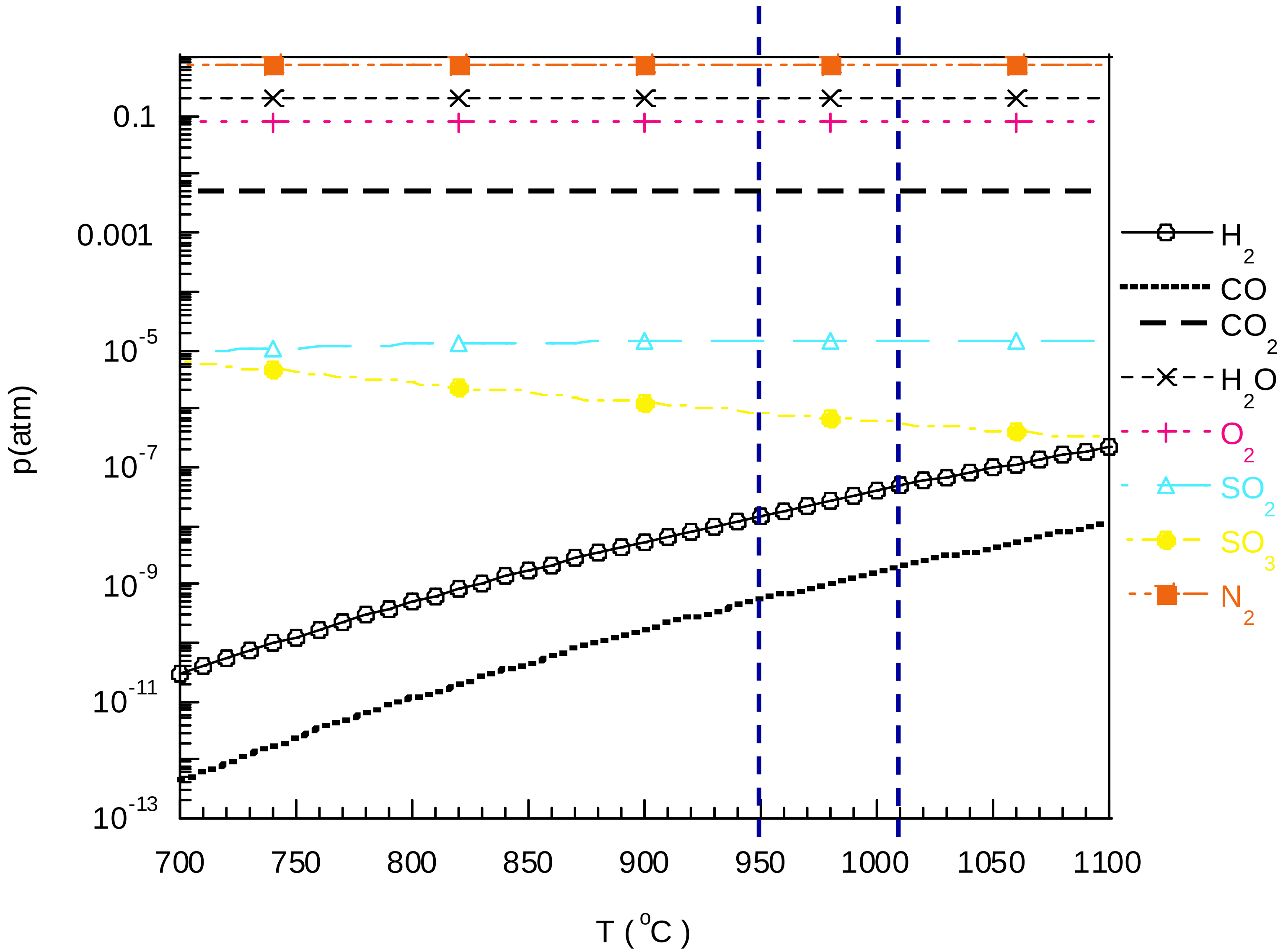
- Samples:
  1. Alloy samples such as IN939, CM247, Rene80, X45, ECY768, and IN738.
  2. Alloys coated with NiCoCrAlY overlay layers.
- Gas environments: the exposure environments include air, CO_2/steam, CO_2/steam/methane, and hydrogen.
- Temperature: two temperatures of 950 °C and 1010°C
- Time: Tests will be conducted for a period of 2000-3000h.

Gas Compositions for tests

Samples will be exposed to following three gases.

Composition	Gas 1	Gas 2	Gas 3
H_2O (vol %)	20.5	17.1	89.8
CO_2 (vol %)	0.5	4.8	10
O_2 (vol %)	7.65	12.6	0.2
Ar (vol %)	0.7	-	
N_2	Balance	Balance	
CO ppm	10	10	
SO_2 ppm	15	15	

Partial Pressures for Gas 1



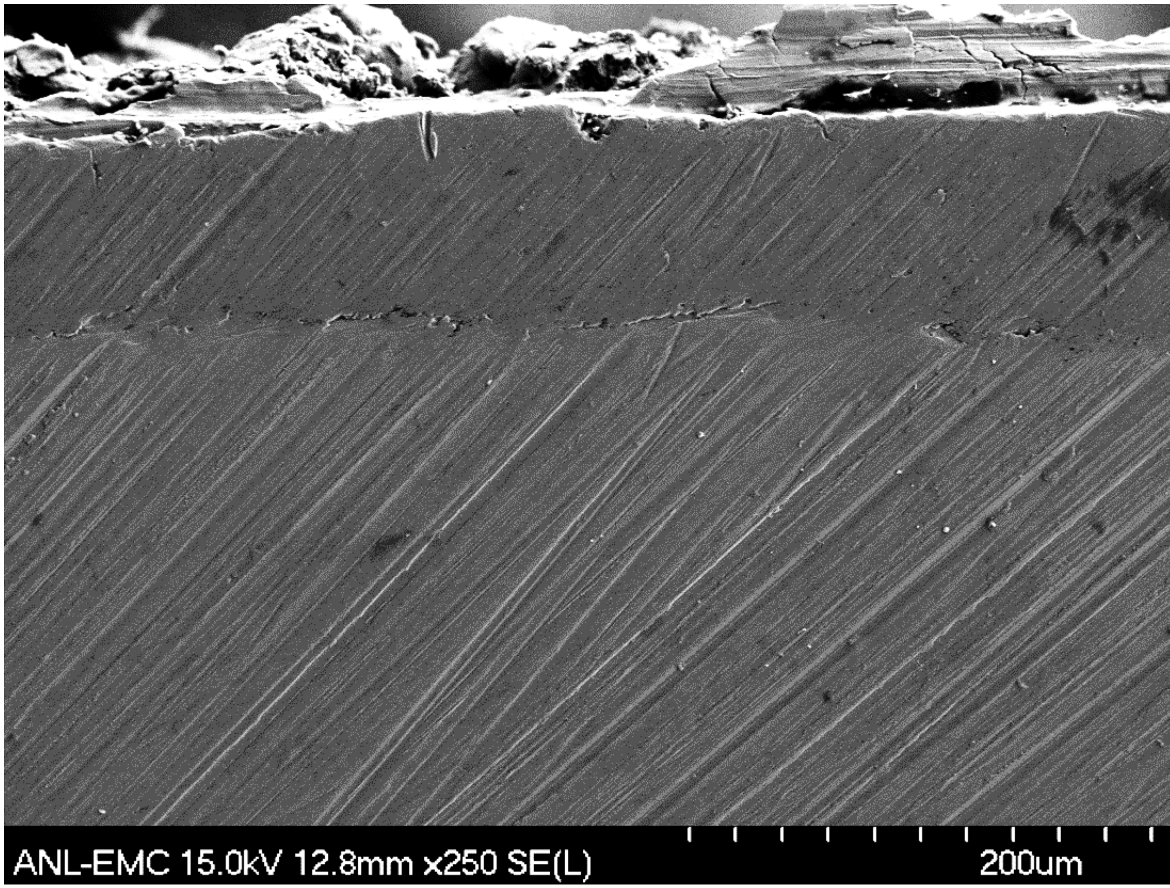
Test facilities at Argonne National Laboratory

Computer Controlling Gas delivering systems

Furnaces

Test Samples, provided by Siemens

SEM Image of SC2464 on Rene80 Before Test



Coating layer

Alloy substrate

Task 1: Test Plan for FY2015

- There are 18 tests proposed in the plan. At present, about 6 short term tests have been conducted.
- The long duration tests of 2000-3000h will be initiated.
- The samples tested for 500 and 1000h are being characterized in terms of scaling, microstructure, and coating integrity.
- The goal of this project is to complete the testing and characterize the exposed specimens to assess the viability of the alloys and coatings at the two high temperatures for turbine application.
- Follow up microstructural analysis planned to input into corrosion model.

Task 1: Test Plan for FY2016 and Beyond

- The long term testing will be continued and the tested specimens will be characterized via weight change vs. time, microscopy, coating appearance (disbonding, cracking, etc.) and comparison of coating data with those of uncoated alloys.
- Development of a model capable of thermo-kinetic modelling of contaminant flux and extrapolation for high temperatures/high pressures for the establishment of corrosion maps for high temperature metallic and ceramic systems will be carried out.

Task 2: NDE Development - Objectives

- Develop and demonstrate advanced NDE technologies for coatings
  - For coating quality inspection
    - Coating property measurement: multilayer analysis (MLA) method
    - Coating defect detection: thermal tomography (TT) method
  - For TBC life prediction
    - Modeling of TBC property degradation with life

Recent NDE Developments

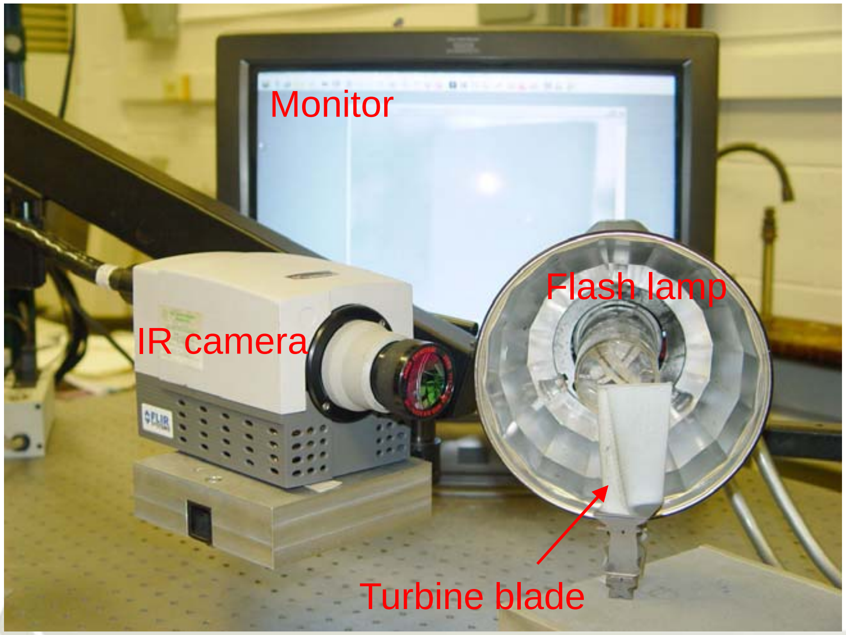
- Continued development of multilayer analysis (MLA) method
  - Verification of MLA measurement accuracy for coatings
    - This is a new technique to measure thermal effusivity for bulk materials
  - Evaluation of surface treatment (black paint) material for TBCs
  - Validation for coating component inspections

- Continued development of TBC life prediction model
  - More efforts expected in next year

Thermal Imaging Multilayer Analysis (MLA) Method

- Basic development for MLA method is complete
  - It measures two coating properties: thermal conductivity and heat capacity (or thickness)
  - It images entire coating surface – the only NDE method in this field
- Its application for various coatings are currently being evaluated

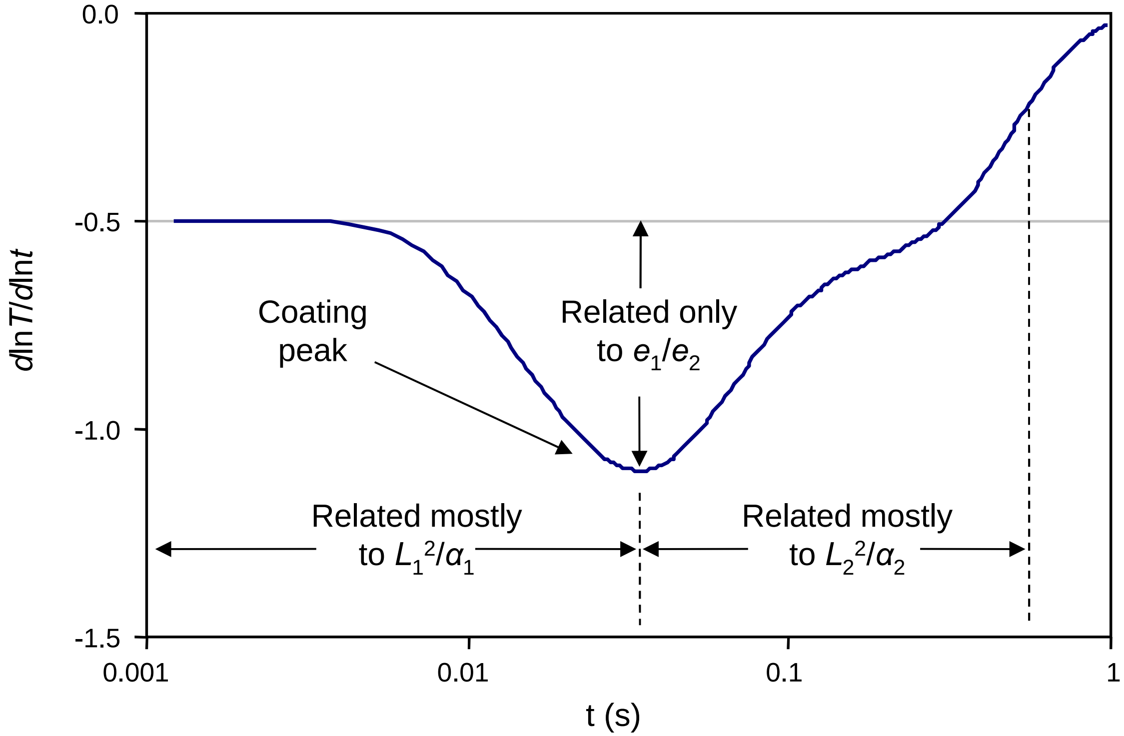
Flash Thermal Imaging Setup



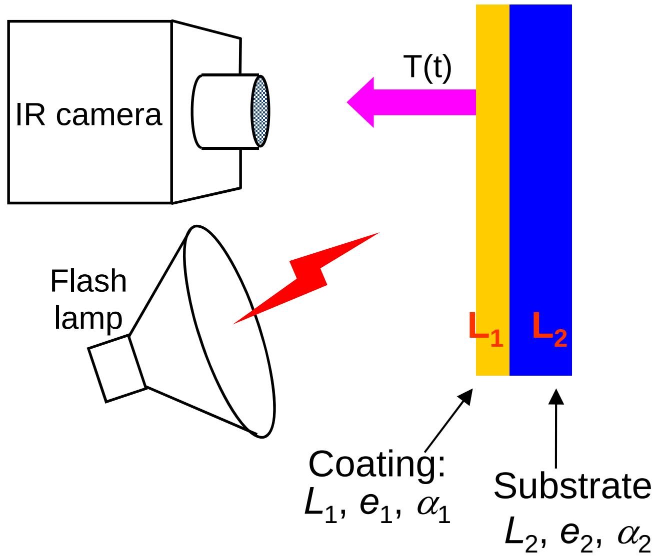
Gas turbine engine components

Principle of Coating Property Measurement by MLA

Characteristics of thermal imaging data T(t)



Test setup



L – thickness
e – thermal effusivity
α – thermal diffusivity

- MLA measures three parameters: e_1/e_2, L_1^2/α_1, and L_2^2/α_2 (e_2 & α_2 are known)
  - e_1/e_2 is determined based only on peak magnitude!
  - Peak location is mostly related to L_1^2/α_1 (and e_1/e_2)

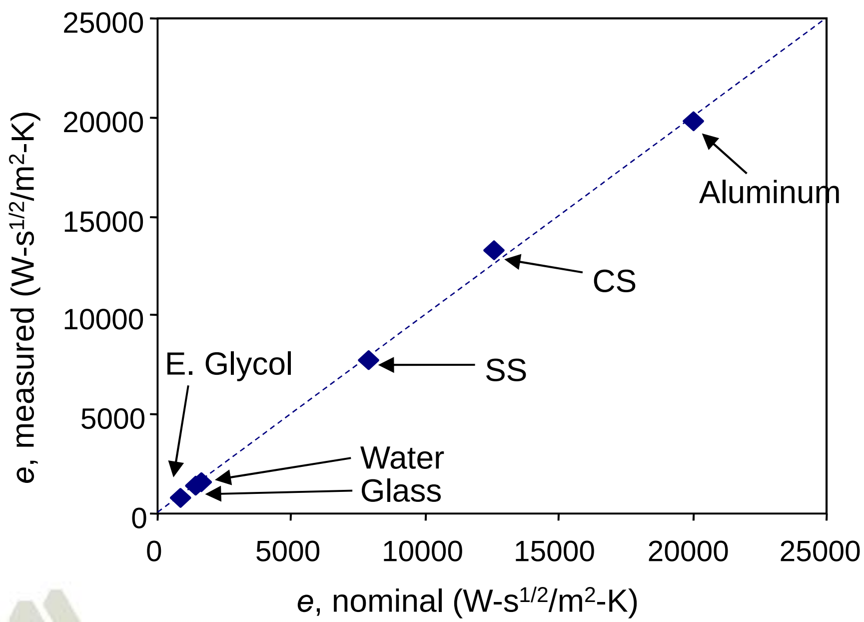
MLA Measurement of Coating Parameters

- MLA only measures two coating parameters: e_1 and L_1^2/α_1
  - Coatings have three parameters: e_1, α_1, and L_1
  - One coating parameter is needed to fully determine coating parameters
- Two scenarios for coating property determination:
  - Determine k_1 and $\rho_1 c_1$ when coating thickness L_1 is known
    - This is the case for coating property measurement
  - Determine k_1 and L_1 when $\rho_1 c_1$ is known
    - This is the case for inspection of coated engine components

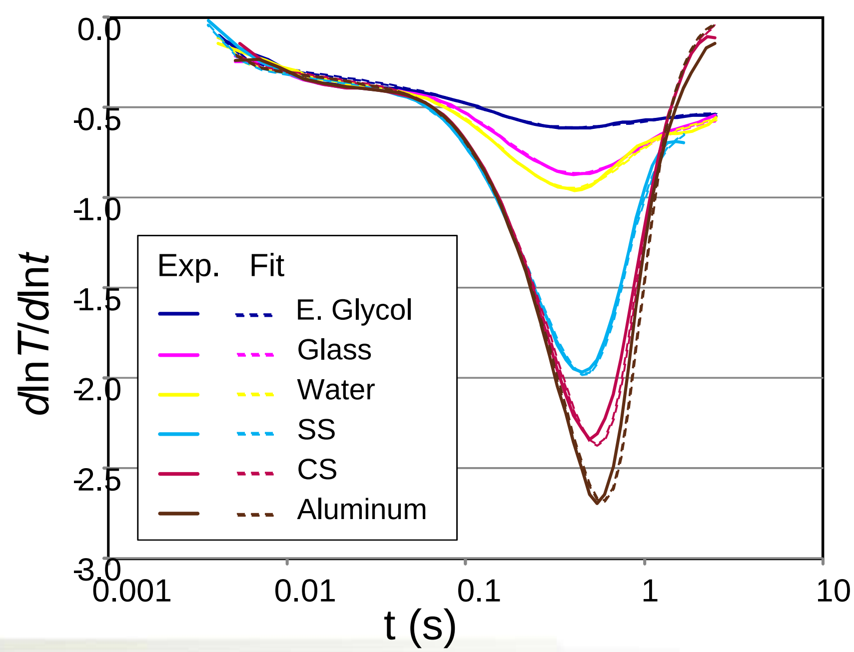
Accuracy for e_1/e_2 Measurement

- A tape was bonded on bulk material to form a two-layer system
- Thermal effusivity of bulk material e_2 is derived from e_1/e_2 (note tape effusivity e_1 is known from a calibration)
  - Absolute effusivity measurement error is <2% of nominal value

Predicted and nominal e values for various standard materials



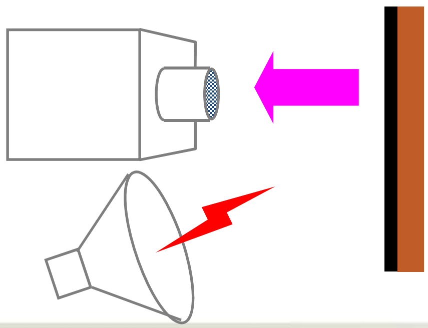
Comparison of predicted and measured thermal imaging results



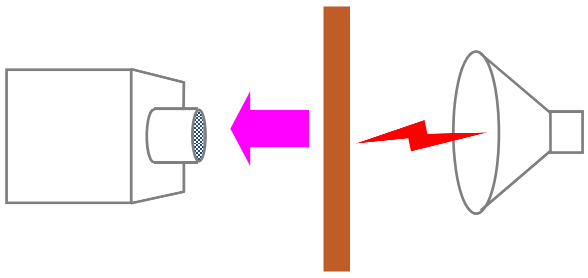
Applications of e_1/e_2 Measurement

- The absolute accuracy for coating property measurement by MLA is also <2% of errors
- MLA is a new technology to measure material's thermal effusivity *e*
- The combination of MLA and two-sided thermal imaging is a new technique to measure thermal conductivity *k* and heat capacity ρc (or specific heat *c* if density ρ is known) from same sample
  - Two-sided thermal imaging measures material's thermal diffusivity (similar to Laser Flash)
  - Specific heat c is currently measured by differential scanning calorimetry (DSC)

MLA test (1-sided)



2-sided test



Example: Thermal Property of Aluminum Plate

- An aluminum alloy plate of unknown properties (3003, 6061, 6063, ??)
  - Heat capacity ρc for all aluminum alloys is 2.41-2.44 J/cm^3-K
  - Thermal conductivity k for all aluminum alloys is 150-210 W/m-K

From MLA: $e = (k\rho c)^{1/2} = 19062$ W-s$^{1/2}$/m^2-K

From two-sided: $\alpha = k/\rho c = 63.6$ mm^2/s

→

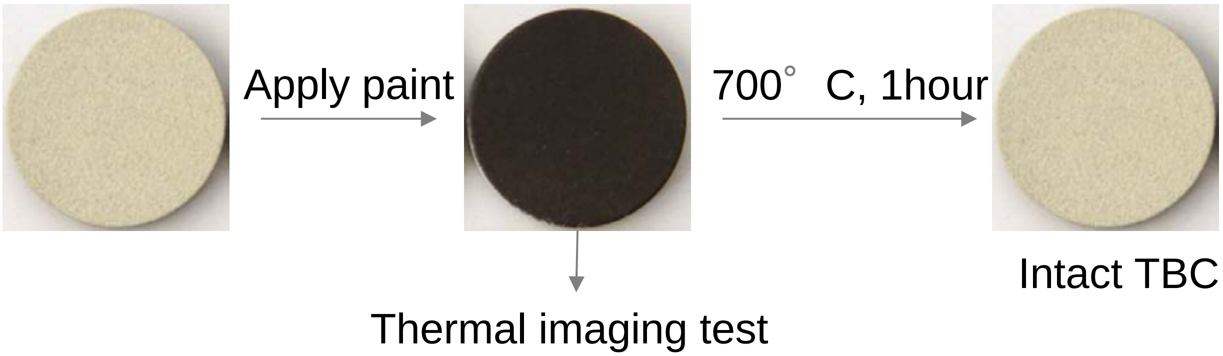
$k = 152$ W/m-K

$\rho c = 2.39$ J/cm^3-K

- The unknown aluminum plate was identified to be of a low-conductivity alloy 3003 material

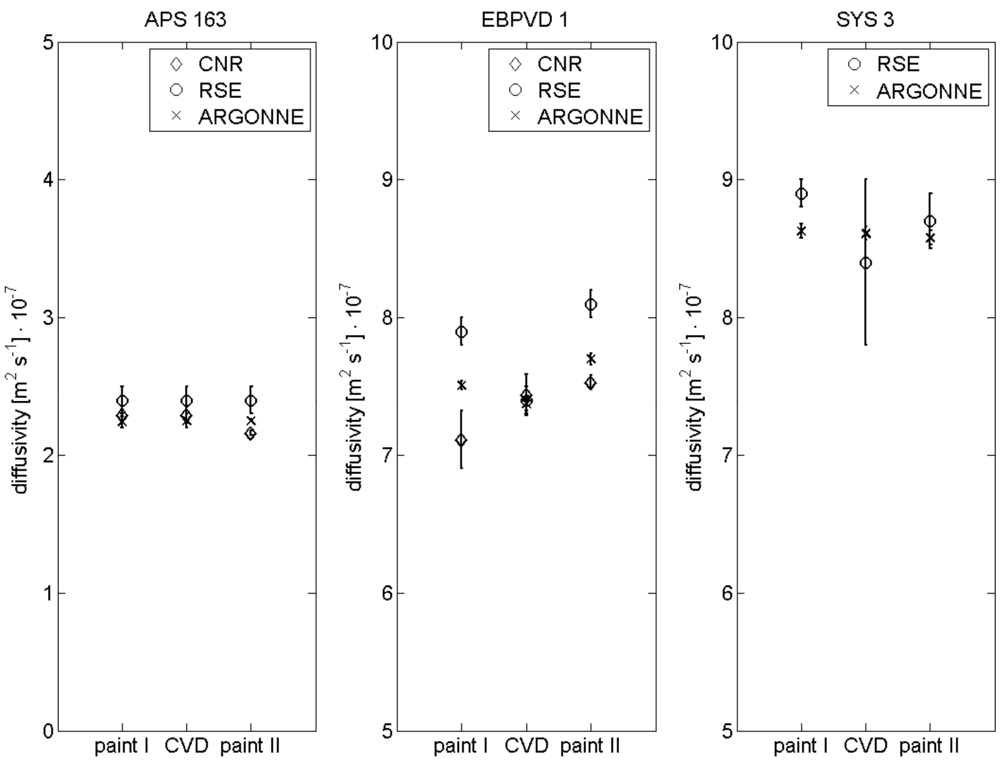
TBC Surface Treatment for Thermal Imaging

- Current thermal-imaging model is for opaque coatings (eg, metallic)
- TBC is translucent, needs surface treatment to make it opaque
  - Common method: apply a thin graphite-based paint on TBC surface



- In collaboration with Dr. Cernuschi and Dr. Bison of Italy, effect of surface treatment on TBC property measurement was evaluated
  - Three different graphite paints
  - Three type TBCs: APS, EB-PVD, PS-PVD

Measured TBC Property with 3 Different Paints

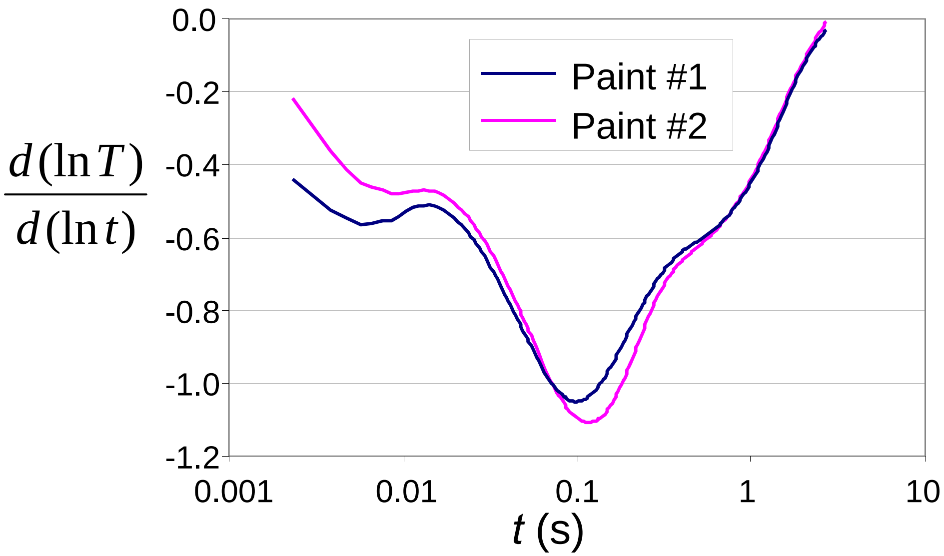


- Measured TBC thermal diffusivities was within 10% between 3 labs
- Black paint does not affect measured TBC parameters

However, Paint Effect Is Not Resolved!

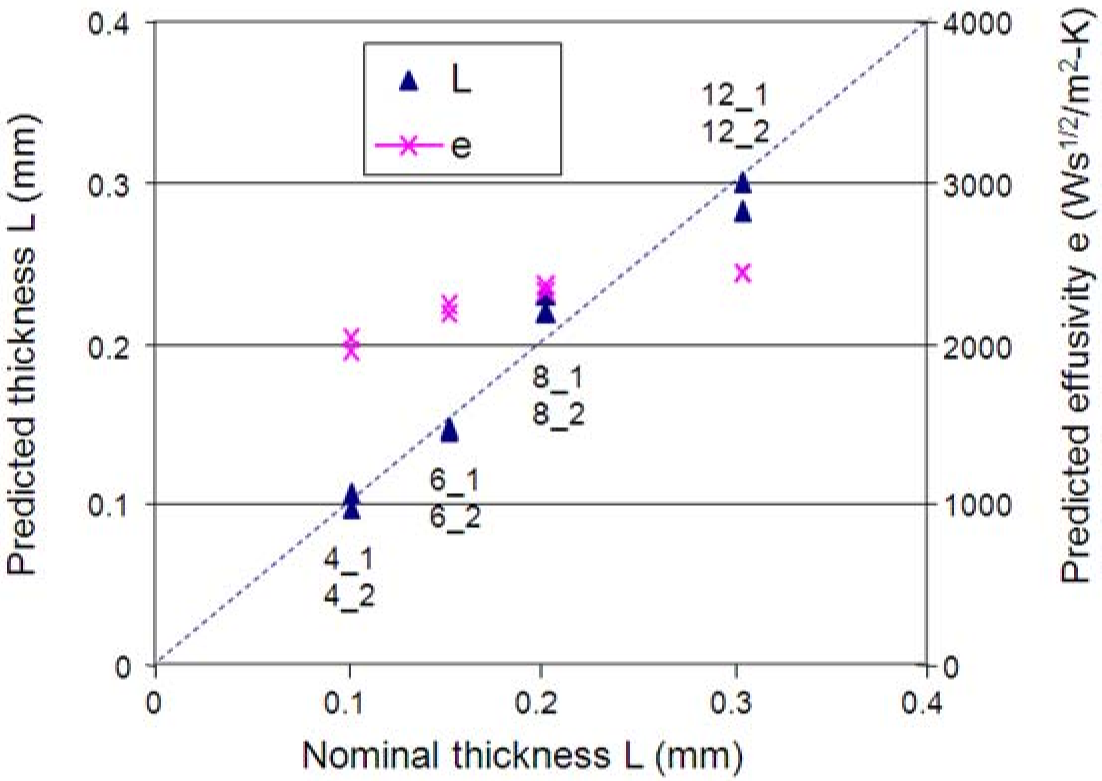
- Each paint was applied on half surface
- APS TBC of 0.15mm thickness

Measured thermal imaging data



- Paints may cause >10% differences – reason is unclear now?
- A systematic study for 4 common black paints are being conducted

Flash Thermography for Metallic Coatings

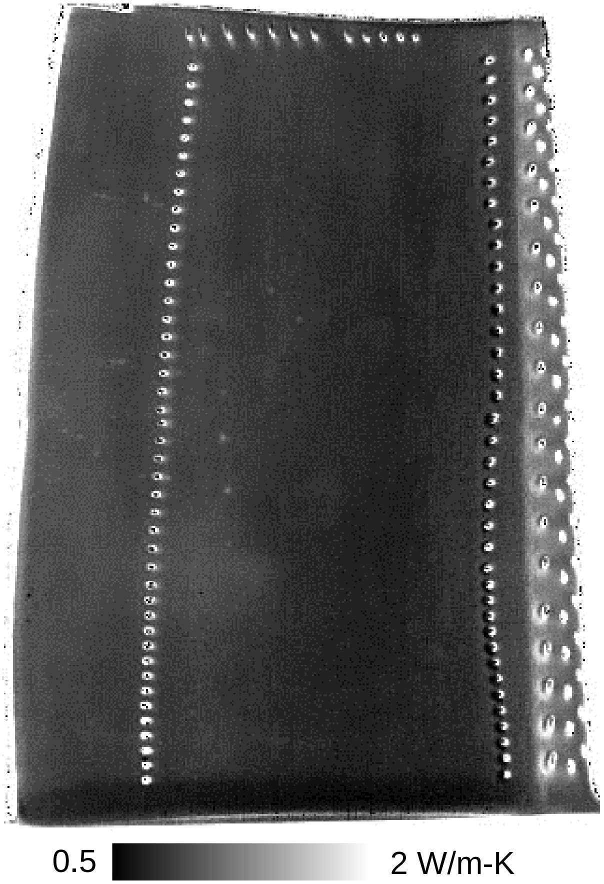


- **MLA prediction is accurate**

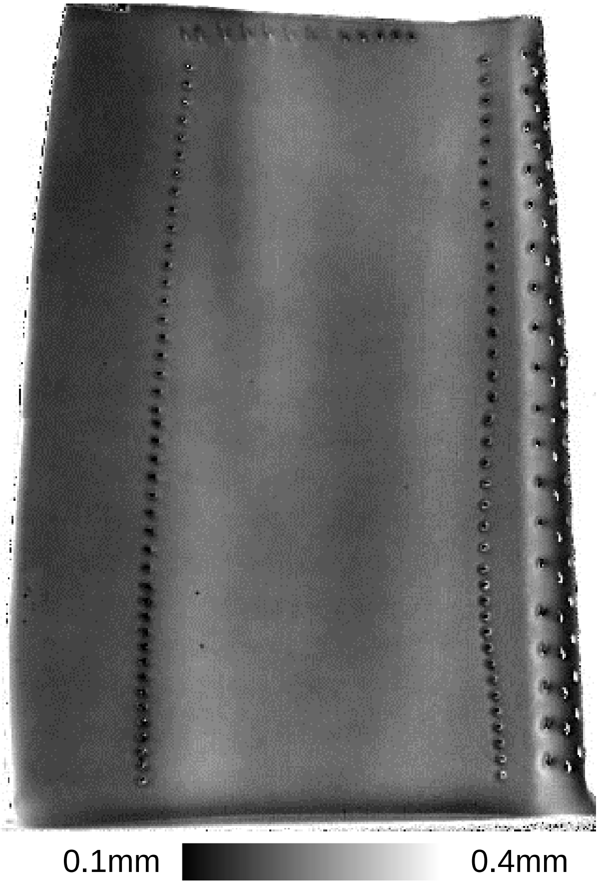
TBC Property Measurement for a Turbine Blade

A TBC-coated gas-turbine blade

TBC thermal conductivity image



TBC thickness image



MLA predictions are reasonable

Task 2: Summary

- Thermal imaging multilayer analysis (MLA) development:
  - Absolute prediction error of <2% is possible
  - A new method for material’s thermal property measurement
  - Several graphite paints were found suitable for TBC surface treatment
  - Successfully tested various coating coupons/components

Task 2: Planned Future Efforts

- Continued development of TBC lifetime prediction models
- Thermal NDE method developments:
  - Study of paint effect
  - Continued validation of NDE data
  - Development of effective display method for NDE data
  - Investigation for field applications of flash thermal imaging
- Tech transfer to industry