GAS TURBINE MATERIALS LIFE ASSESSMENT AND NONDESTRUCTIVE EVALUATION

J.G. Sun[1] and A. Kulkarni[2]
[1]Argonne National Laboratory, Argonne, IL, USA
[2]Siemens Corporation, Charlotte, NC, USA

2017 University Turbine Systems Research Project Review Meeting
Pittsburgh, PA
November 1-2, 2017

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 nondestructive evaluation (NDE) technologies for coatings
- Project duration FY2015-FY2017

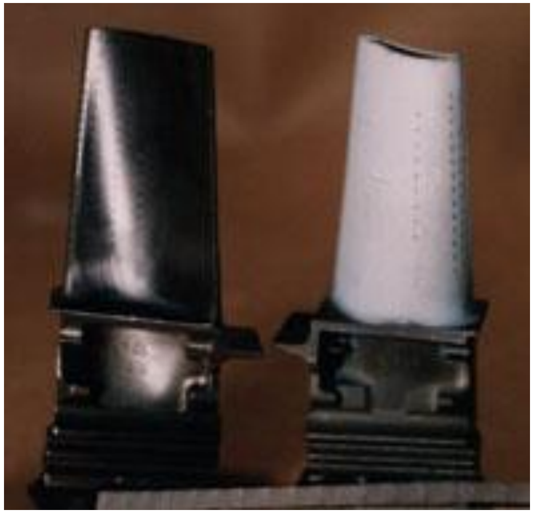
NDE Objective

- Develop and demonstrate advanced thermal-imaging NDE technologies for coatings (mostly TBCs)

TBC Background – Material and Structure

- Thermal barrier coatings (TBCs) are commonly used to insulate high-temperature metallic components in gas turbines
  - TBCs may reduce metal surface temperature by >100ºC
- TBCs are “prime reliant” material → nondestructive evaluation (NDE) is needed for their condition monitoring and life prediction
  - Need 100% coating surface inspection by imaging NDE

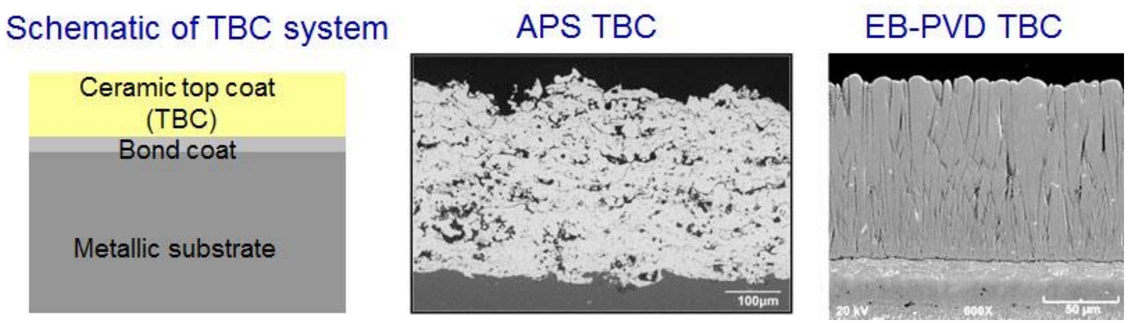
Uncoated and TBC-coated turbine blades



- TBC material: YSZ
- TBC processing: APS or EB-PVD

TBC Background – NDE Development

- Many NDE technologies were evaluated for TBCs in last few decades → generally not very successful
  - No NDE tools for industrial applications
- Current TBC analysis and quality control still relies on destructive method – microscopy:



- This research has established Pulsed Thermal Imaging – Multilayer Analysis (PTI-MLA) as a promising NDE method for entire TBC lifetime evaluation

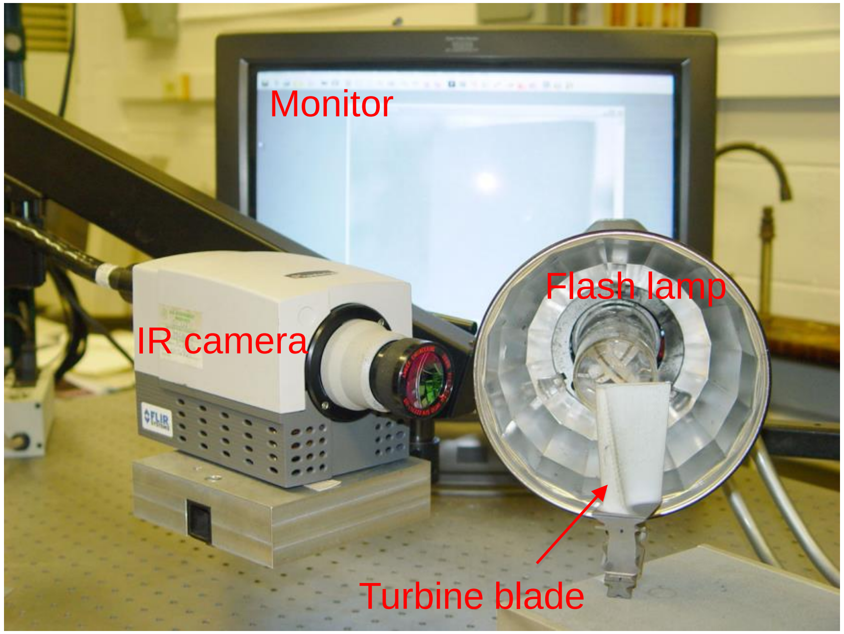
Presentation Outline

- PTI-MLA method and capabilities
- PTI-MLA for TBC life prediction
- PTI-MLA for industrial applications
  - 3D mapping of MLA data for engine components
  - Evaluation of low-cost IR camera

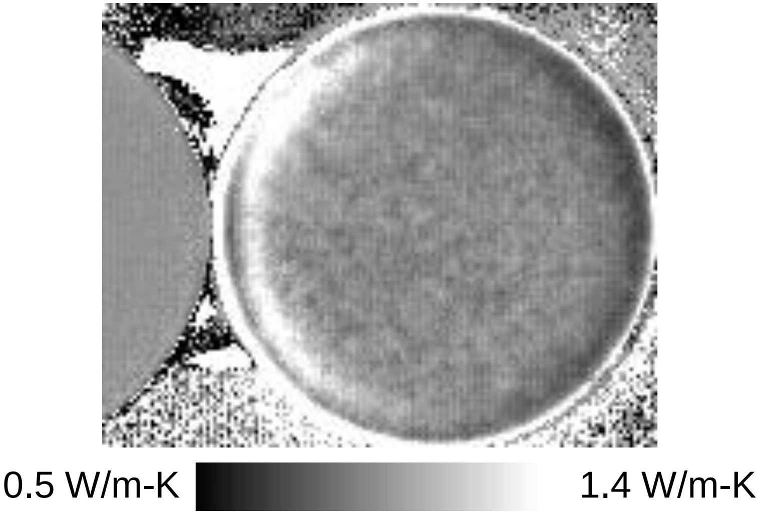
Pulsed Thermal Imaging – Multilayer Analysis (PTI-MLA)

- PTI-MLA consists of a pulsed thermal imaging (PTI) experimental system and a multilayer analysis (MLA) data-processing code
- PTI-MLA images two coating properties over entire coating surface

PTI experimental setup

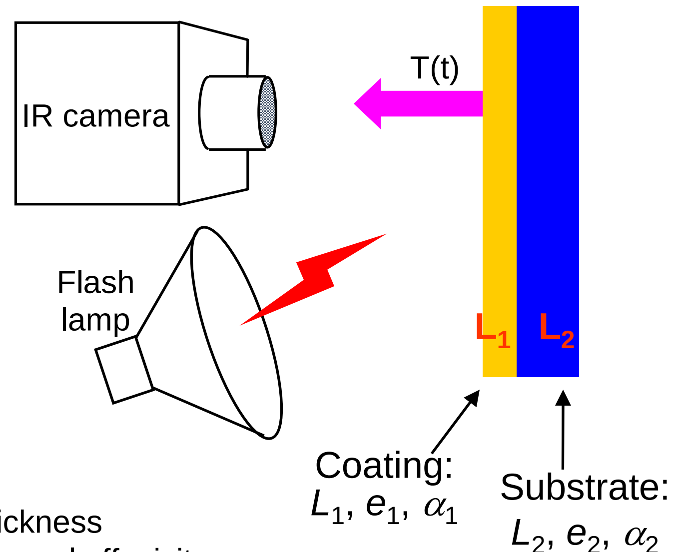


Thermal conductivity image



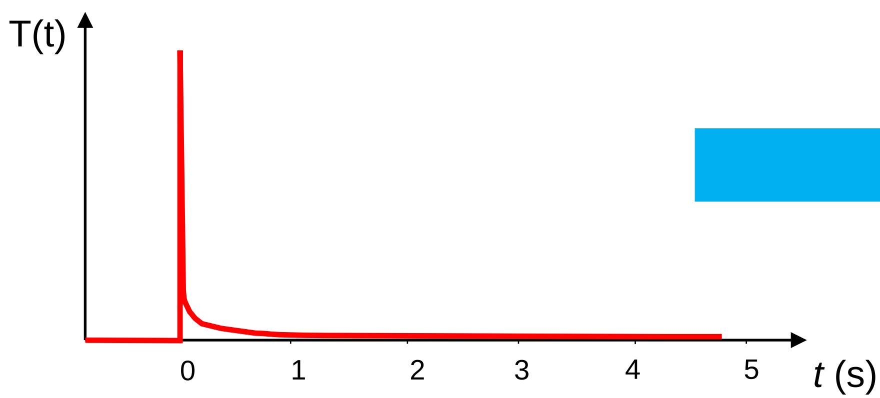
PTI-MLA: Principle for Coating Analysis

PTI system setup



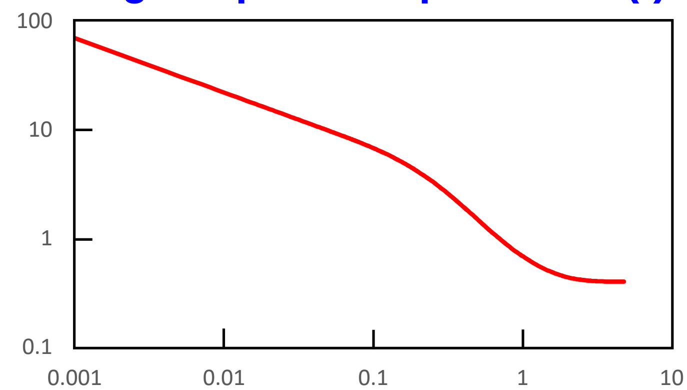
L – thickness
e – thermal effusivity
α – thermal diffusivity

Temperature profile *T*(*t*) at each pixel

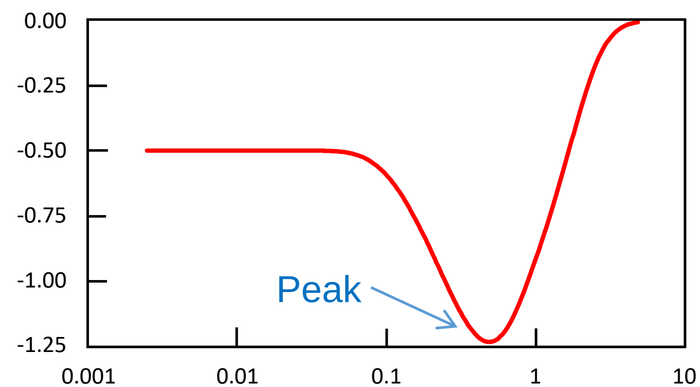


MLA analysis

Log temperature profile ln*T*(*t*)

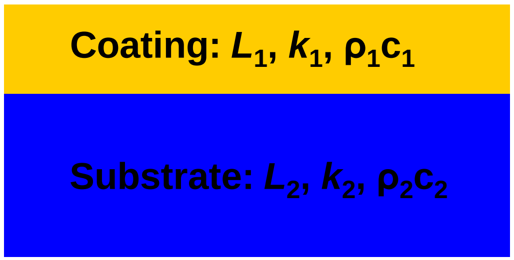


Log slope profile *d*(ln*T*)/*d*(ln*t*)



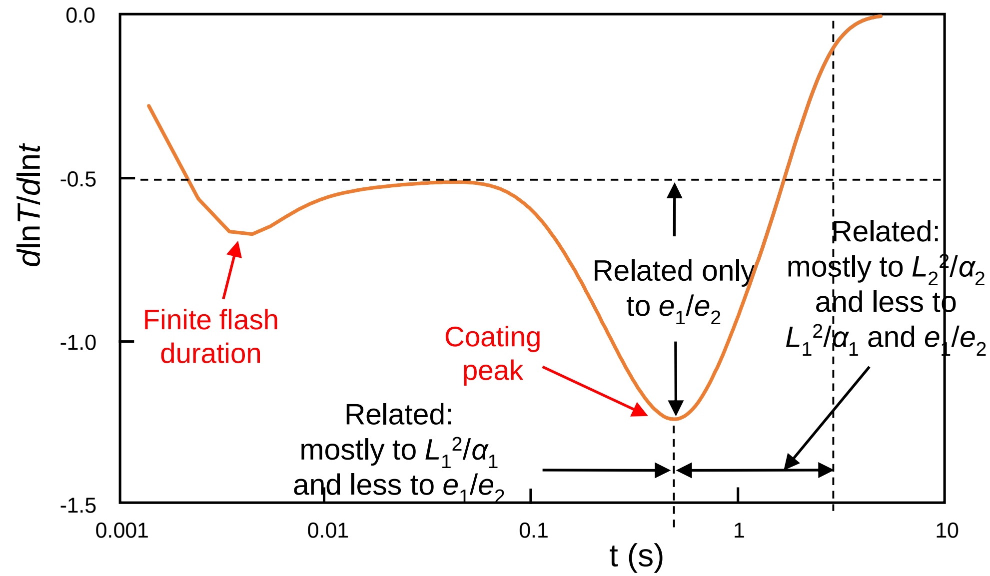
PTI-MLA: Measurement Principle

Coating/Substrate Model



L – thickness
k – thermal conductivity
ρc – heat capacity
$e = (k\rho c)^{1/2}$ – thermal effusivity
$\alpha = k/\rho c$ – thermal diffusivity

MLA Model Solutions

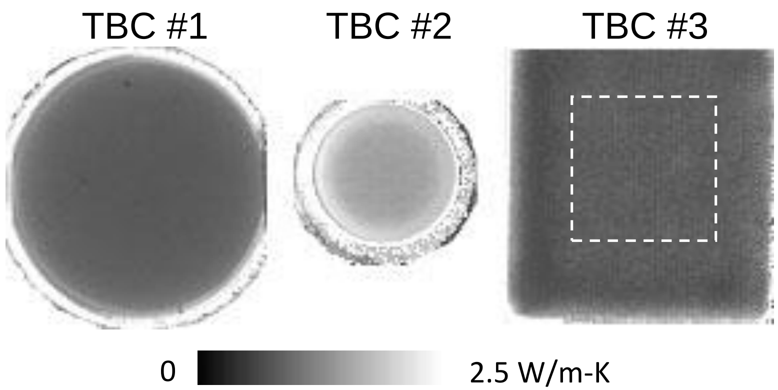


- MLA method: solve governing equation for layered materials and then fit the solution with experimental data (for all pixels)
- MLA determines 3 parameters: e_1/e_2, L_1^2/α_1, and L_2^2/α_2 (e_2 & α_2 are known)
  - For coating: (1) k & ρc when L is known; (2) k & L when TBC porosity is known
  - For substrate: L (substrate's k & ρc are already known)
  - Accuracy: <3% error typical

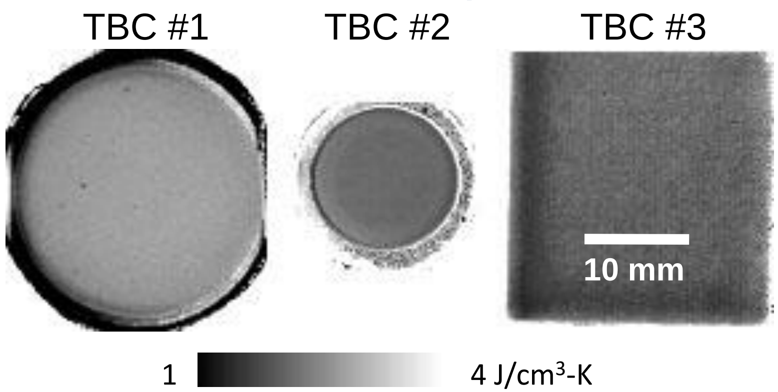
Argonne NATIONAL LABORATORY

PTI-MLA Results for typical 1-layer TBCs

Thermal conductivity *k* images

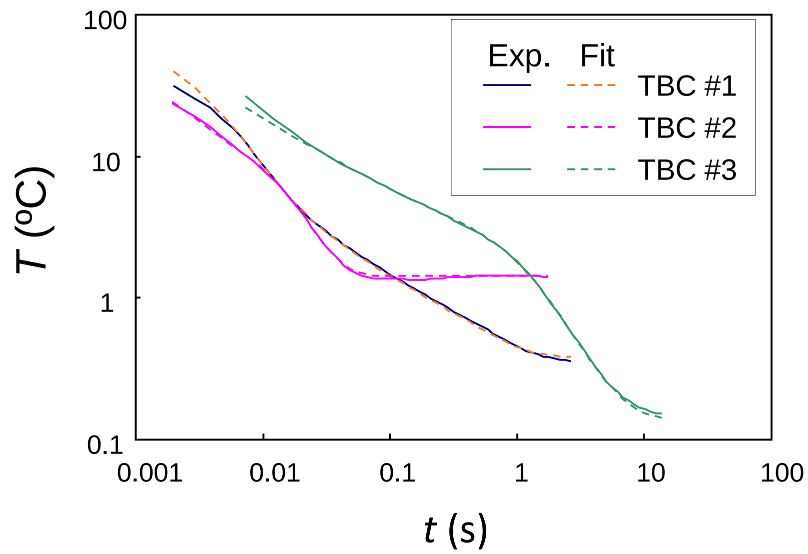


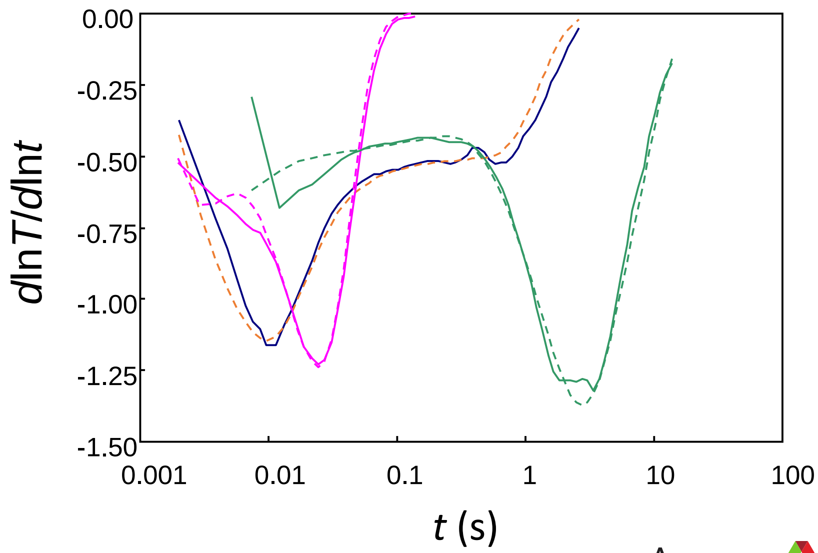
Heat capacity ρc images



TBC#	Type	*L*(mm)	*k*(W/m-K)	ρc(J/cm^3-K)
1	EB-PVD	0.050	0.87	2.90
2	EB-PVD	0.138	1.63	2.22
3	APS	0.86	0.93	2.19

Typical pixel fitting curves

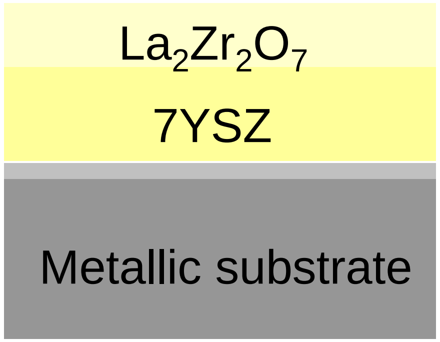




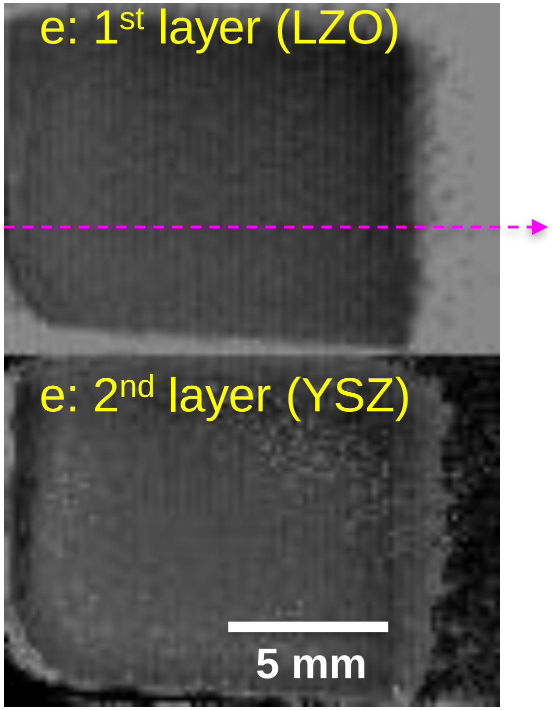
Argonne NATIONAL LABORATORY

PTI-MLA Predictions for 2-layer TBCs

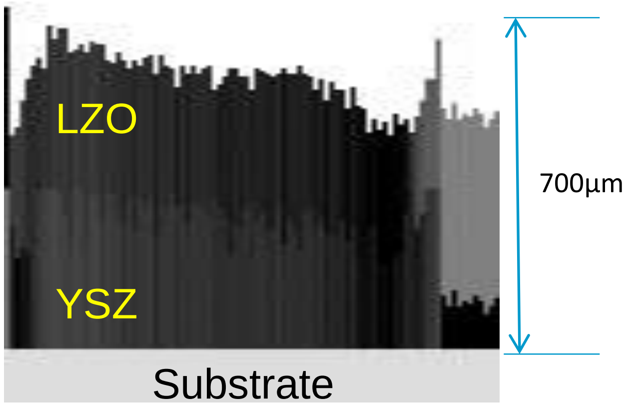
Double-layer TBC



Predicted layer effusivity

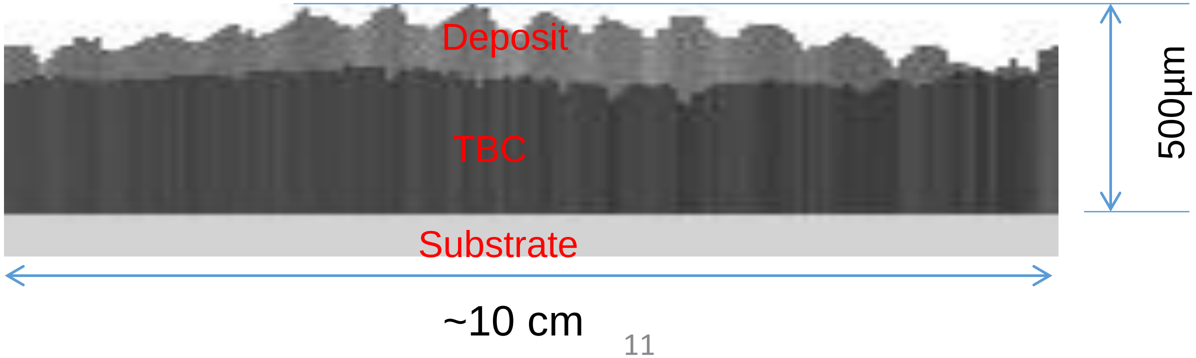


Predicted thickness profiles



Predicted thickness profiles for a used turbine vane

Grayscale is proportional to thermal effusivity



Argonne NATIONAL LABORATORY

Summary of PTI-MLA Capabilities

- PTI-MLA measures 2 coating properties:
  - k & ρc when L is known
  - k & L when TBC porosity (or density) is known (c is constant for TBC)

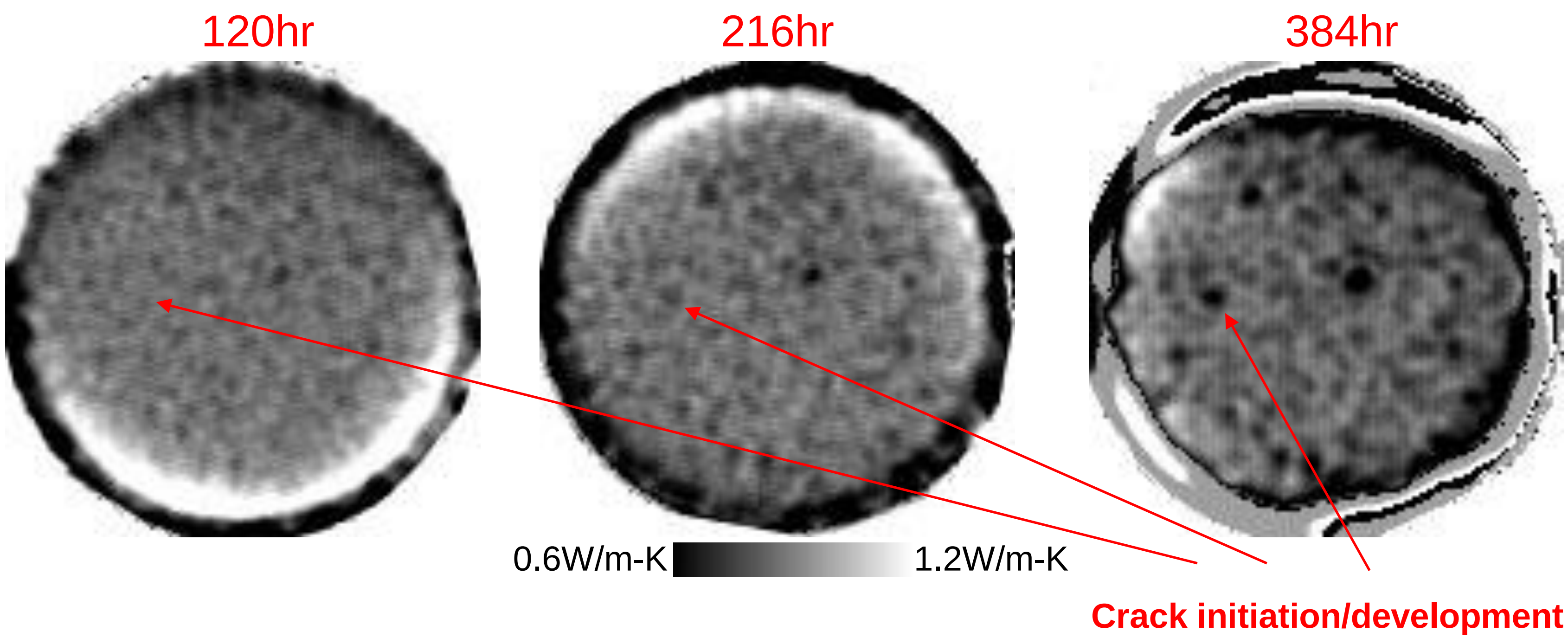
- PTI-MLA has unique capabilities:
  - Sample can be any size and geometry
  - Imaging property distribution over entire surface with desired resolution
  - Current code works for 1- & 2-layer coatings (more layers possible)
  - Also determines substrate thickness L
  - High accuracy: <3% error typical
  - Fast test (few seconds), fully automated data processing (~minute)
  - Can be miniaturized for inside engine inspection

Presentation Outline

- PTI-MLA method and capabilities
- PTI-MLA for TBC life prediction
- PTI-MLA for industrial applications
  - 3D mapping of MLA data for engine components
  - Evaluation of low-cost IR camera

TBC Property Change with Life

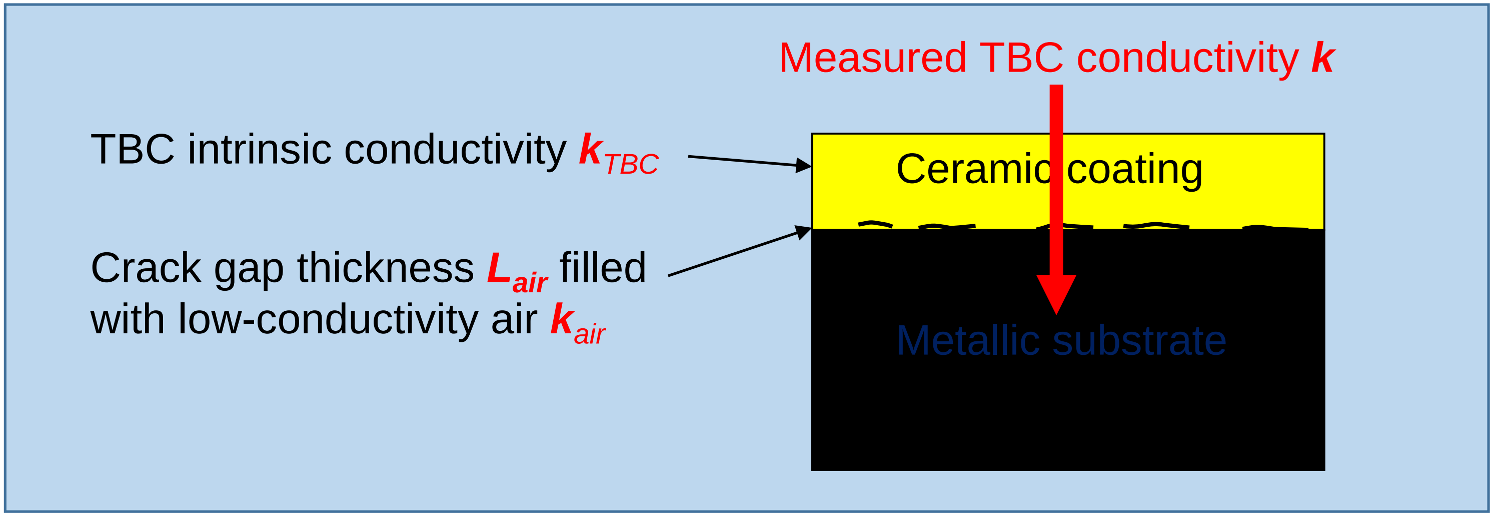
Thermal conductivity images for a thermal-cycled TBC (@1100° C)



- Cracks initiate and increase in size with time (conductivity decrease)
- Intrinsic TBC conductivity increases with time

TBC Life Prediction Model

- Measured overall TBC thermal conductivity ***k*** is affected by two factors:
  - (1) Intrinsic TBC material conductivity $\boldsymbol{k_{TBC}}$ increases with time due to sintering ($\boldsymbol{k_{TBC}}$ is usually modeled by Larson-Miller parameter, or LMP)
  - (2) Interface cracking/delamination is filled by air with low conductivity $\boldsymbol{k_{air}}$

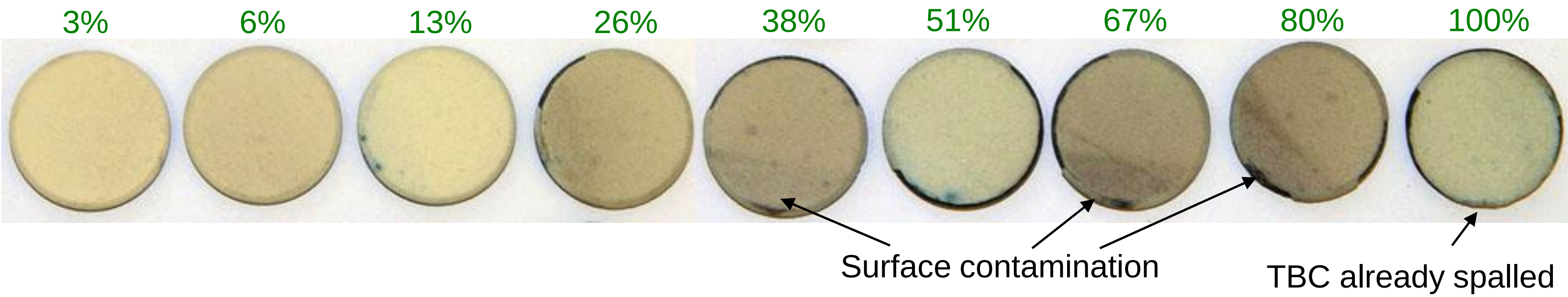


- Air-gap thickness L_{air} can be estimated from: $$\frac{L_{TBC} + L_{air}}{k} = \frac{L_{TBC}}{k_{TBC}} + \frac{L_{air}}{k_{air}}$$

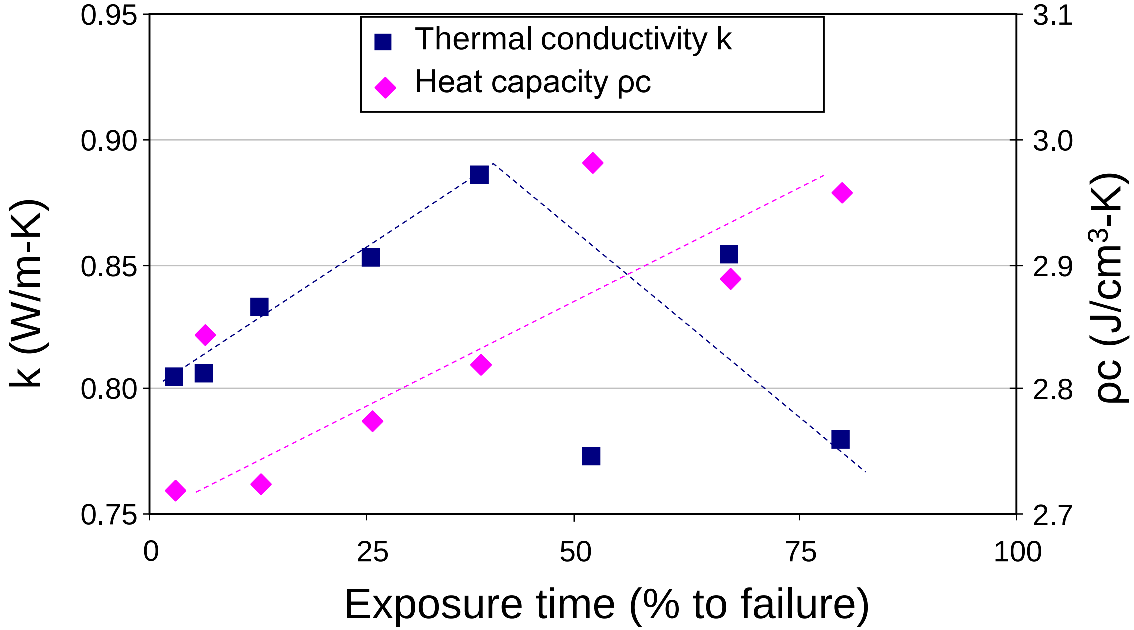
  where L_{TBC}, k and k_{air} are known; k_{TBC} can be obtained from LMP correlation

- TBC delaminates (or fails) when L_{air} is large (value?)

Thermal Cycled APS TBC Samples

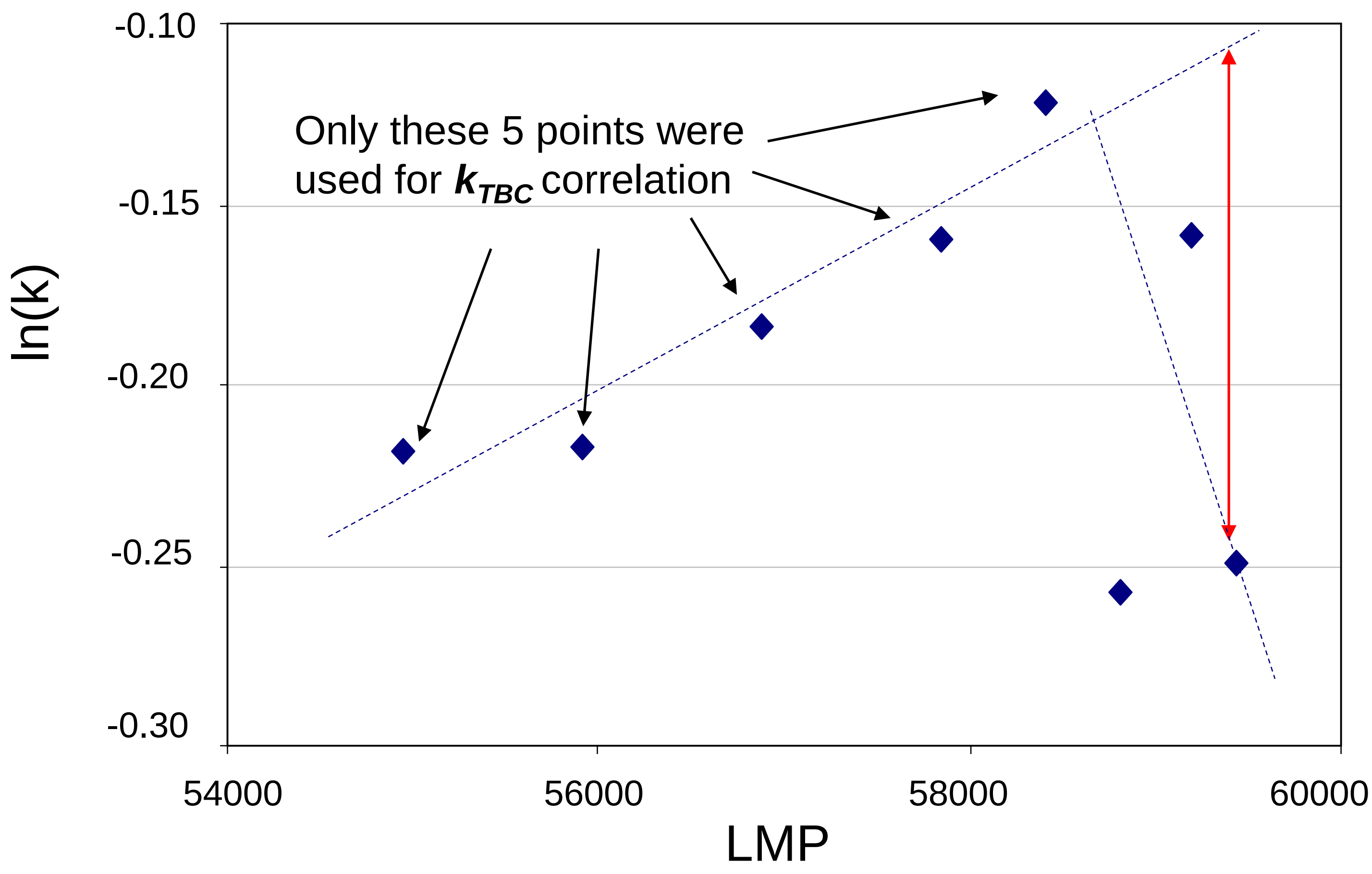


Measured Average TBC Properties (nominal TBC thickness 0.3mm)

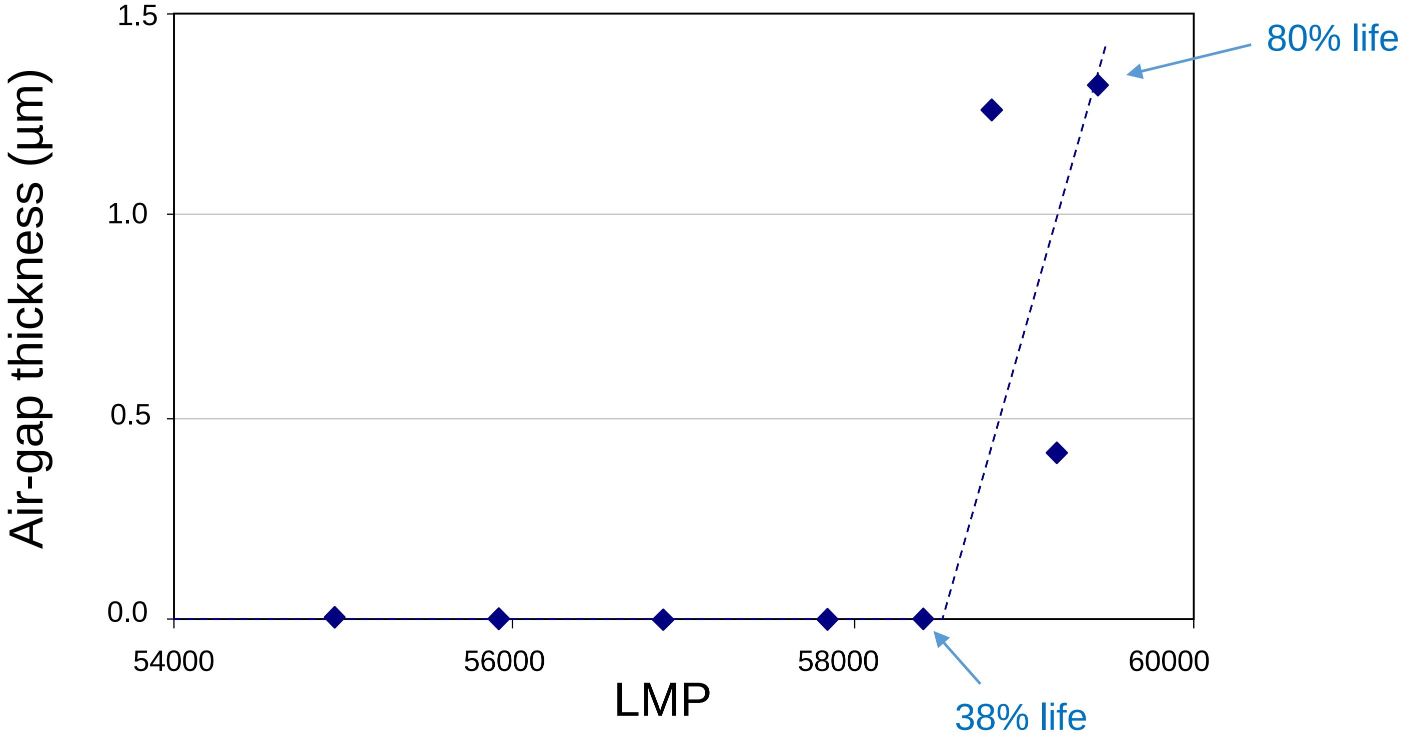


- Note: only ~10% conductivity increase in lifetime

Intrinsic TBC Conductivity k_{TBC} with LMP



Air-Gap Thickness L_{air} for Delamination



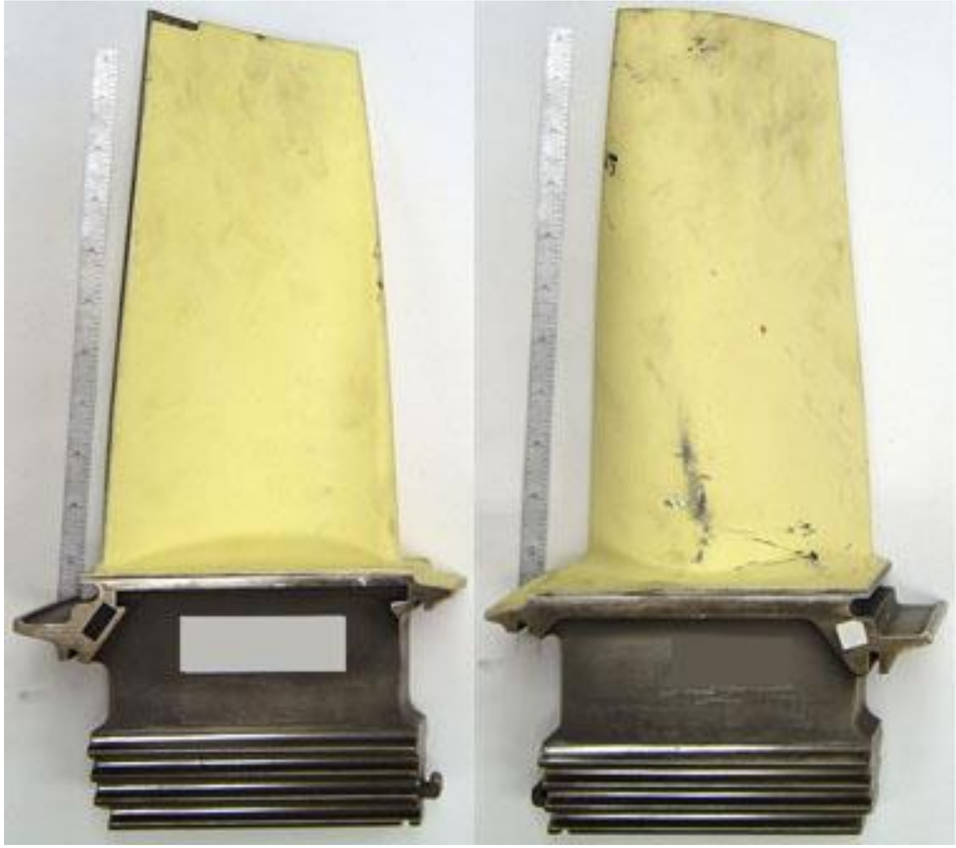
- Data suggest that TBC delaminates at L_{air} ~ 2µm
- This is a complete TBC life prediction model: k → L_{air}

Presentation Outline

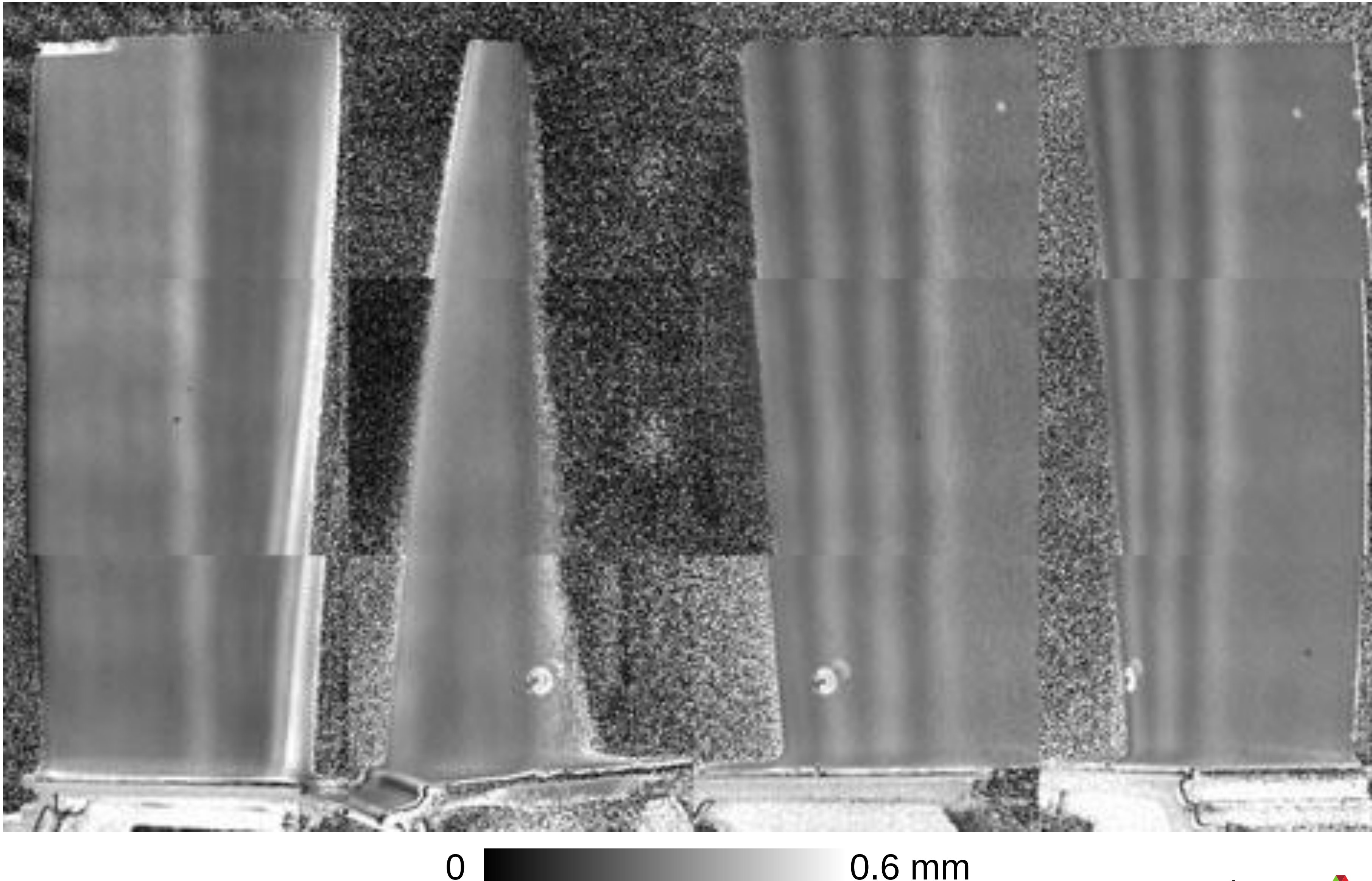
- PTI-MLA method and capabilities
- PTI-MLA for TBC life prediction
- PTI-MLA for industrial applications
  - 3D mapping of MLA data for engine components
  - Evaluation of low-cost IR camera

NDE for TBCs on Engine Components

- PIT-MLA can easily obtain NDE data for entire engine part
- However, entire NDE data may be difficult to present if part is complex
- Example for a simpler part: engine blade



TBC Thickness Image for Entire Blade (total 12 sub-images)



Argonne NATIONAL LABORATORY

Why 3D Mapping of NDE Image Data?

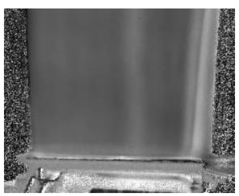
- Current NDE image data are simply compiled
- Such NDE results can be difficult to use:
  - Difficult to understand NDE images if part is complex
  - Difficult to perform dimensional analysis
  - Difficult to use NDE data for TBC life prediction
- Solution: 3D NDE data representation

Mapping NDE Data onto 3D Object

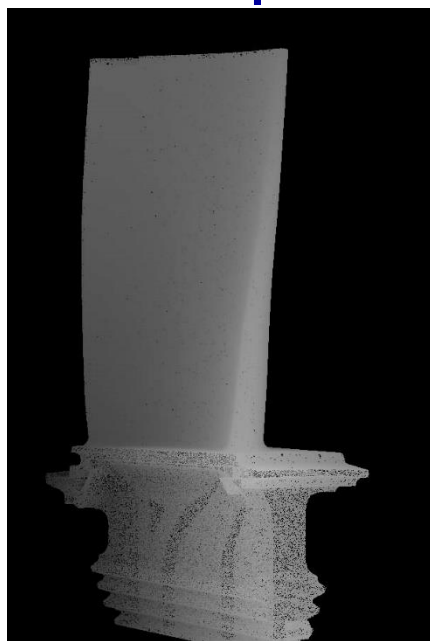
- Input data:
  - Surface cloud points of 3D part
  - 2D NDE images (for entire 3D part surface)
- Step 1: Calculating normal vectors of cloud points (if not available)
- Step 2: Mapping/stitching NDE images onto surface cloud points
  - Matching each NDE test image with corresponding projection image of 3D part and transferring NDE data to surface points
  - Automated weighting to eliminate data with poor or no flash heating
- Step 3: 3D NDE data can be displayed in any views (or videos)

Matching NDE Image with Projection Image of 3D Part

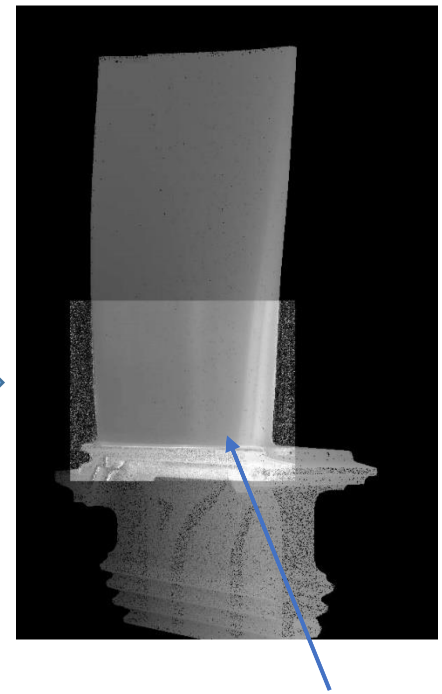
NDE image



Projection image of cloud points



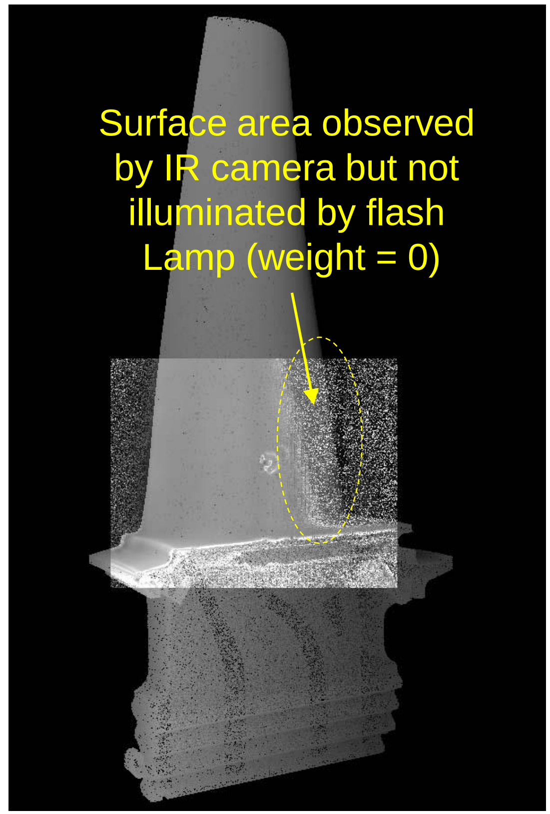
Matched image



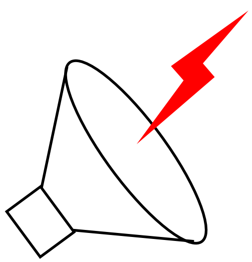
NDE data on image pixels are transferred to surface points

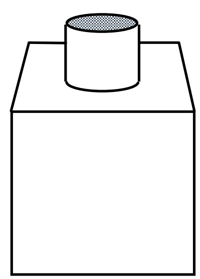
Argonne NATIONAL LABORATORY

Weighted Data in Overlapped Areas

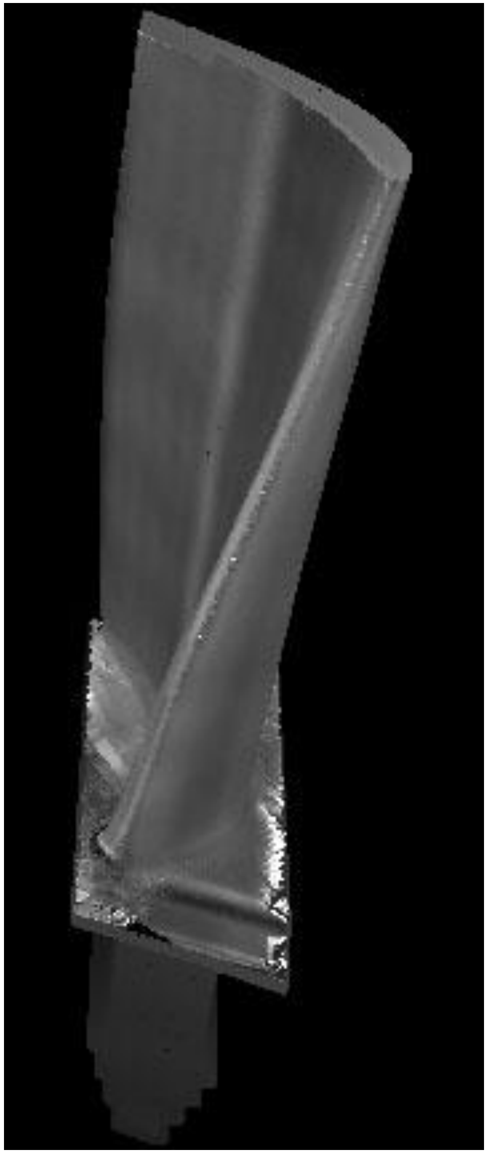


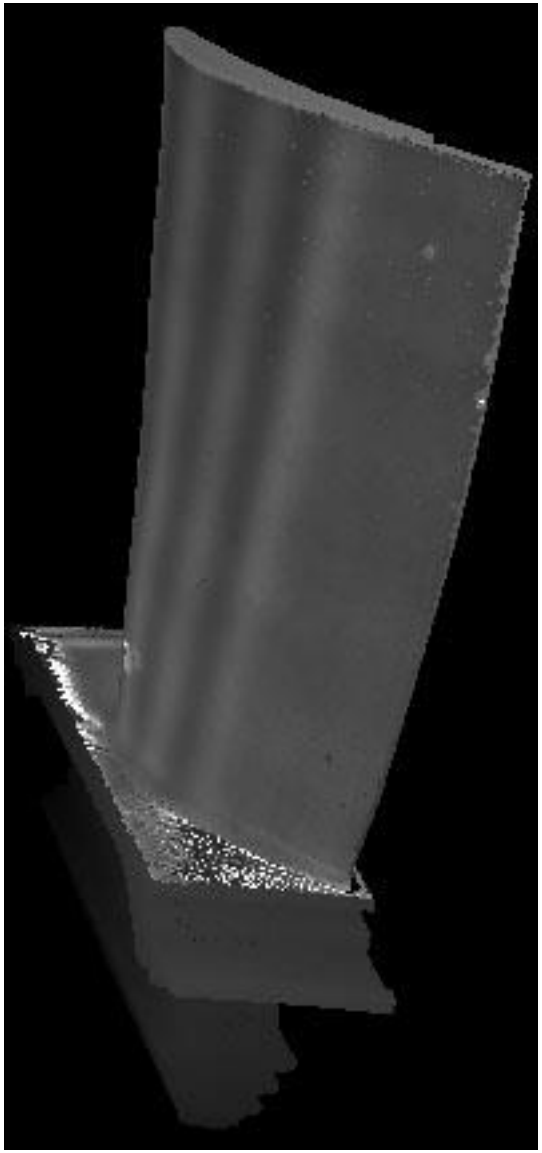
Weight is related to flash intensity at each surface point





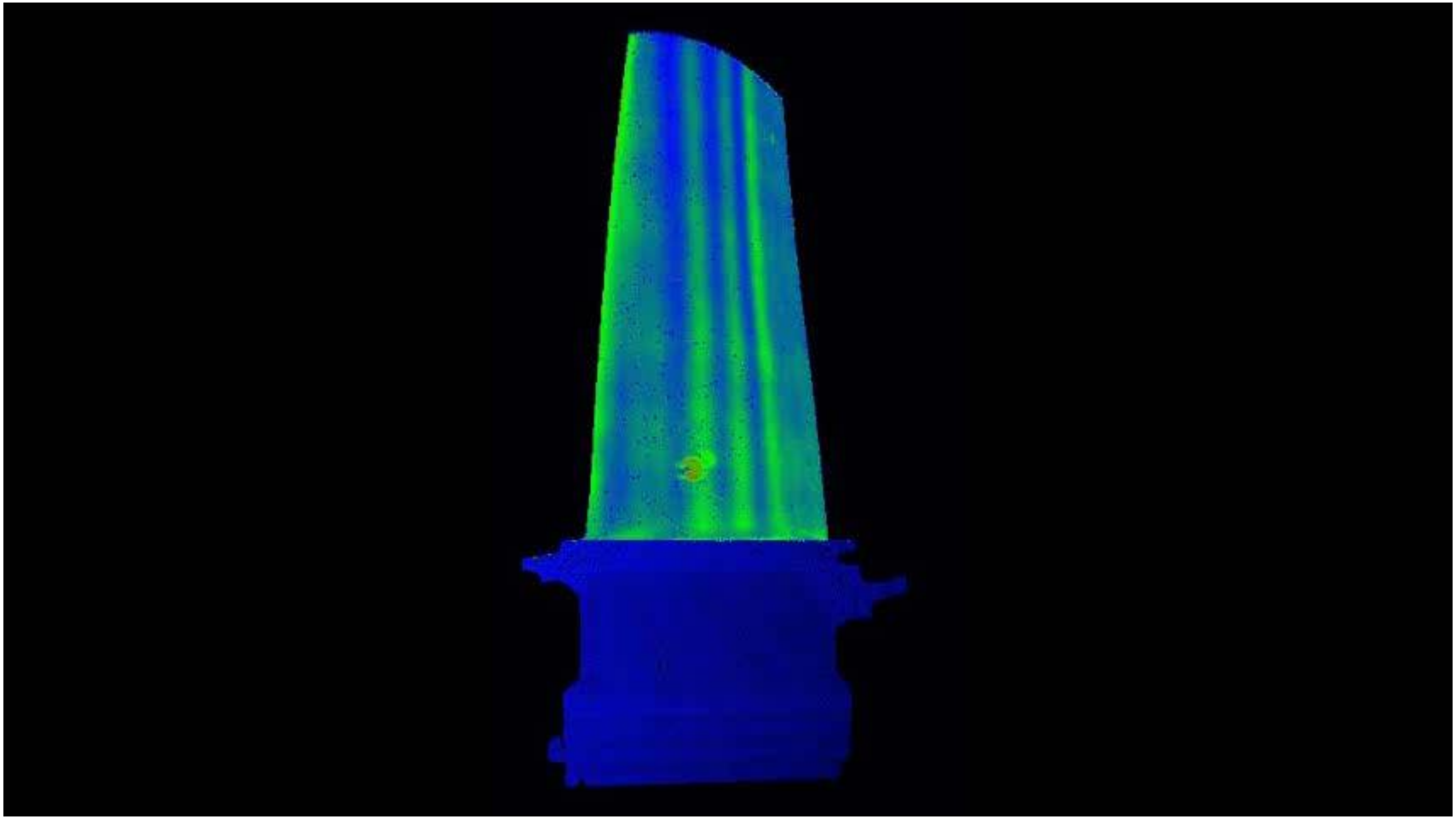
Final Result: TBC Thickness on Entire Blade





All 12 NDE sub-images are seamlessly mapped onto blade surface

TBC thickness for 3D blade



Presentation Outline

- PTI-MLA method and capabilities
- PTI-MLA for TBC life prediction
- PTI-MLA for industrial applications
  - 3D mapping of MLA data for engine components
  - Evaluation of low-cost IR camera

PTI-MLA for Industrial Applications

- Two factors affect PTI-MLA NDE for industrial applications:
  - TBC translucency requires surface treatment (usually graphite paint)
  - High-cost and large size of high-end IR cameras

- Solution: use low-cost LWIR camera (bolometer)
  - TBC is naturally opaque at LWIR (7-13μm) (no paint required)
  - Bolometers are small and much cheaper (~10% of cooled IR camera)

State-of-the-art IR camera: SC4000
(Cooled, MWIR, 320x256, high speed)

(Bolometer)
Low-cost IR camera: A35
(RT, LWIR, 320x256, 60Hz)

Evaluation of a FLIR A35 IR camera

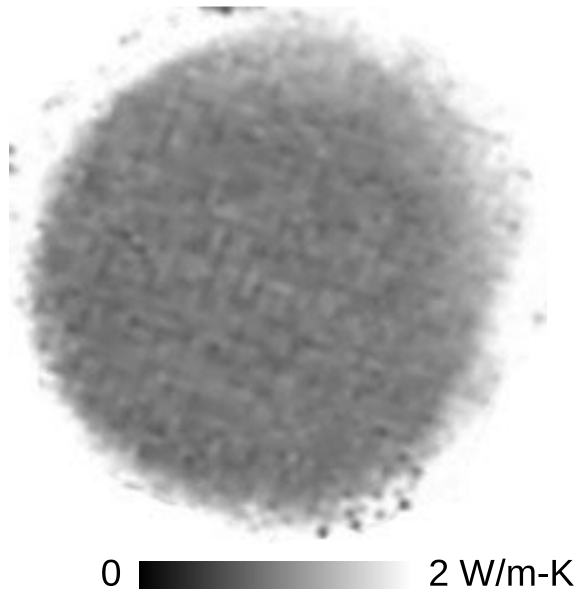
- Various TBC samples were tested using SC4000 and A35
- A35 results were compared with SC4000 results (as “exact”)
  - Compared parameters: TBC thickness and thermal conductivity

30

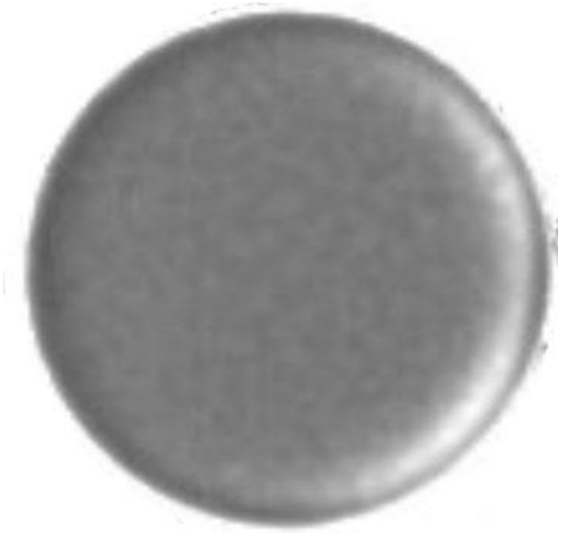
Measured conductivity images for 0.36mm TBC

A35, unpainted TBC

A35, painted TBC



SC4000, painted TBC



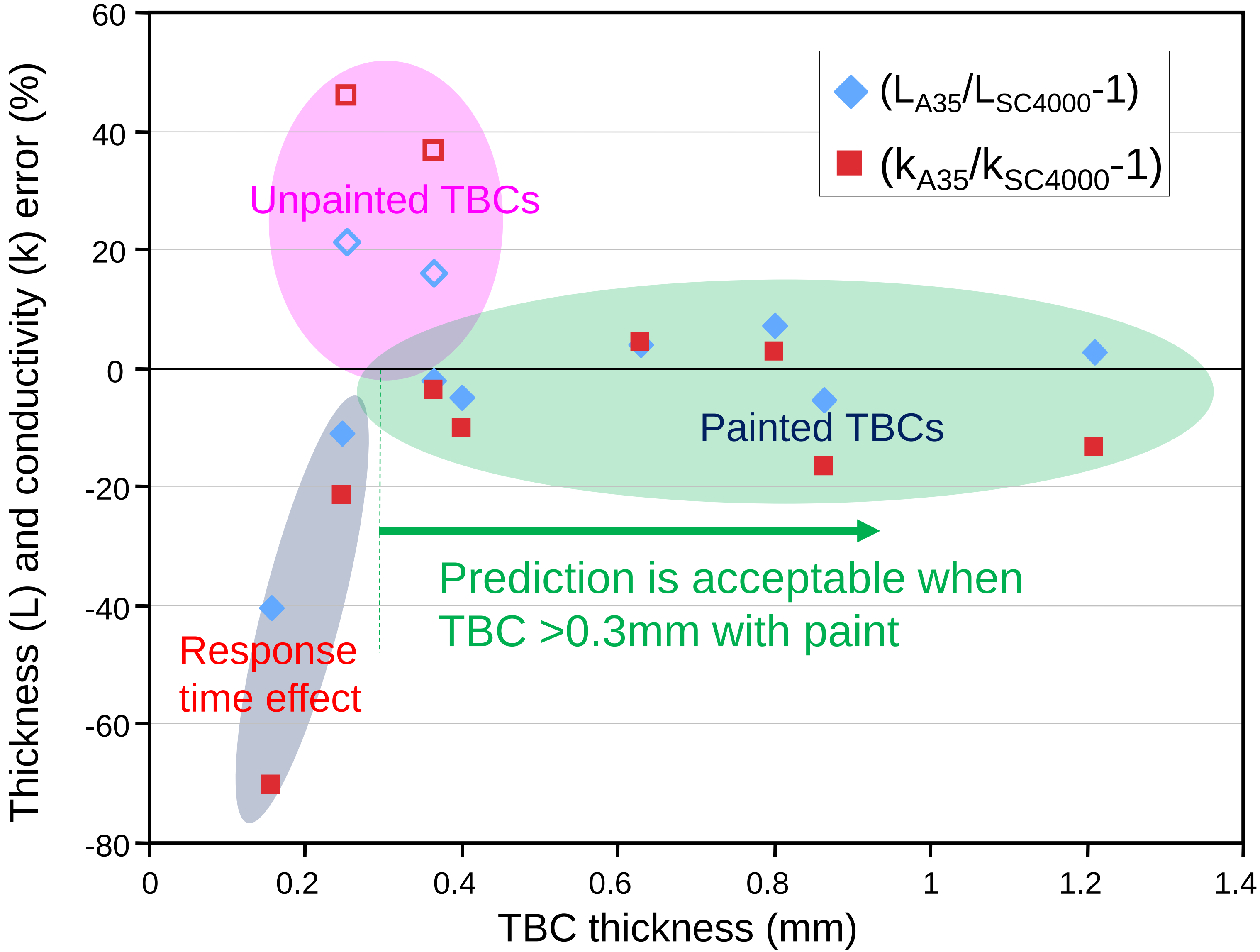
Error: +37%

Error: - 4%

Assumed: exact

- Comparison for TBC thickness are better (+16% and -2%)
- Note: same code was used for all data processing

TBC measurement error by A35 camera



Argonne NATIONAL LABORATORY

32

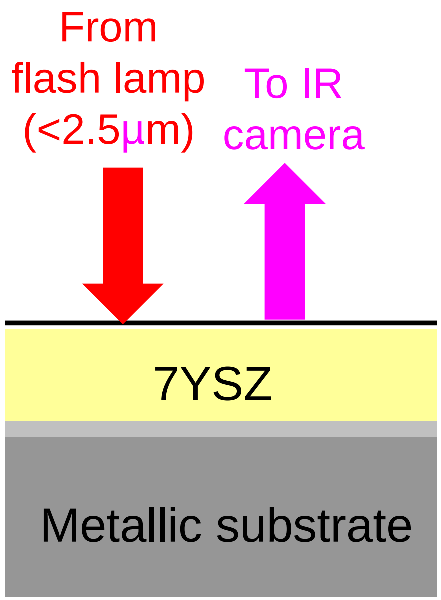
PTI-MLA Development for Bolometers

- Modeling flash-heat absorption inside translucent TBCs
- Modeling bolometer response time

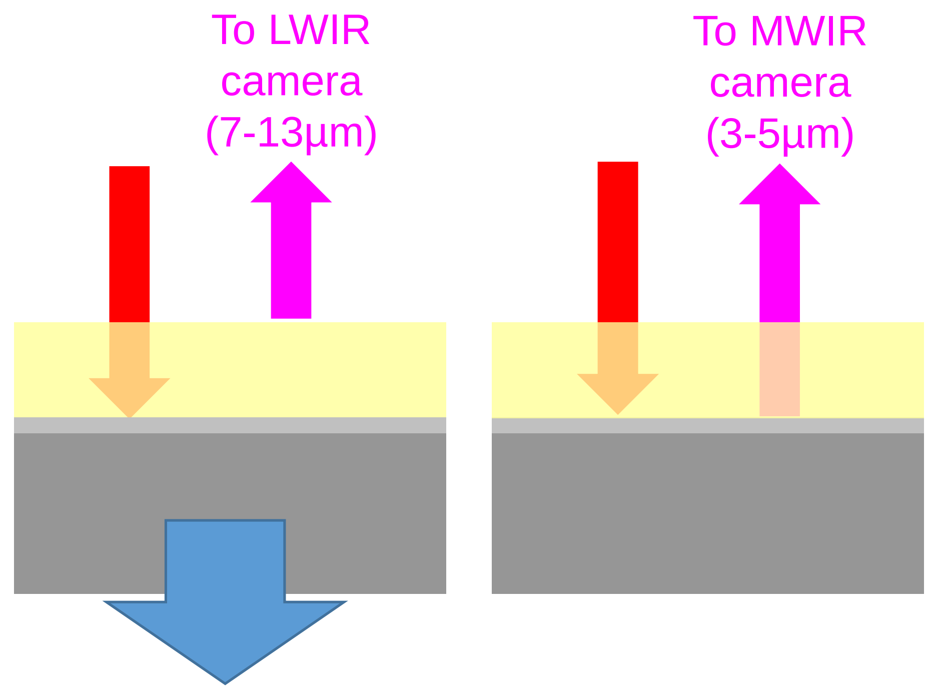
33

Optical Model for TBC Heat Absorption

Painted TBC



Unpainted TBC



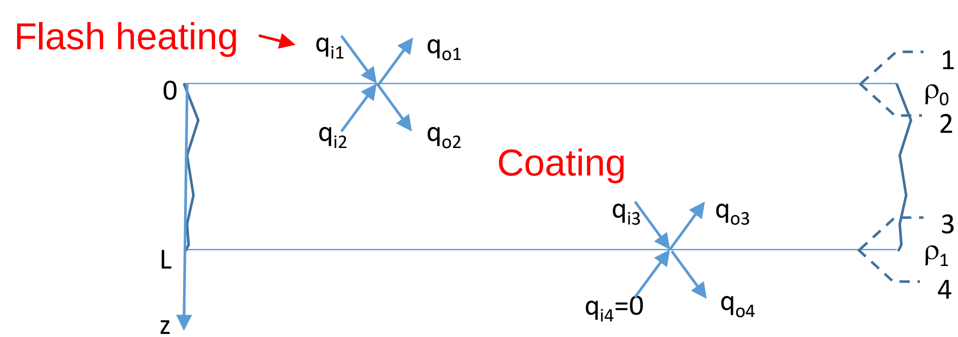
Flash heating as a function of coating depth q(z):

$$q(z) = q_{i1}(1-\rho_0)\frac{e^{-\alpha z} - \rho_1 e^{-\alpha(2L-z)}}{1-\rho_0\rho_1 e^{-2\alpha L}}$$

α = optical attenuation coefficient

ρ_0 & ρ_1 = surface reflectivity

L = coating thickness



Argonne NATIONAL LABORATORY

34

Modeling Bolometer Response Time

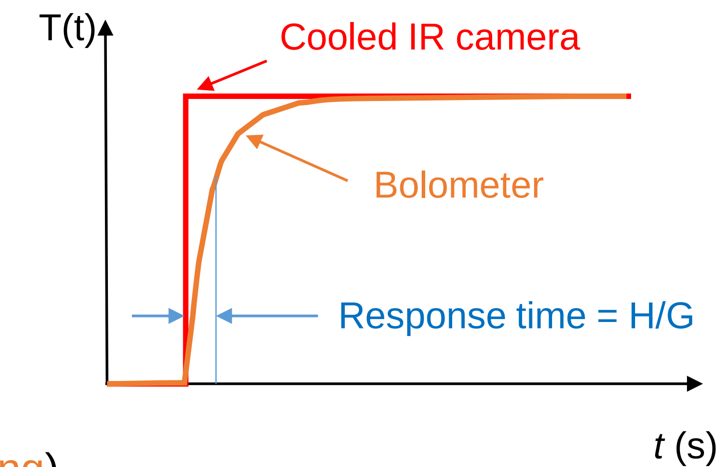
- In bolometer, pixel temperature change from absorbed incident thermal energy is used to sense radiation intensity

- This process is modeled by:

$$P(t) = G\Delta T + H\frac{d\Delta T}{dt}$$

P(t) = incident power,
G = thermal conductance of thermal link
H = pixel heat capacity
ΔT = relative pixel temperature (bolometer reading)

IR camera reading to abrupt incident radiation change



- When P(t) changes abruptly from 0 to a constant P at t=0, ΔT follows:

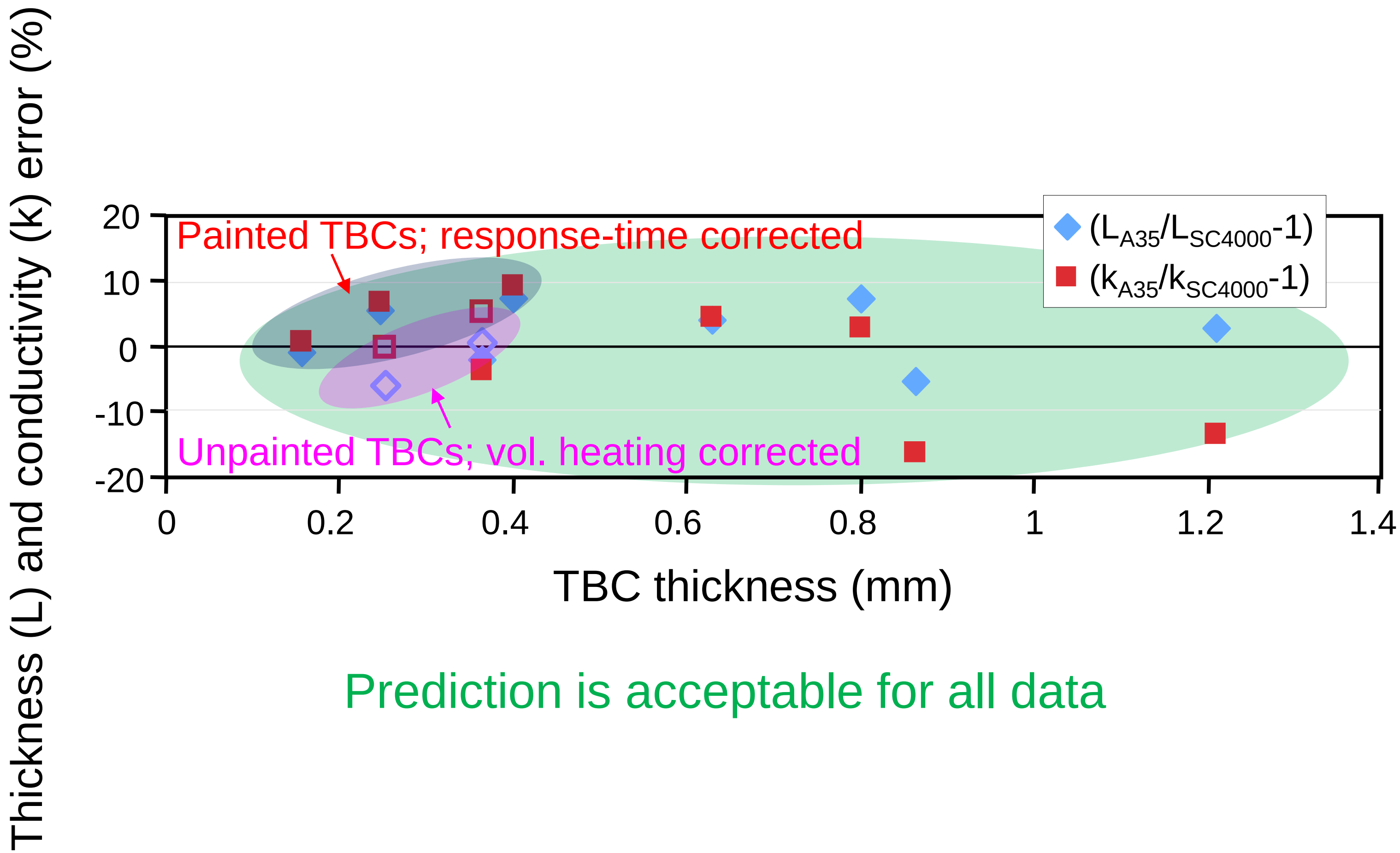
$$\Delta T = \frac{P}{G}\left(1 - e^{-\frac{G}{H}t}\right)$$

H/G = bolometer response time

- Response time for A35 is 12ms (← reason for poor NDE results for thin TBCs)

Argonne NATIONAL LABORATORY
35

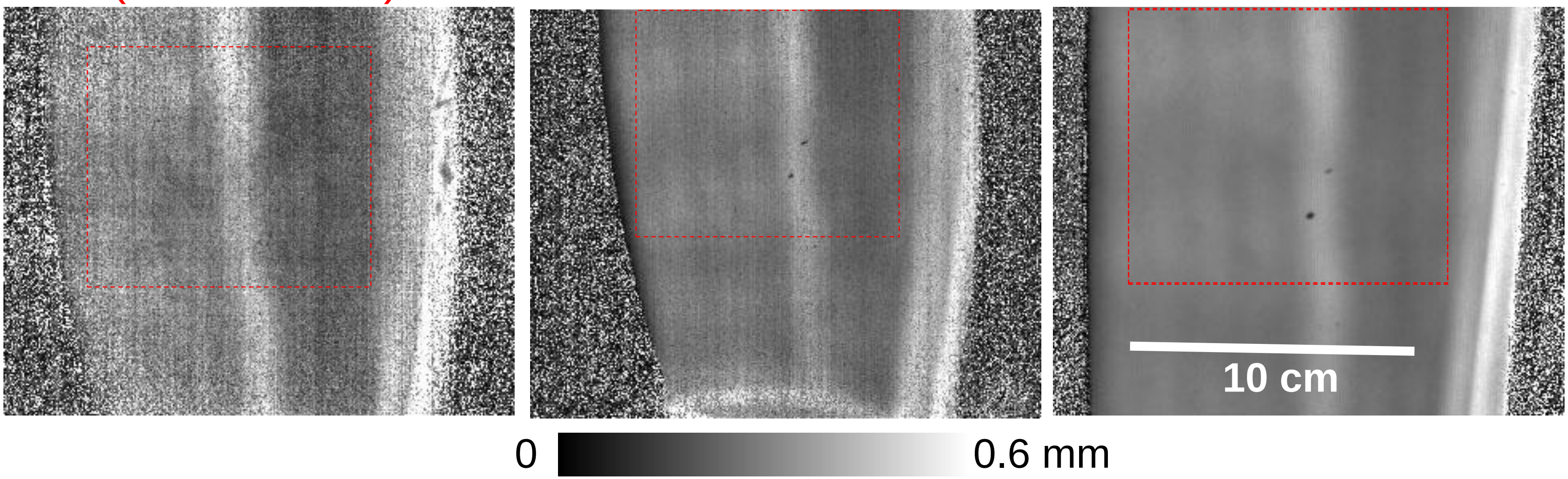
TBC measurement error by A35 camera
- with heat absorption and response time models



Prediction is acceptable for all data

Typical Measured TBC Thickness on Blade

A35, unpainted TBC (α = 3.9 mm^{-1}) | A35, painted TBC | SC4000, painted TBC



Error: - 7.2% | **Error: - 6.5%** | **Assumed: exact**

- Error for measured TBC conductivity is similar (+7.7% and +7.4%)
  - Note: errors of <10% are generally considered acceptable
  - Note: same bolometer code was used for all data processing
- Errors in A35 results are mostly due to noise → higher flash heating will reduce them! (especially for unpainted and thicker TBCs)

Summary

- PTI-MLA can accurately measure TBC properties

- PTI-MLA can nondestructively evaluate TBCs in their entire lifetime
  - For TBC life prediction
  - For industrial applications

- PTI-MLA has essentially solved the TBC NDE issue!
  - PTI-MLA is a turn-key technology and can be licensed from Argonne