DEVELOPMENT OF NDE METHODS FOR CERAMIC COATINGS

J.G. Sun,
Nuclear Engineering Division
Argonne National Laboratory
Argonne, IL, USA

26th Annual Conference on Fossil Energy Materials
Pittsburgh, PA
April 17-19, 2012

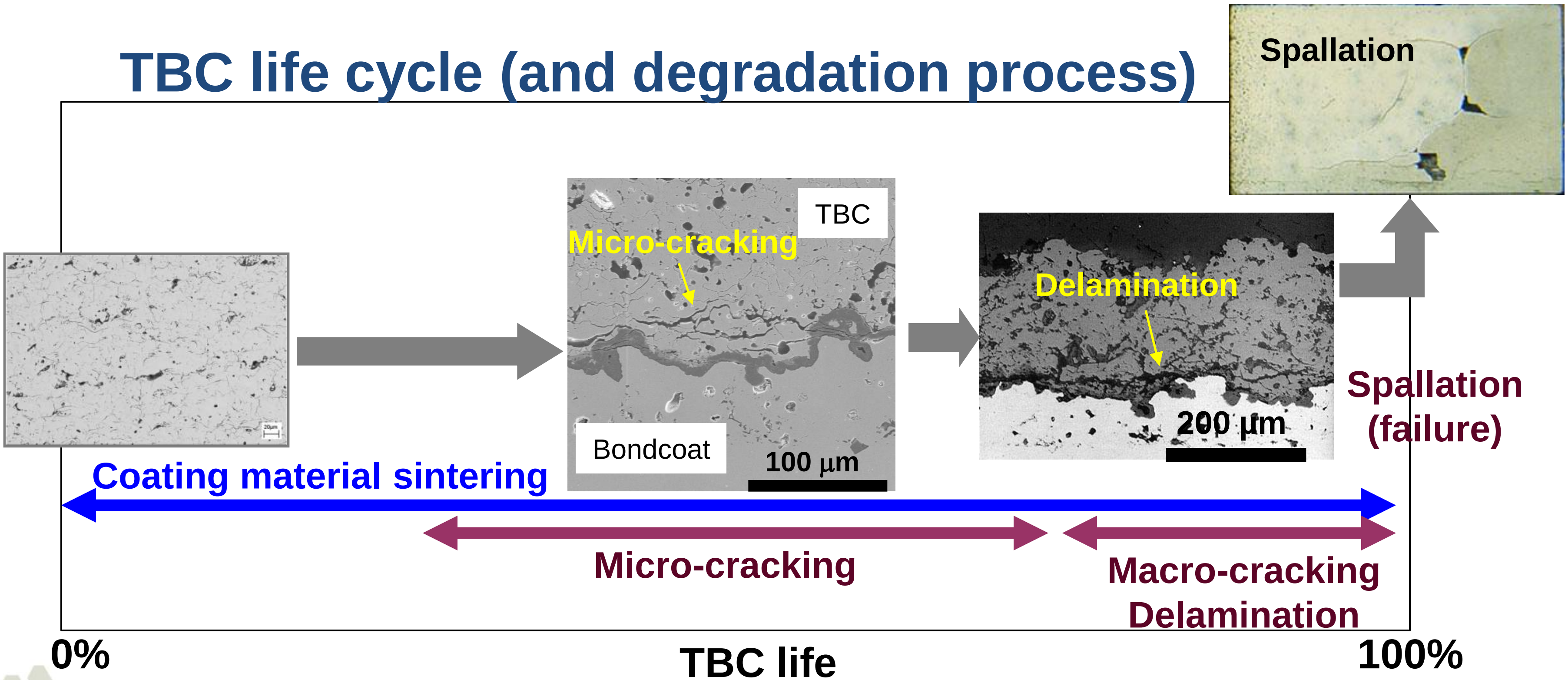
Work supported by U.S. Department of Energy,
Office of Fossil Energy,
Advanced Research-Materials Program

Outline

- Background on TBC degradation and NDE
- Objectives
- Recent NDE development for TBC life prediction
  - Optical methods: Laser backscatter and mid-IR reflectance
  - Thermal multilayer analysis method: model and validation
- Summary
- Planned future efforts

Background

- Thermal barrier coatings (TBCs) are required for high-temperature metallic components in advance turbine systems to be operated with higher efficiency and low emission
- TBCs have become “prime reliant” material → their condition monitoring and lifetime prediction by NDE is important



NDE Applications for TBCs

- Two characteristics of TBC degradation/failure:
  - (1) Ceramic top coat continuously sinters with minimal damage
  - (2) Cracks and delaminations develop and expand near interface
- NDE methods based on detection of cracking & its effect (2^{nd} factor)
  - Photo-luminescence piezo-spectroscopy for stress accumulation
    - Detailed stress distribution for thin TBCs in lab tests (not suitable for field use)
  - Electrochemical impedance spectroscopy for cracking and phase transformation
    - Not exactly a NDE method (requires permanent attachment)
  - Laser-backscatter and mid-IR reflectance (MIRR) for crack detection
    - Optical methods have some success for thin coatings (mostly in lab tests)
  - Thermal imaging for crack/delam detection
    - Successful for large cracks and delaminations (for TBCs near end of life)
- NDE methods based on property measurement (1^{st} and 2^{nd} factors)
  - Thermal imaging for TBC thermal property measurement
    - TBC conductivity evolves with TBC life (in predictable trend?)

NDE for TBC Life Prediction

- Current NDE methods have limited capability for TBC life prediction
  - Spectroscopy methods are not suitable for real component field application
  - Optical methods have some success for thin coatings in lab tests
    - Investigated under this project; may have potential for field application
  - Traditional NDE methods for delamination detection are not quantitative
    - Many NDE methods are usable; thermal imaging is most effective
- Advanced NDE methods are required for TBC characterization
  - Life prediction (based on quantitative TBC property measurement)
  - High-resolution detection of crack initiation and propagation
  - Applicable to new more complex TBC systems (eg, duel-layer)

Objectives of This Project

- Develop and evaluate advanced NDE methods for (1) TBC life prediction and (2) high-resolution detection of coating flaws
  - (1) For life prediction:
    - laser backscatter, mid-IR reflectance
    - thermal multilayer analysis
  - (2) For high-resolution flaw detection
    - thermal tomography
- Develop NDE methods for functional materials (gas-separation membrane, fuel cell, etc)
  - Synchrotron x-ray CT, thermal tomography

Recent NDE Developments under This Project

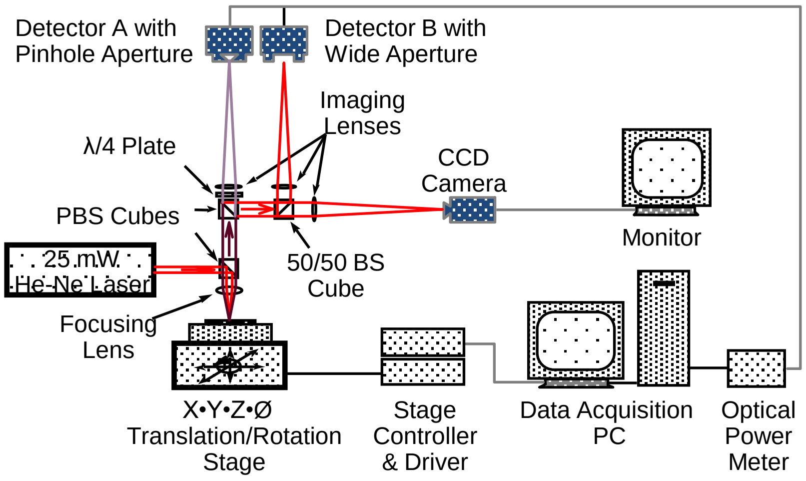
- Continued evaluation of optical NDE methods (mid-IR reflectance and laser backscatter) for TBC life prediction
  - New samples from Siemens and Harvard Univ.
- Continued development of two thermal imaging methods
  - Thermal multilayer analysis for TBC life prediction
    - Evaluate TBC life prediction model based on measured TBC thermal properties (thermal conductivity)
    - Continued calibration for TBC property measurement accuracy from collaboration with researchers in Japan and Italy
    - Investigate property measurement for duel-layer TBCs
  - Thermal tomography method (3D imaging)
    - Continued development of new algorithm for high-resolution imaging
    - Applied to a DARPA SBIR project with success

Presentation Focus: NDE for TBC Life Prediction

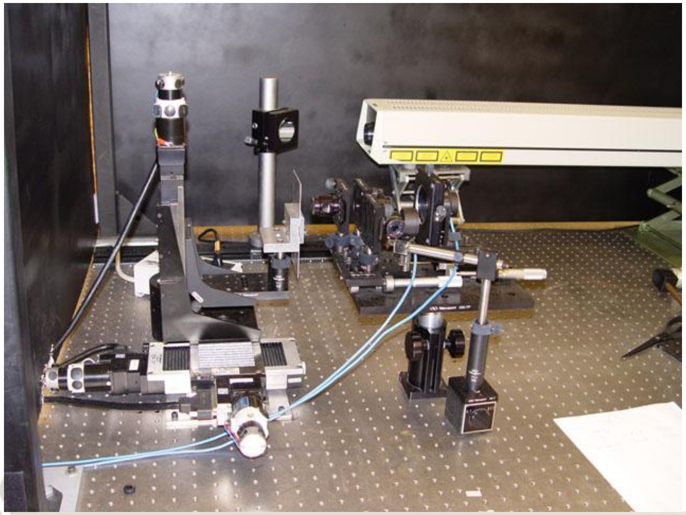
- Optical methods: Laser backscatter and Mid-IR reflectance (MIRR)
  - Method evaluation
- Thermal imaging methods: multilayer analysis method
  - TBC life prediction model
  - Model evaluation

Laser Backscatter for TBC Life Prediction

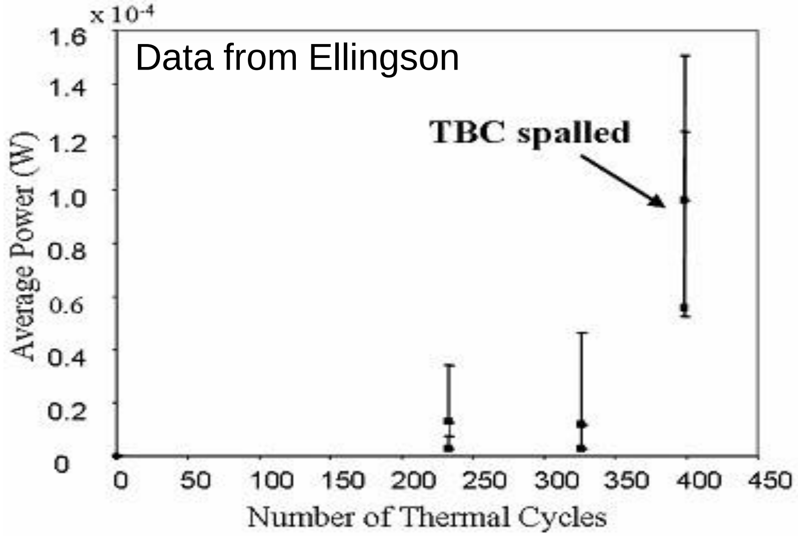
Schematics



Experimental setup



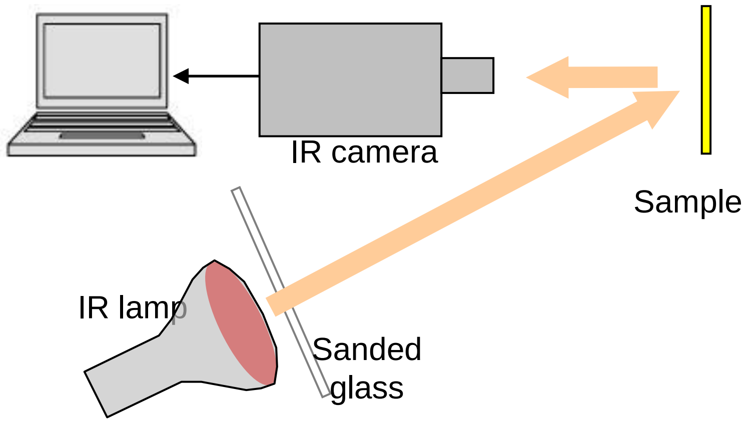
Scatter intensity vs. TBC life



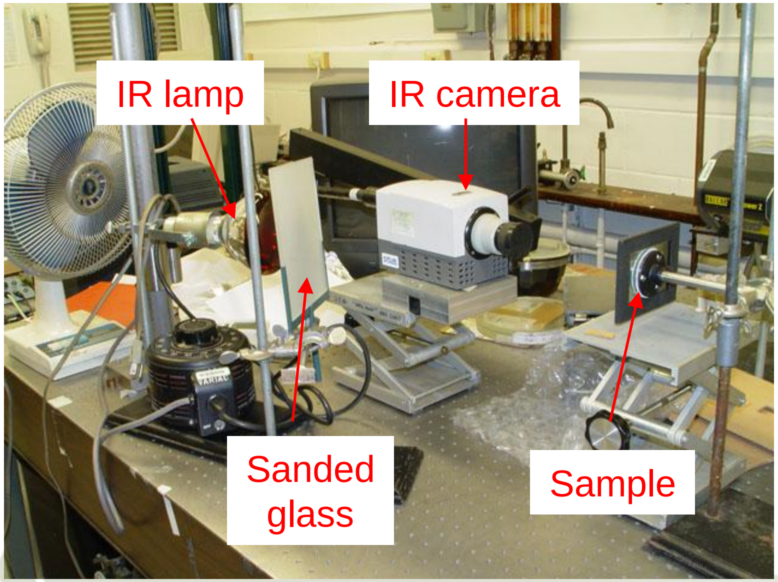
- Technology developed at ANL by Dr. Ellingson
- Detect backscattered laser light from subsurface, not surface reflection
- Backscatter signal may be correlated with TBC degradation (cracking)

Mid-IR Reflectance for TBC Life Prediction

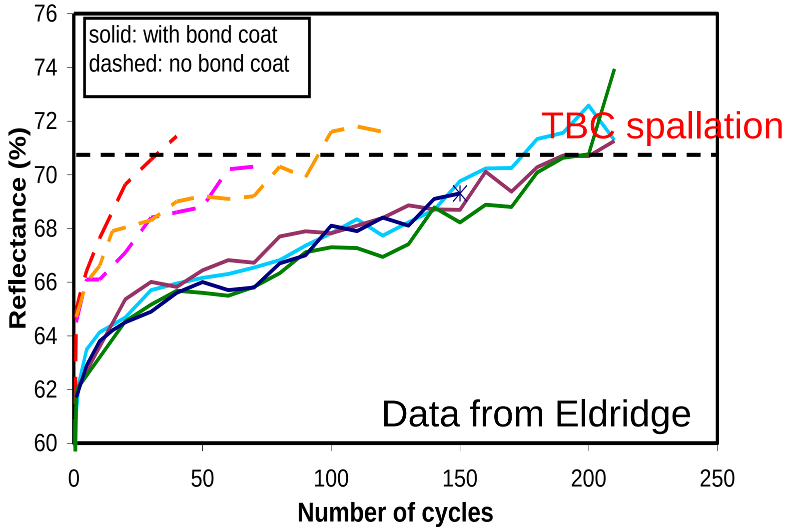
Schematics



Experimental setup at ANL



Reflectance vs. TBC life



- Technology developed by Dr. Eldridge of NASA
- Reflectance increases with TBC cracking
- Mid-IR reflectance developed at ANL
  - Use entire 3-5µm wavelength (narrow band in NASA system)
  - Use weaker IR source (low thermal heating)
  - Test/data processing procedure established

Comparison/Discussion of Optical Methods

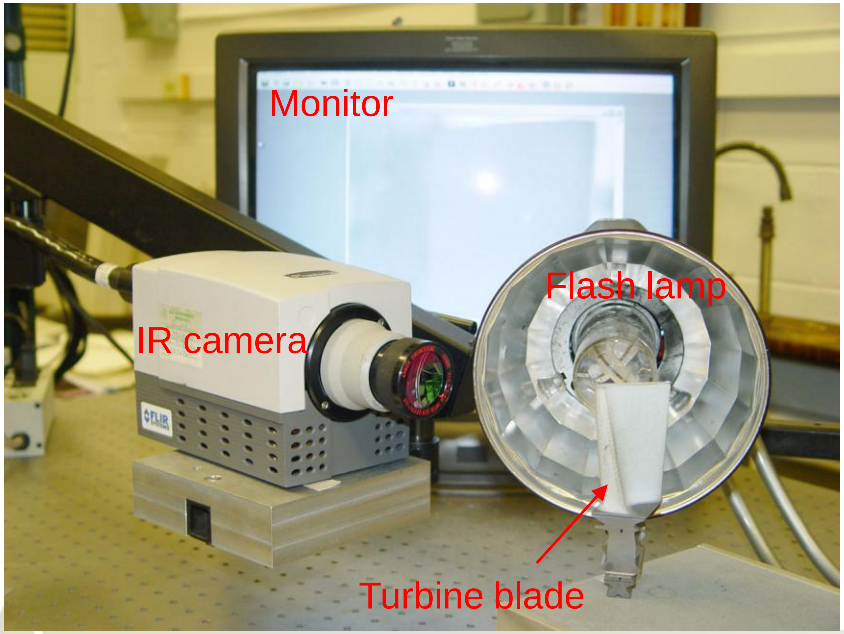
- Laser backscatter (visible 633nm wavelength)
  - Sensitive only to internal scatter (from TBC volume and interface)
  - Low penetration depth → lower sensitivity to interface signal
- MIRR (infrared 3-5µm wavelengths)
  - Sensitive to all reflections/scatters (from TBC surface, internal, interface)
  - Deep penetration depth → more sensitive to interface condition

- **Advantages**
  - Non-contact, remote, direct 2D imaging
  - Instantaneous (point-and-read), signal can be scaled (quantitative)
- **Disadvantages**
  - Limited detection depth (typically up to 300µm coating thickness)
  - Signal intensity is a function of TBC thickness (in addition to flaws)
  - Susceptible to surface contaminations

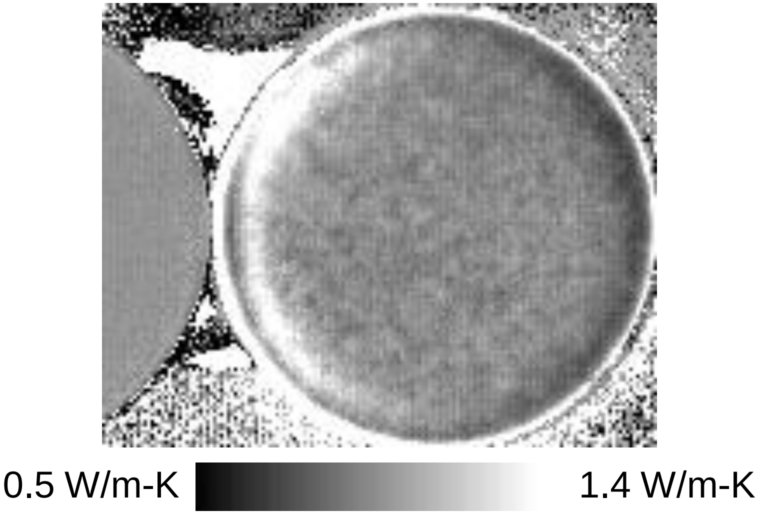
TBC Life Prediction Based on TBC's Thermal Property

- To use thermal property for TBC life prediction, ANL developed a NDE method that can accurately measure TBC thermal properties
  - Multilayer analysis method measures two TBC properties:
    - Thermal conductivity distribution
    - Heat capacity distribution (or thickness distribution)
  - Applicable to all coating systems on engine components

One-sided experimental setup

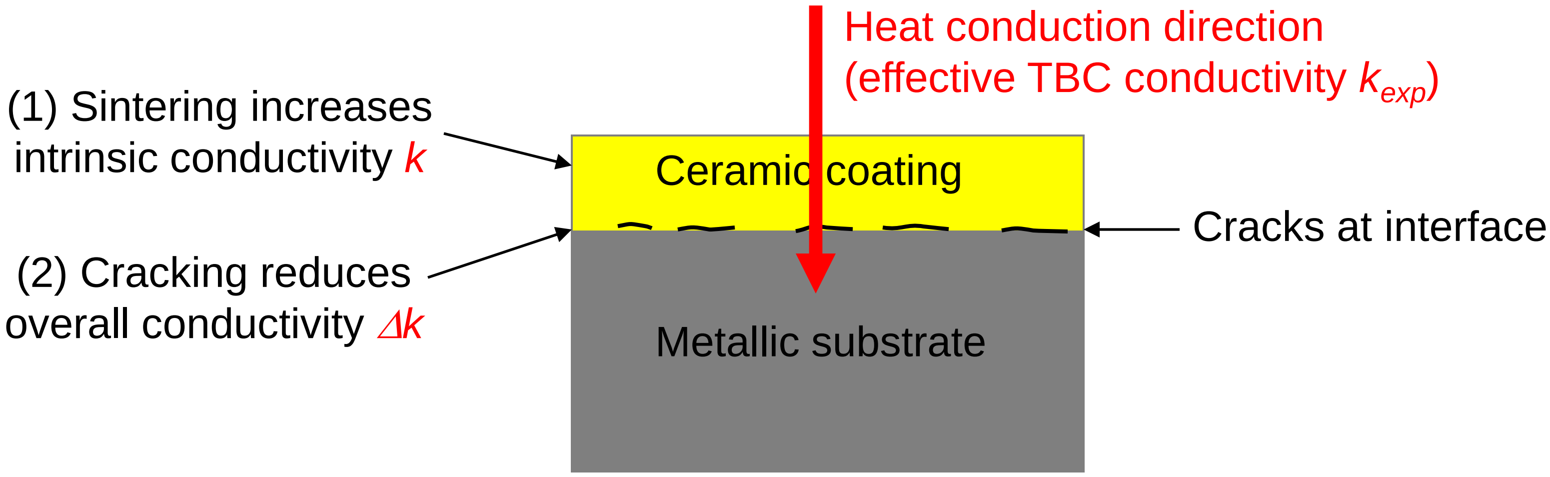


Thermal conductivity imaging



Modeling TBC Conductivity Change with Life

- TBC thermal conductivity is affected by two factors:
  - (1) Conductivity increase due to coating material sintering
    - Measured by laser flash on stand-alone coating samples
  - (2) Conductivity decrease due to cracking/delamination at interface
- A TBC conductivity-life model should account for both factors



Effective (measured) k_{exp} = (intrinsic k) - (cracking reduction Δk)

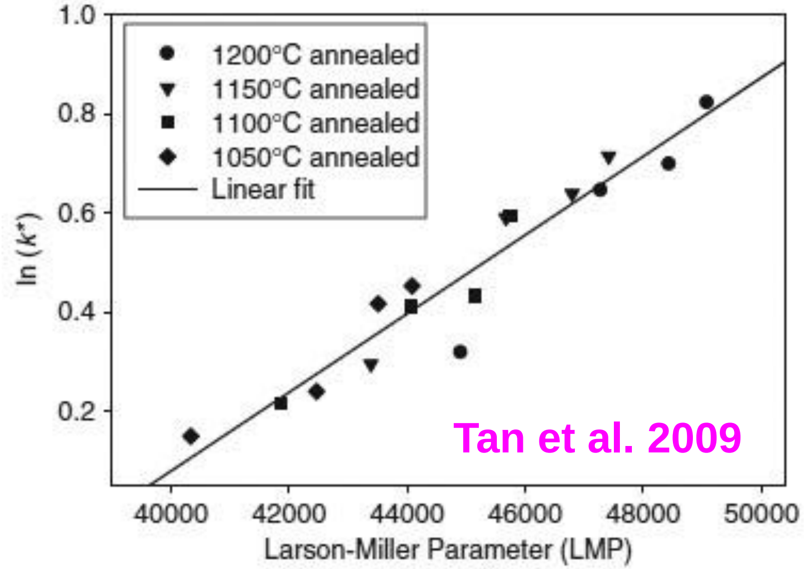
Intrinsic Coating Conductivity due to Sintering

- Intrinsic coating conductivity change due to sintering (annealing) is commonly correlated with LMP (Larson-Miller parameter):

$$\ln(k/k_0) = a + b*\text{LMP},$$

$$\text{LMP} = T*(\ln t + C),$$

k = conductivity (W/m-K),
k_0 = initial conductivity (at t=0),
T = temperature (K),
t = time (s),
a,b,C = fitting constants



- Note: k_0 and a can be combined, because:

$$\ln(k/k_0) = \ln(k) - \ln(k_0) = \ln(k) - \text{constant}$$

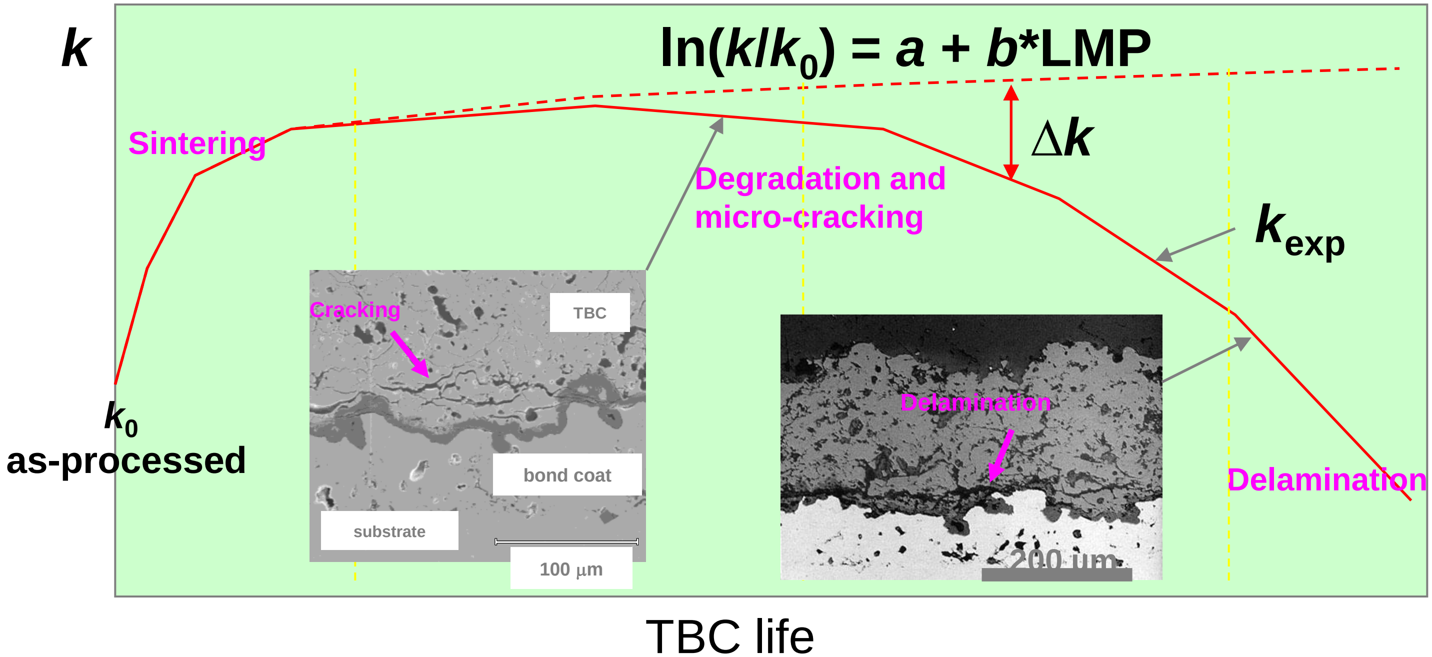
TBC Conductivity - Life Prediction Model

- TBC life may be predicted from conductivity reduction due to cracking:

$$\Delta k = k - k_{exp}, \quad \text{(need to determine } \Delta k \text{ at 100\% life)}$$

k is determined from LMP correlation (exposure condition dependent)

k_{exp} is measured by thermal imaging

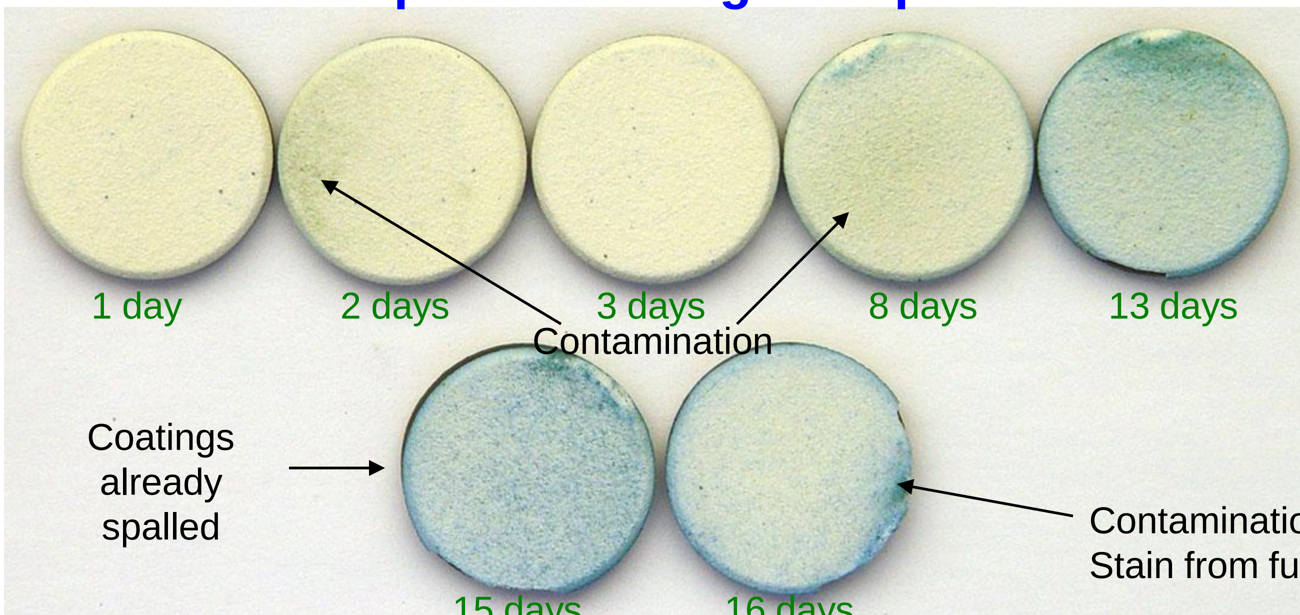


Evaluation of NDE Methods for TBC Life Prediction

- TBC samples from Dr. Kulkarni of Siemens
- Optical methods: laser backscatter and mid-IR reflectance (MIRR)
- Thermal imaging method

Siemens APS TBC Samples

TBCs exposed at a high temperature

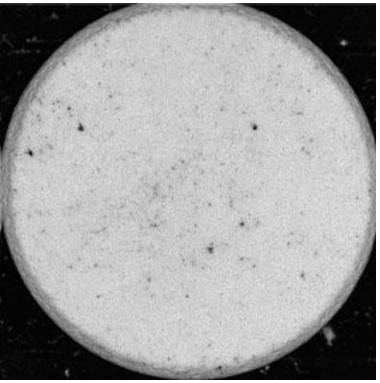


TBCs exposed at lower temperatures

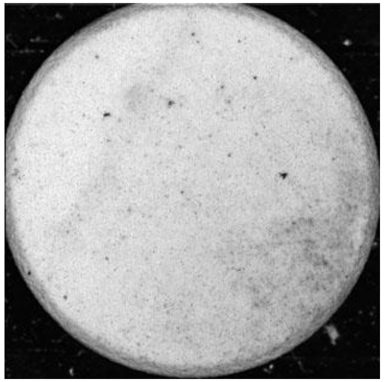
T1 < T2

Laser Backscatter Scan Images

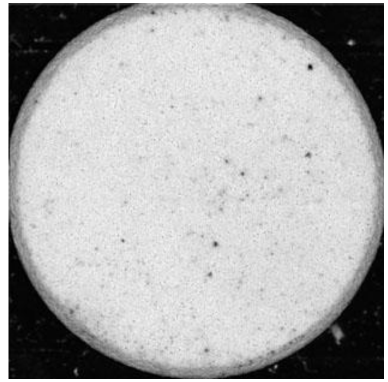
TBCs exposed at a high temperature



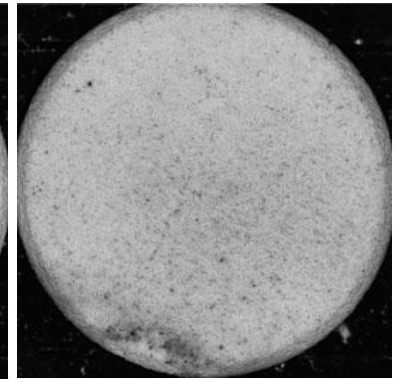
1 day



2 days

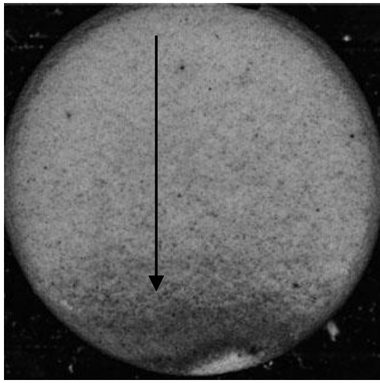


3 days



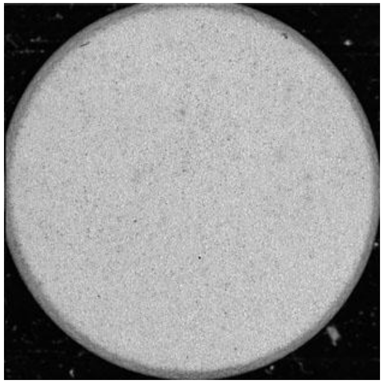
8 days

Contamination from furnace fume

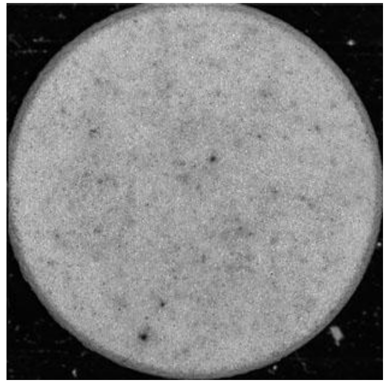


13 days

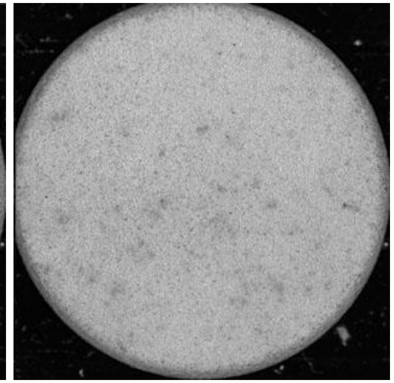
TBCs exposed at lower temperatures



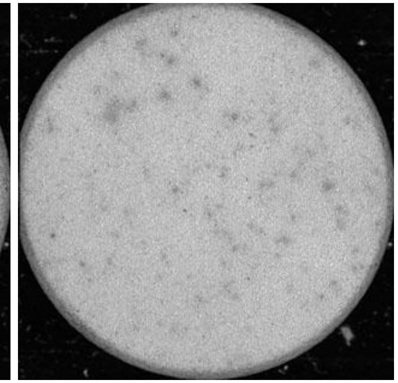
T1, 6 days



T1, 22 days

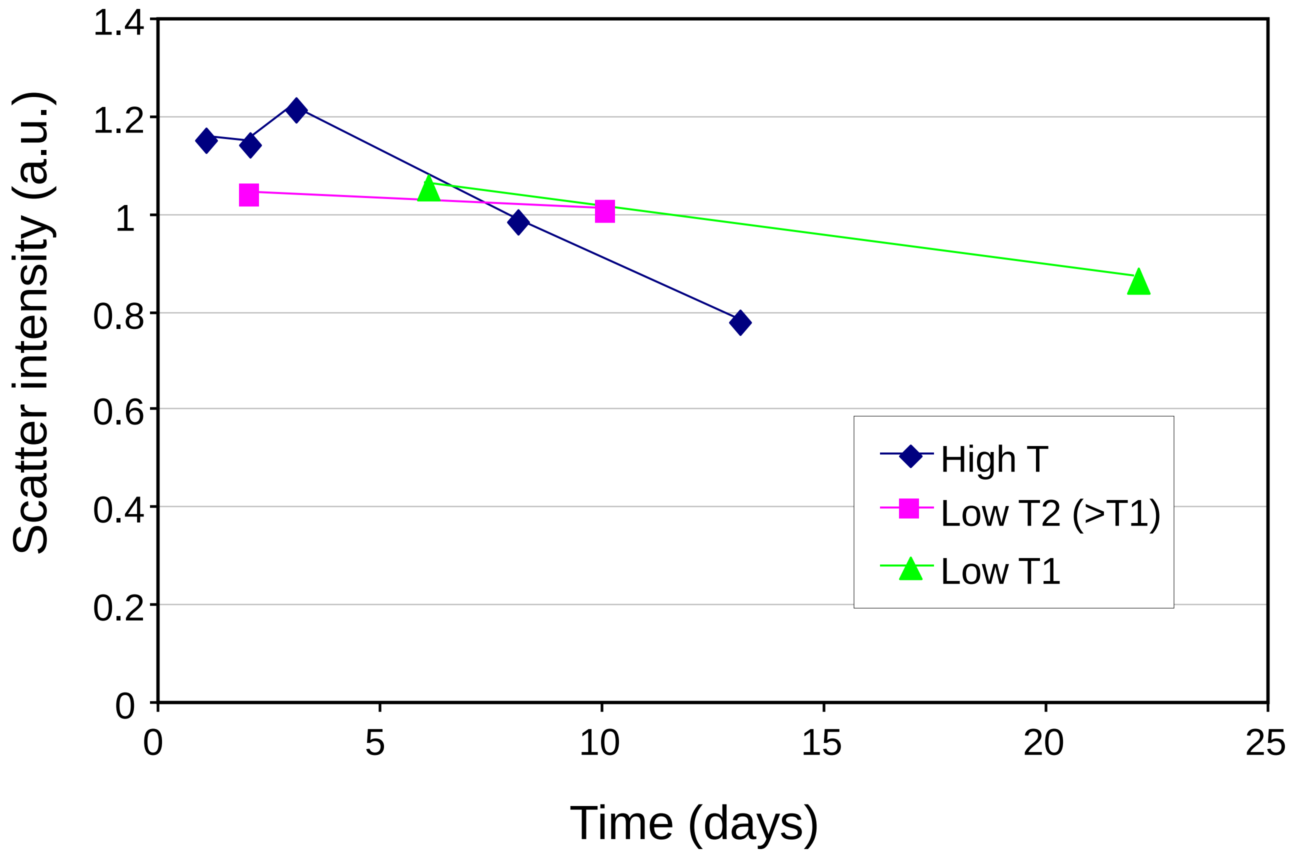


T2, 2 days



T2, 10 days

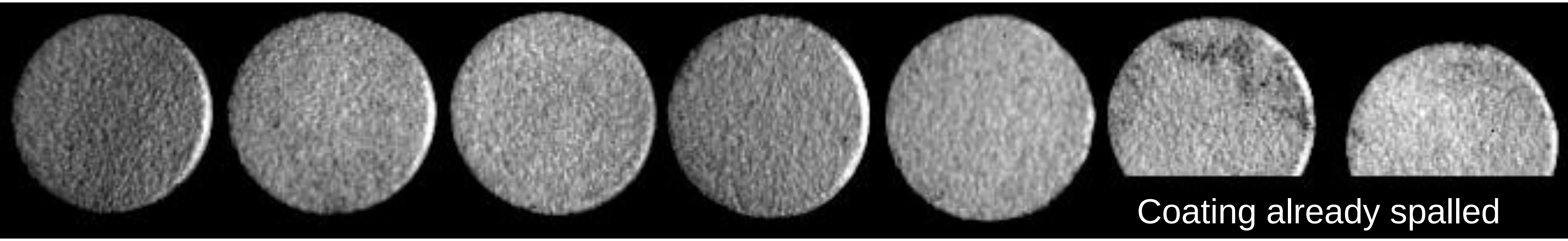
Laser Backscatter Intensity vs. Time



- Backscatter intensity reduces with TBC life (?)
- May require operation in IR wavelength to improve correlation

Mid-IR Reflectance Images

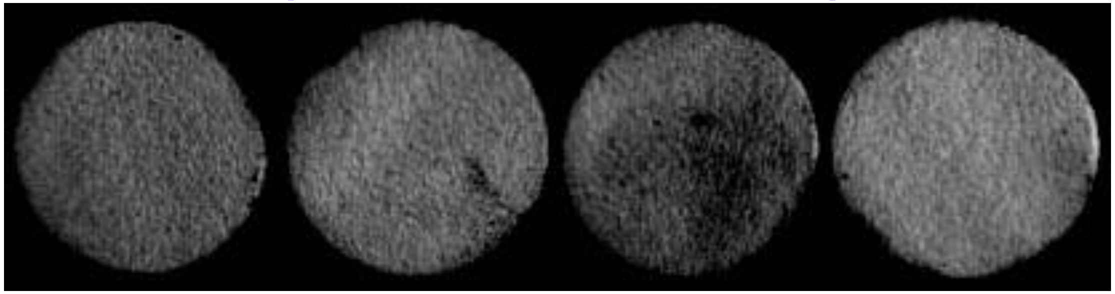
TBCs exposed at a high temperature



1 day **2 days** **3 days** **8 days** **13 days** **15 days** **16 days**

Furnace fume contamination not visible, both other contamination presents

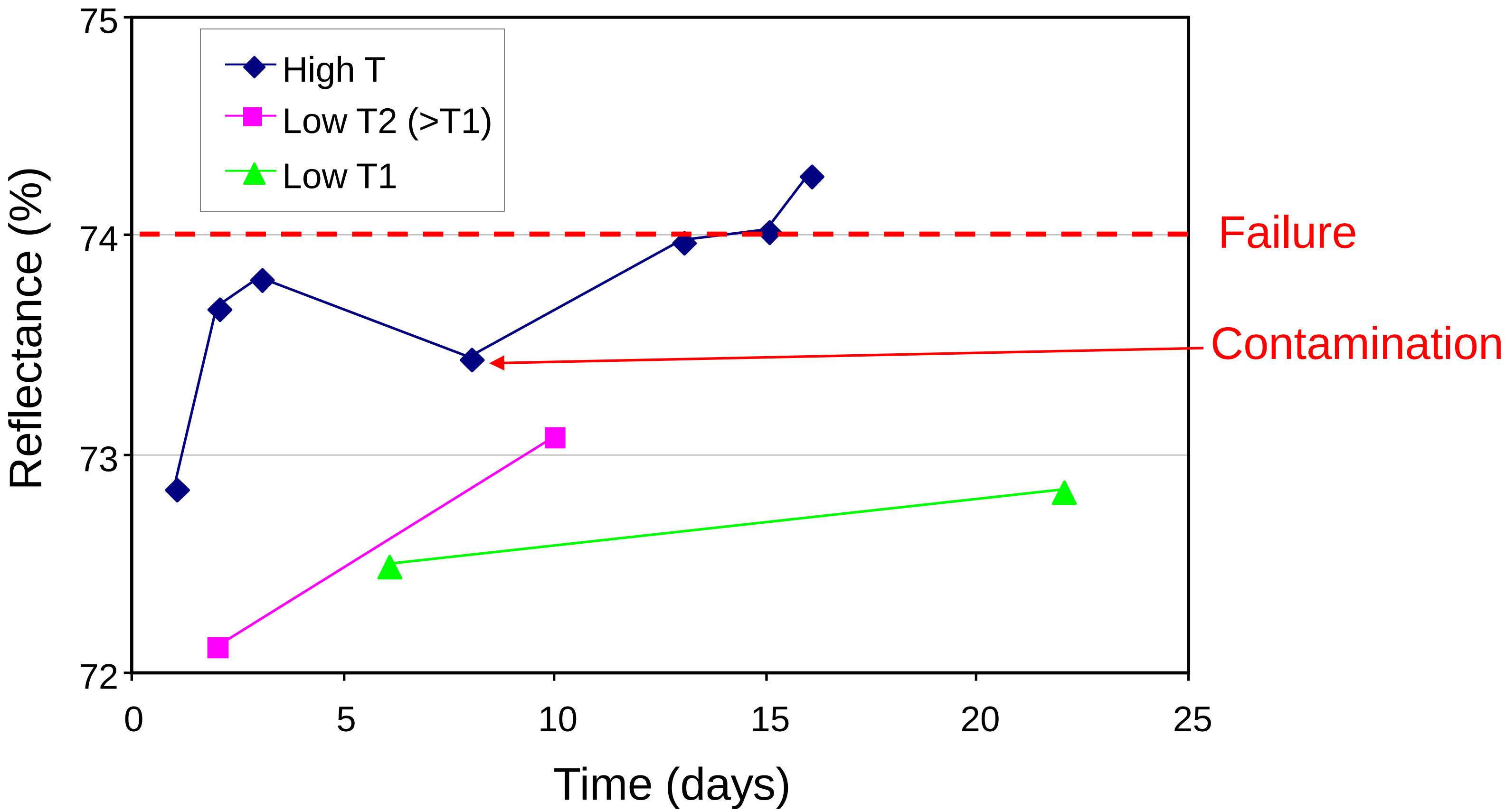
TBCs exposed at lower temperatures



T1, 6 days **T1, 22 days** **T2, 2 days** **T2, 10 days**

71%  75%

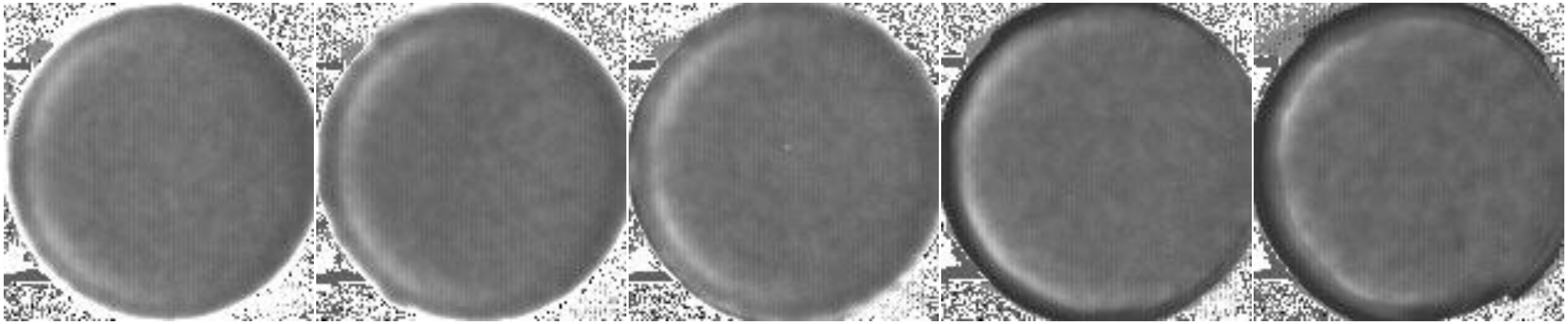
Mid-IR Reflectance Intensity vs. Time



- Mid-IR reflectance is correlated with TBC life (small range!)
- Contamination is an issue
- Failure (delamination) level is a function of TBC thickness

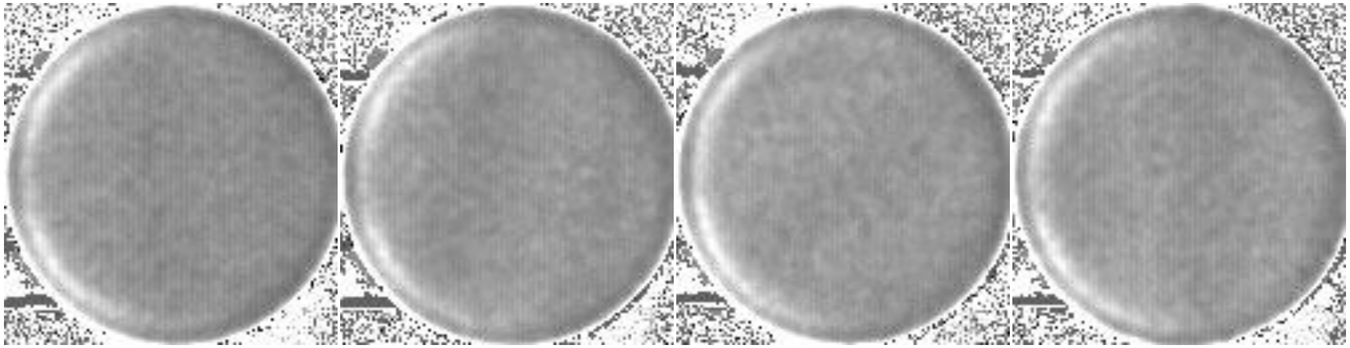
Thermal Conductivity Images

TBCs exposed at a high temperature



1 day | 2 days | 3 days | 8 days | 13 days

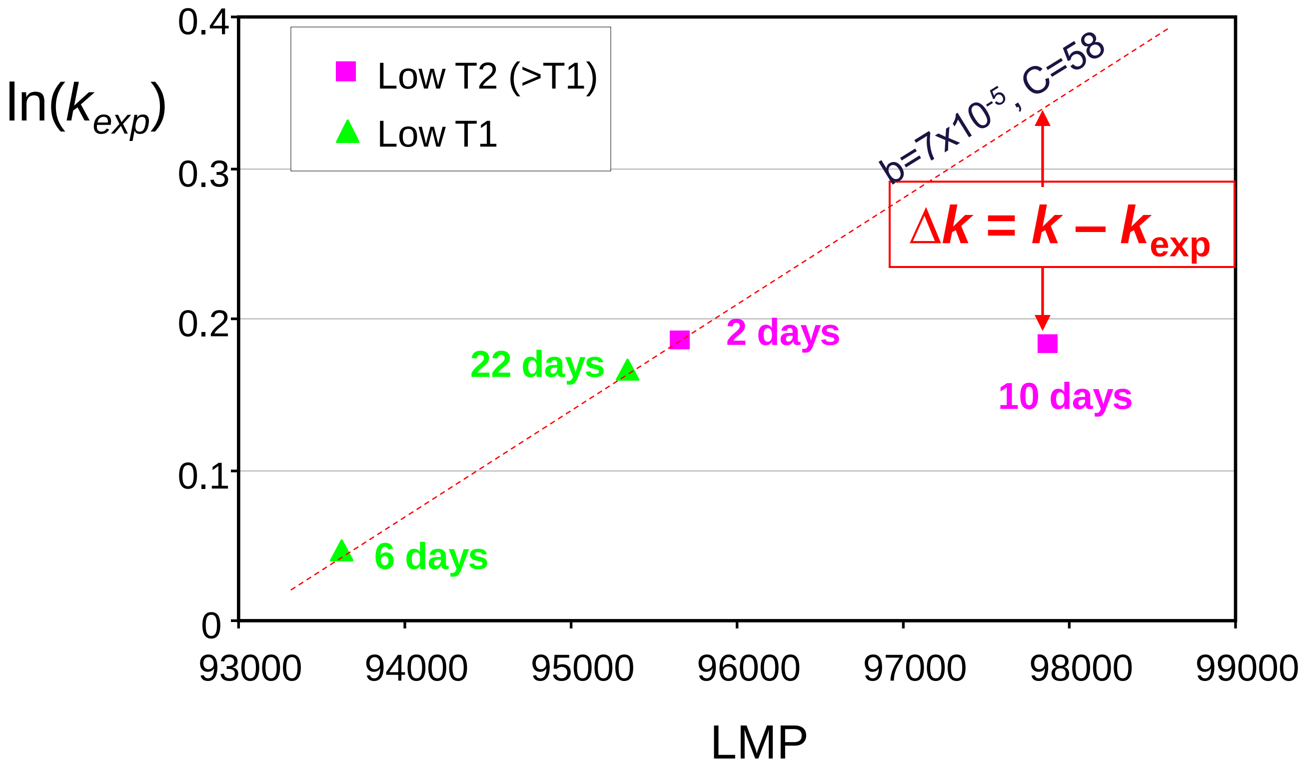
TBCs exposed at lower temperatures



T1, 6 days | T1, 22 days | T2, 2 days | T2, 10 days

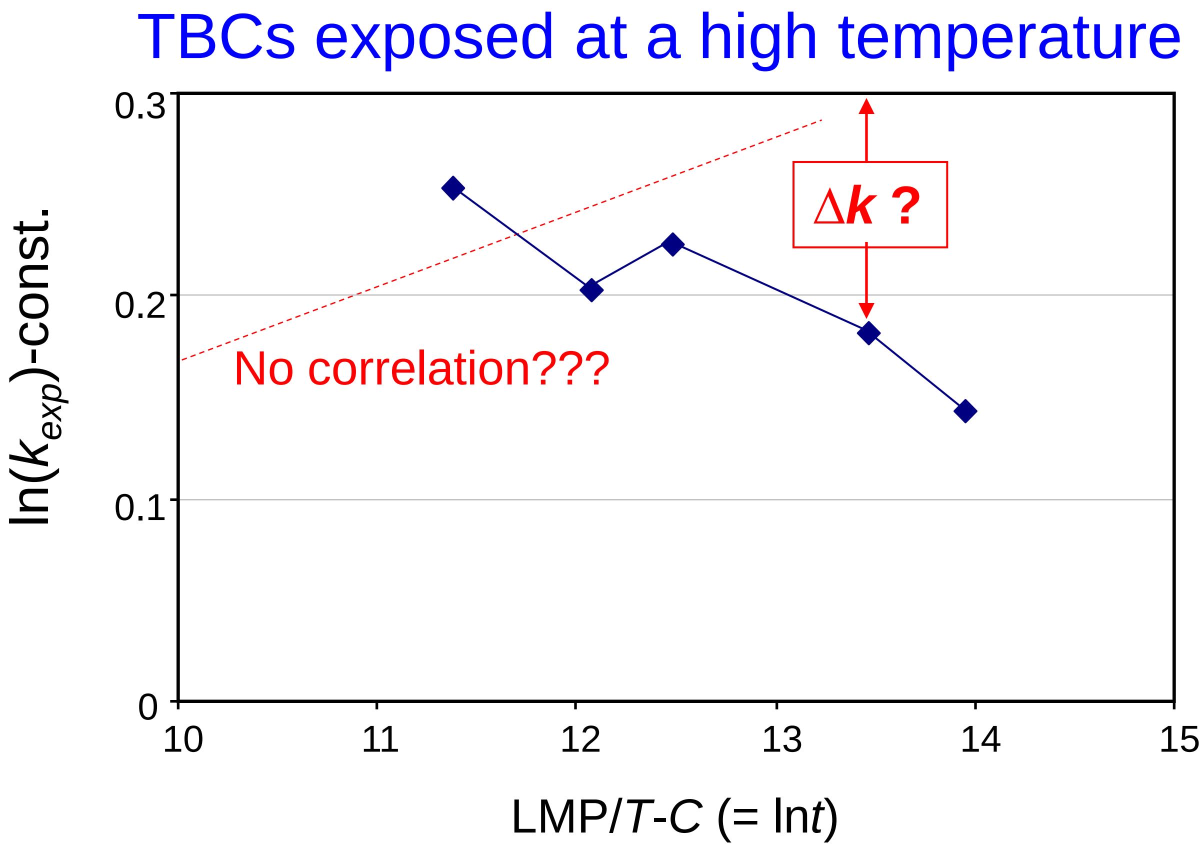
TBC Life Prediction Based on TBC Conductivity

TBCs exposed at lower temperatures



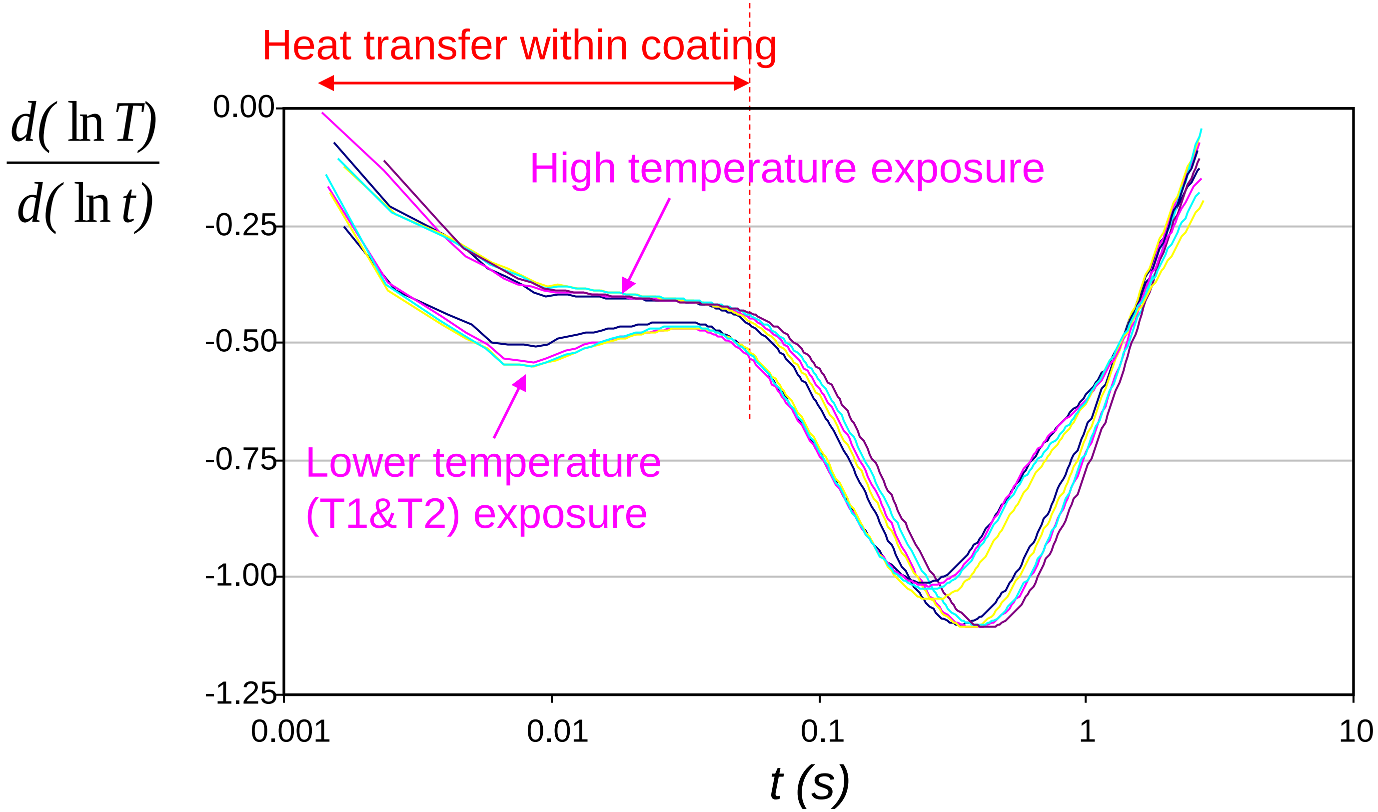
- TBC exposed at higher T2 for 10 days has some damage
- This is for illustration only because few samples (4) were used

TBC Life Prediction Based on TBC Conductivity



- No correlation:
  - All TBC have some damage?
  - Coating thickness varies between samples?
  - TBC conductivity is not constant along depth?

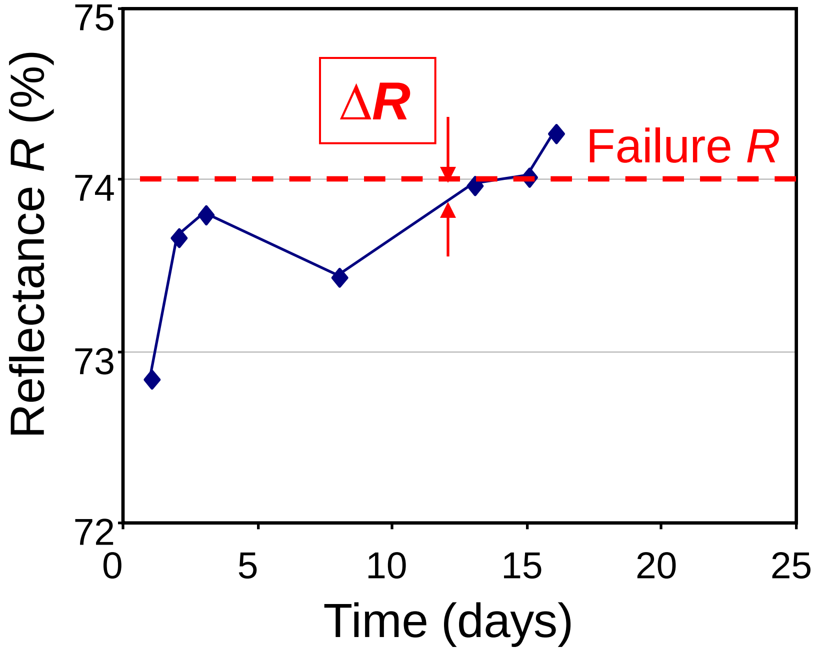
Thermal Imaging Data for All TBCs



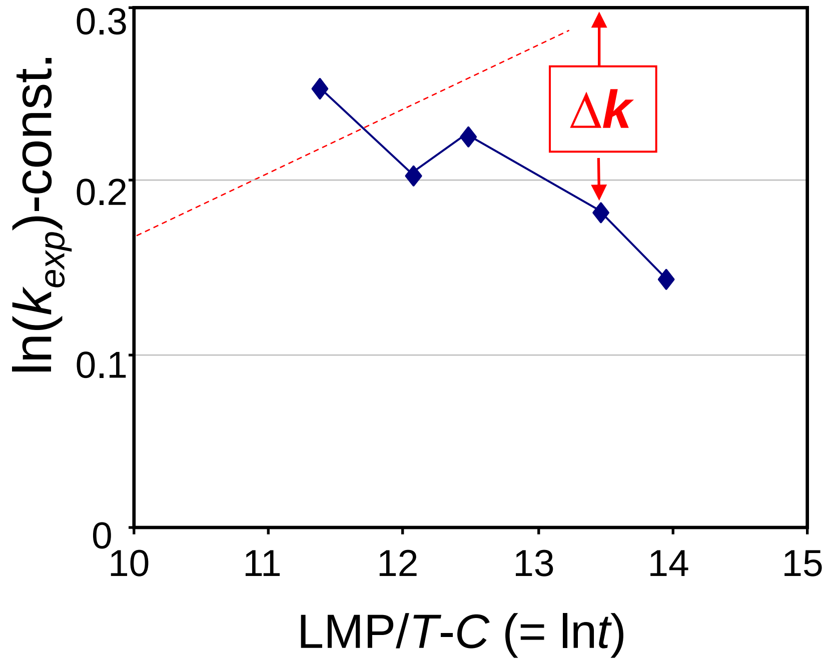
- TBC samples exposed at a high temperature are different:
  - Data suggesting a high conductivity at surface and low conductivity at interface; this effect was not accounted for by the conductivity measurement algorithm
  - Further study is needed

Comparison of NDEs for TBC Life Prediction

Mid-IR reflectance model



Thermal conductivity model



- Δ*R* decreases near failure → more difficult to detect
  - Failure *R* is a function of many parameters
- Δ*k* increases near failure → more sensitive (and easier to detect)
  - Failure Δ*k* also relates to some factors, but large data sets exist!

Summary

- Three NDE imaging methods were evaluated for TBC life prediction
  - Laser backscatter (optical)
    - Not sensitivity to TBC life; may need IR laser to improve sensitivity
  - Mid-IR reflectance (optical)
    - Good correlation to TBC life, although sensitivity is within a small range
    - Contamination, thickness limit, and failure level are remaining issues
  - Thermal multilayer analysis method (thermal)
    - TBC life prediction model is based on conductivity reduction due to interface cracking
    - Preliminary data showed good potential for TBC life prediction
    - Effective conductivity for TBCs with depth-dependent conductivity variation needs to be defined and measured

- Thermal TBC life prediction model could be more sensitive than optical because the "damage parameter" becomes larger in thermal (Δk) while smaller in optical (ΔR) when TBC is near failure

- NDE methods for TBC life prediction are well developed; further evaluation for TBCs with various exposure conditions is needed

Planned Future Efforts

- Continued evaluation of NDEs for TBC lifetime prediction
- Development of thermal multilayer analysis method:
  - For complex coatings: dual-layer, conductivity depth gradient
  - Investigate prediction accuracy due to secondary effects
- Development of thermal tomography method
  - Correlate NDE data with destructive examination results
  - Develop new high-resolution algorithm for data processing