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HEALTH MONITORING OF THERMAL BARRIER COATINGS BY MID-INFRARED REFLECTANCE

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ABSTRACT

Mid-infrared (MIR) reflectance is shown to be a powerful tool for monitoring the integrity of 8wt% yttria-stabilized zirconia (8YSZ) thermal barrier coatings (TBCs). Because of the translucent nature of plasma-sprayed 8YSZ TBCs, particularly at MIR wavelengths (3 to 5 μm), measured reflectance does not only originate from the TBC surface, but contains strong contributions from internal scattering within the coating as well as reflectance from the underlying TBC/substrate interface. Therefore, changes in MIR reflectance measurements can be used to monitor the progression of TBC delamination. In particular, MIR reflectance is shown to reproducibly track the progression of TBC delamination produced by repeated thermal cycling (to 1163°C) of plasma-sprayed 8YSZ TBCs on René N5 superalloy substrates. To understand the changes in MIR reflectance with the progression of a delamination crack network, a four-flux scattering model is used to predict the increase in MIR reflectance produced by the introduction of these cracks.

INTRODUCTION

While thermal barrier coatings (TBCs) provide thermal protection for turbine engine components, the risk of TBC spallation severely restricts the use of TBCs by either forcing extreme safety margins to guide TBC replacement or by limiting TBC application to engine temperatures at which an unprotected component can still survive. This situation has produced a growing need for a reliable and routine method for nondestructive TBC health monitoring. Because TBC failure results from crack/flaw propagation near the TBC/bond coat interface, any useful health monitoring tool must be able to monitor damage evolution beneath the overlying TBC. One approach is to take advantage of the TBC translucency, as demonstrated by the successful application of piezospectroscopy (Cr^{3+} luminescence) to monitor the stress state of the thermally grown oxide (TGO) that forms beneath the TBC.[1-3] Unfortunately, the TGO stress state does not provide a good indication of remaining TBC life because the indication of impending TBC failure by TGO stress relaxation tends to occur immediately preceding failure and therefore does not present sufficient warning. In this paper, we present a new approach employing mid-infrared (MIR) reflectance as a diagnostic tool for evaluating the fraction of TBC lifetime remaining by correlating the MIR reflectance with the progress of the buried TBC delamination crack network that ultimately produces TBC failure. This approach offers the advantage of working at wavelengths where the TBC has much greater transmittance than for visible light,[4] and therefore can be applied to highly attenuating (compared to EB-PVD) plasma-sprayed TBCs that are difficult to probe by piezospectroscopy.[2] A hemispherical transmittance measurement (Fig. 1) for a freestanding plasma-sprayed 8wt% yttria-stabilized zirconia (8YSZ) TBC clearly shows that

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Motivation

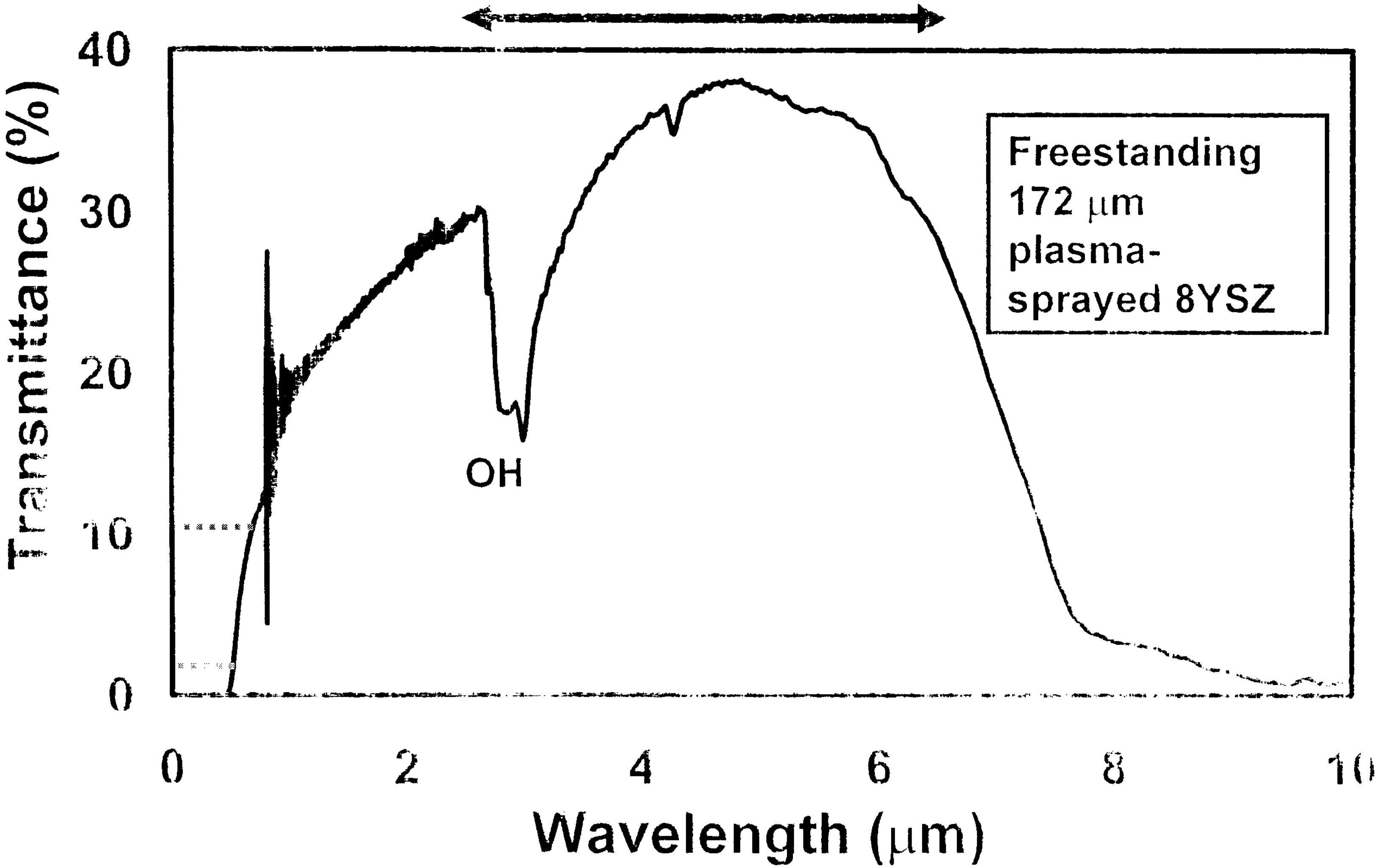
- Risk of TBC failure restricts application of TBCs
  - Requires extreme safety margins for TBC replacement

    or
  - Limited to temperatures at which unprotected component can survive
- Reliable TBC health monitoring will overcome these restrictions.

Background

- Any TBC health monitoring tool (optical, electrical, acoustic) must be able to monitor *buried* damage evolution.
  - Optical techniques most amenable to non-contact monitoring.
- Piezospectroscopy (Cr^{3+} luminescence) has been demonstrated to monitor stress state in thermally grown oxide (TGO) beneath TBC. (U. California—Santa Barbara, U. Connecticut)
  - Very difficult to obtain luminescence signal through highly attenuating plasma-sprayed TBCs.
  - Measured TGO stress relaxation occurs immediately preceding or simultaneous with TBC failure; therefore does not provide early warning.
- Mid-infrared (MIR) reflectance examined for advantages as TBC health monitoring tool.
  - Uses wavelengths where TBC has maximum transmittance.
  - Potentially more sensitive to earlier stages of TBC failure.

Maximum Transmittance at MIR Wavelengths

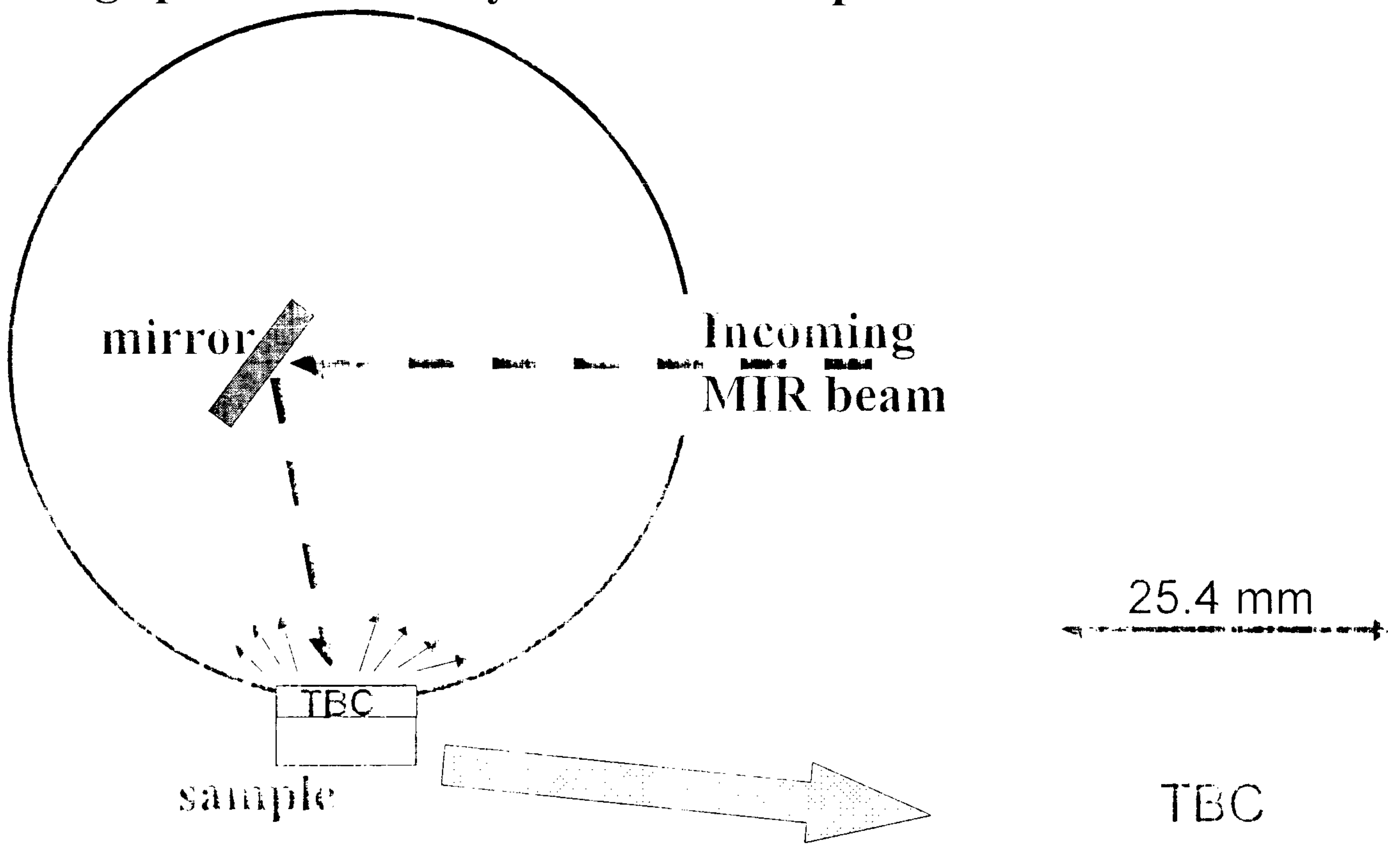


Experimental Approach

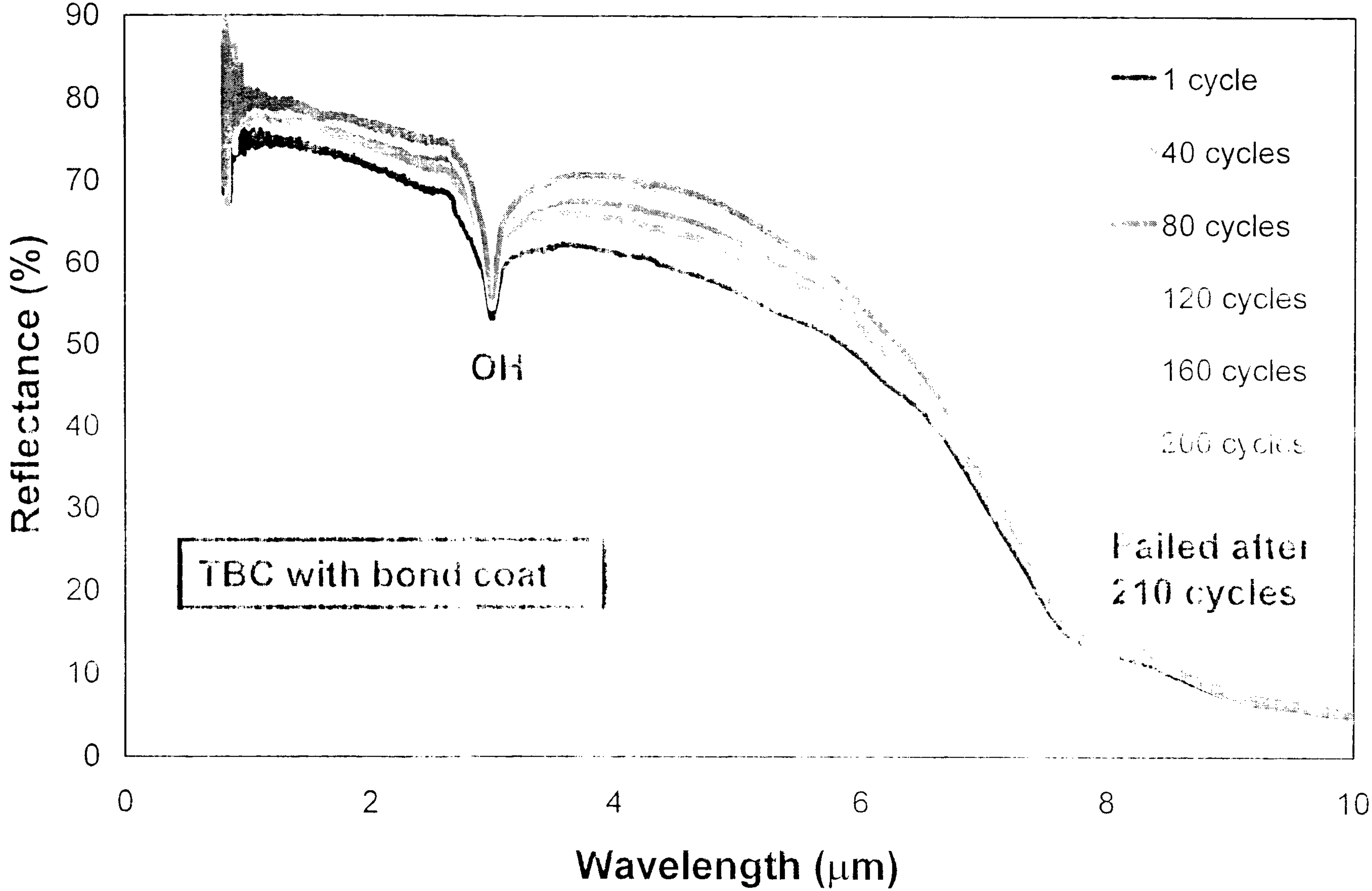
- Two types of TBC specimens:
  - with bond coat (4)
    - 200 μm atmospheric plasma-sprayed 8YSZ
    - 120 μm low-pressure plasma-sprayed NiCrAlY bond coat
    - René N5 superalloy substrate
  - no bond coat (3)
    - 200 μm atmospheric plasma-sprayed 8YSZ
    - René N5 superalloy substrate
- Monitor changes in MIR hemispherical reflectance with interrupted furnace cycling.
  - 1 cycle = 45 min @1163°C + 15 min cooling to 120°C in air
  - Measure MIR reflectance after 1st cycle & every 10th cycle.
  - Inspect for TBC failure (>20% delamination)

Directional Hemispherical Reflectance Measurements

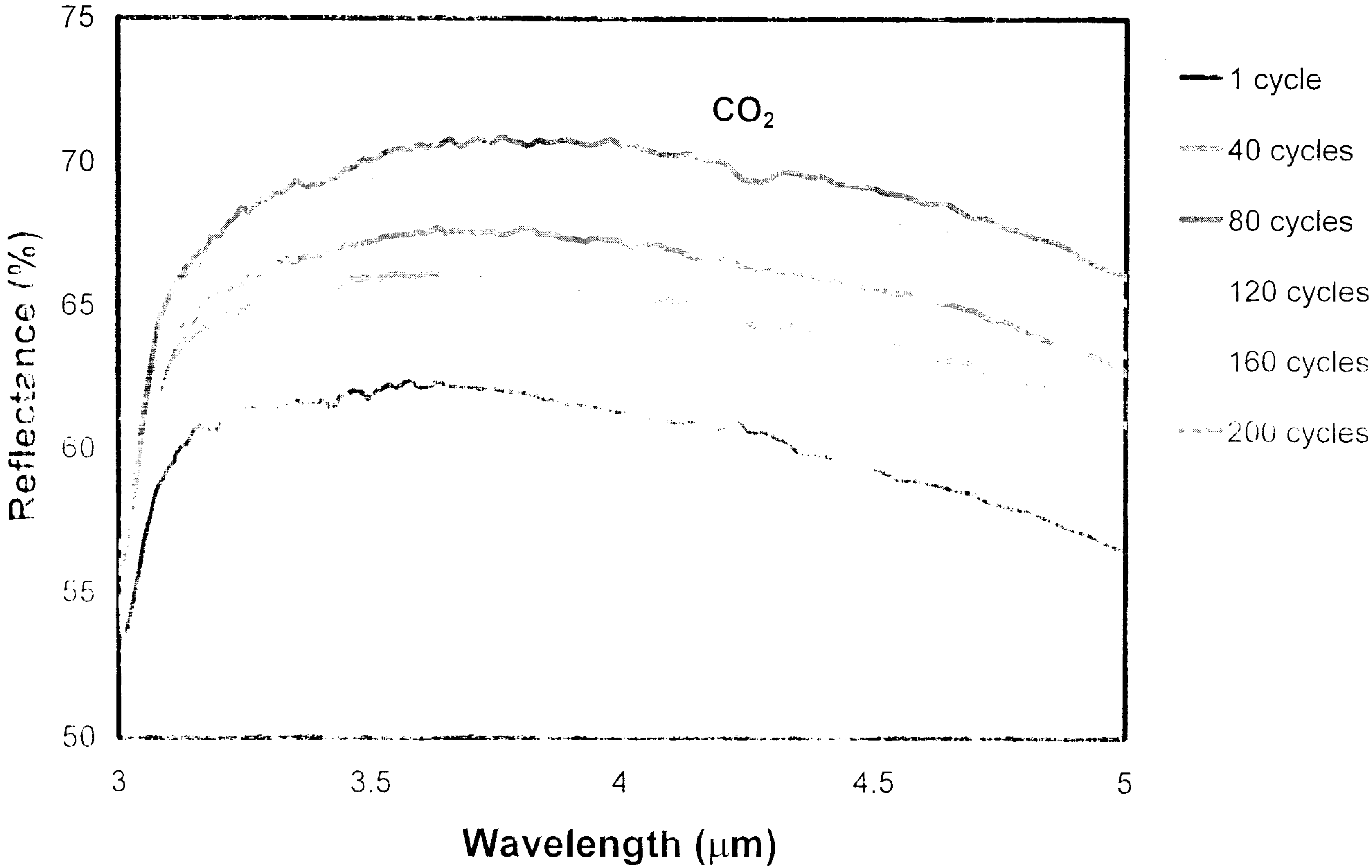
integrating sphere accessory inside FTIR spectrometer

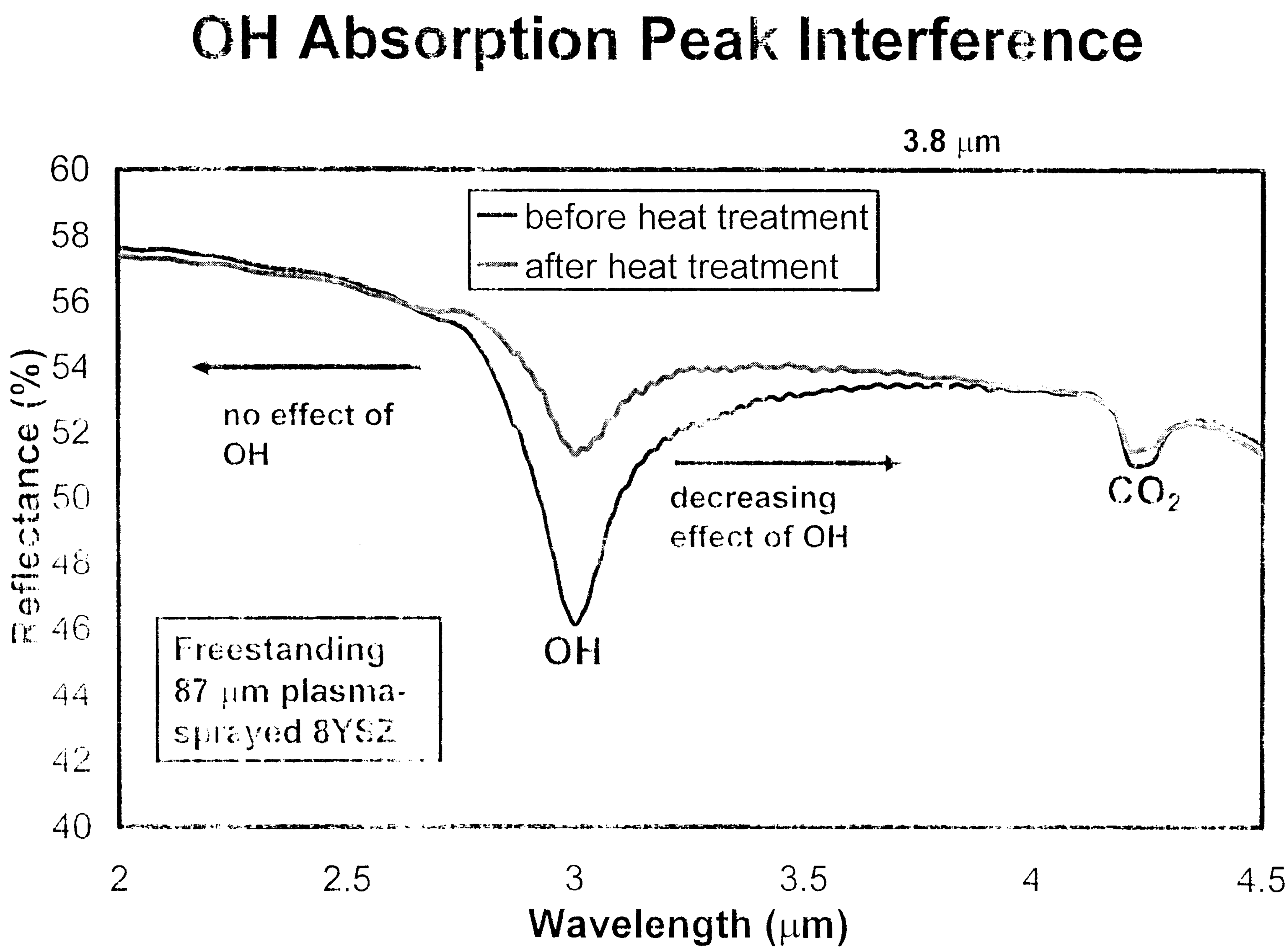


Effect of Furnace Cycling on Hemispherical Reflectance



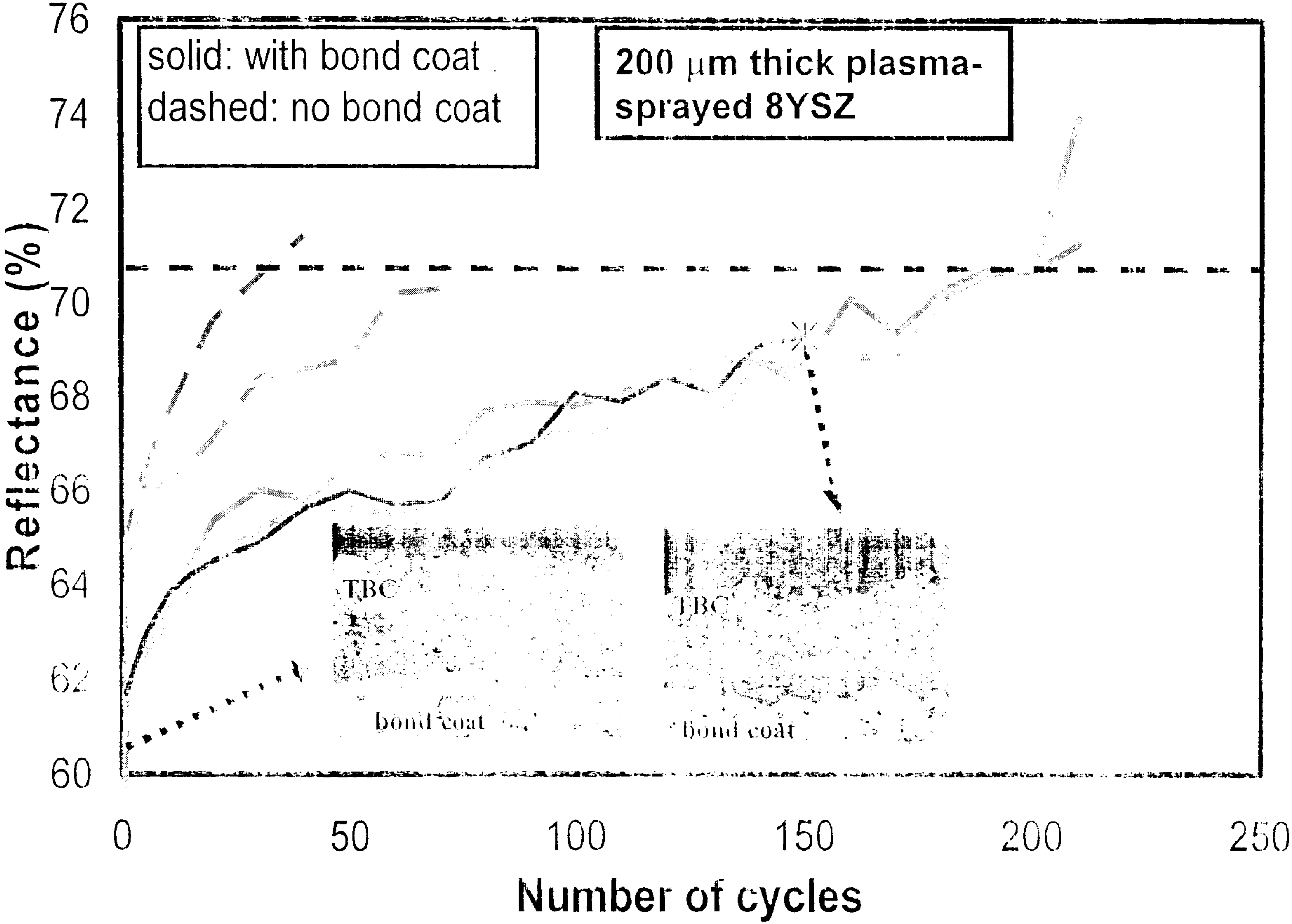
Effect of Furnace Cycling on Hemispherical Reflectance (expanded scale)





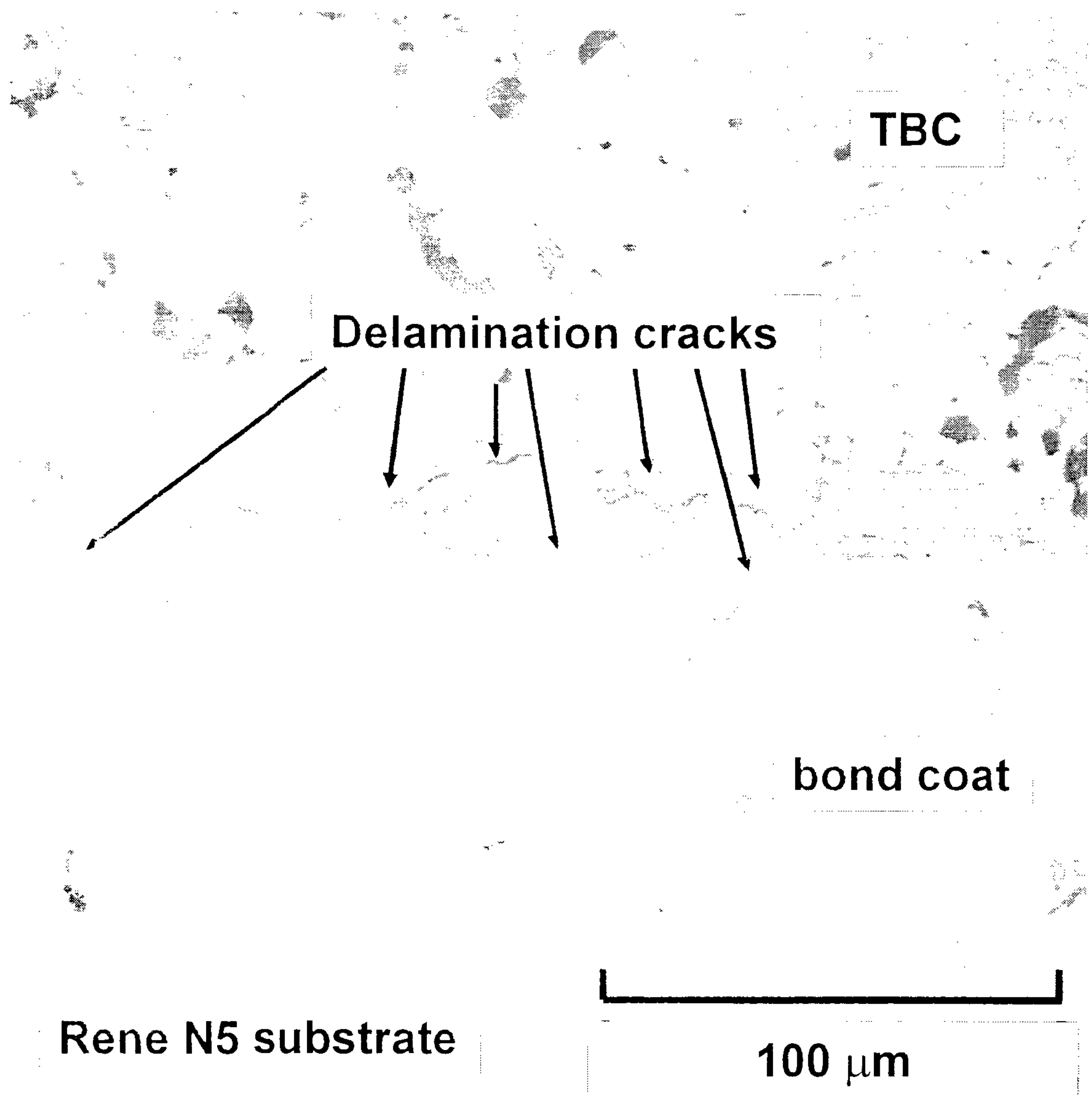
OH Absorption Peak Interference
3.8 μm
before heat treatment
after heat treatment
no effect of OH
decreasing effect of OH
OH
CO2
Freestanding 87 μm plasma-sprayed 8YSZ
Reflectance (%)
60
58
56
54
52
50
48
46
44
42
40
2
2.5
3
3.5
4
4.5
Wavelength (μm)

Hemispherical Reflectance (λ=3.8 μm) Monitors Progress of TBC Delamination

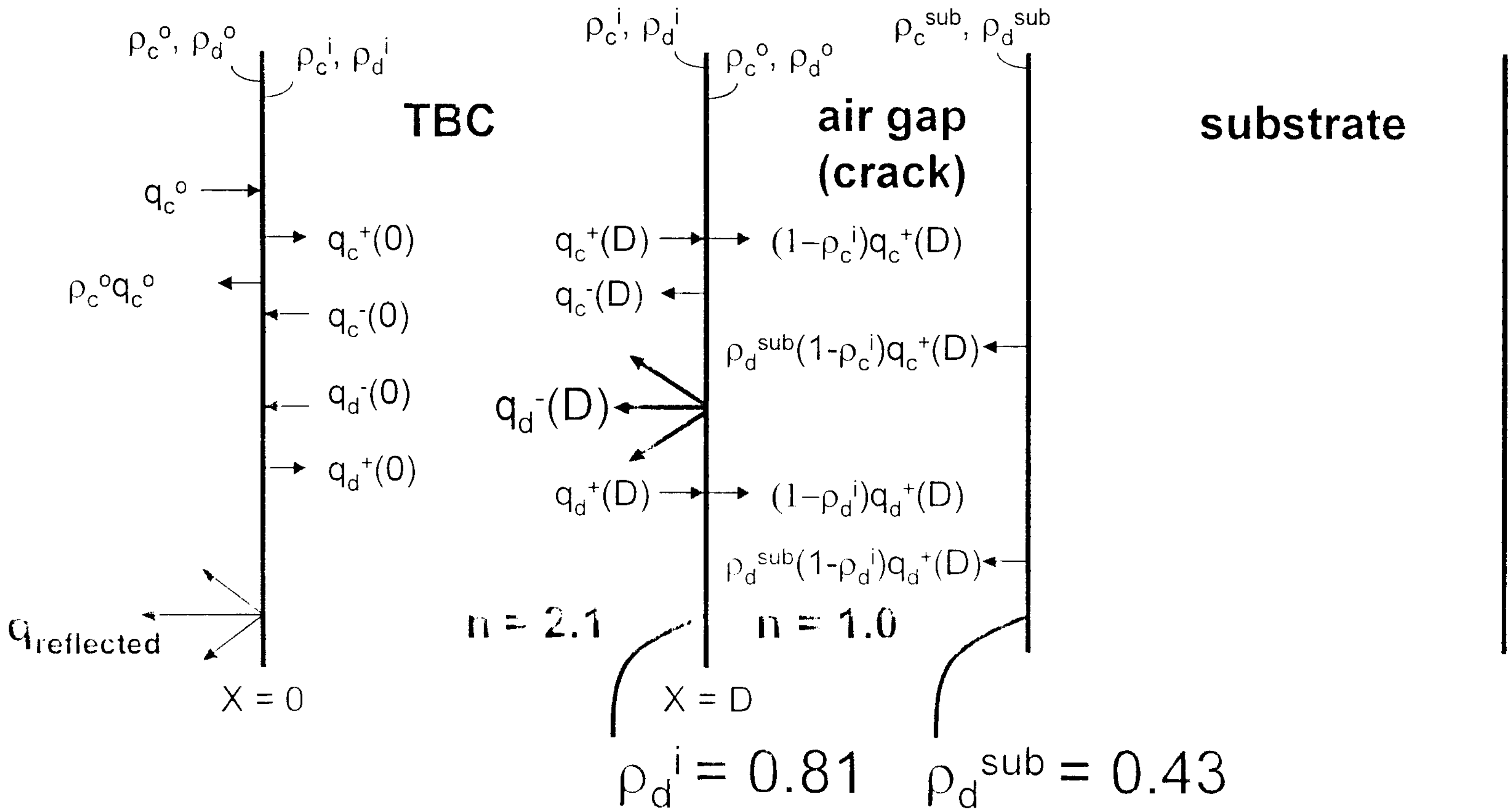


Delamination crack network formed after 150 cycles

Gradual progression allows effective health monitoring



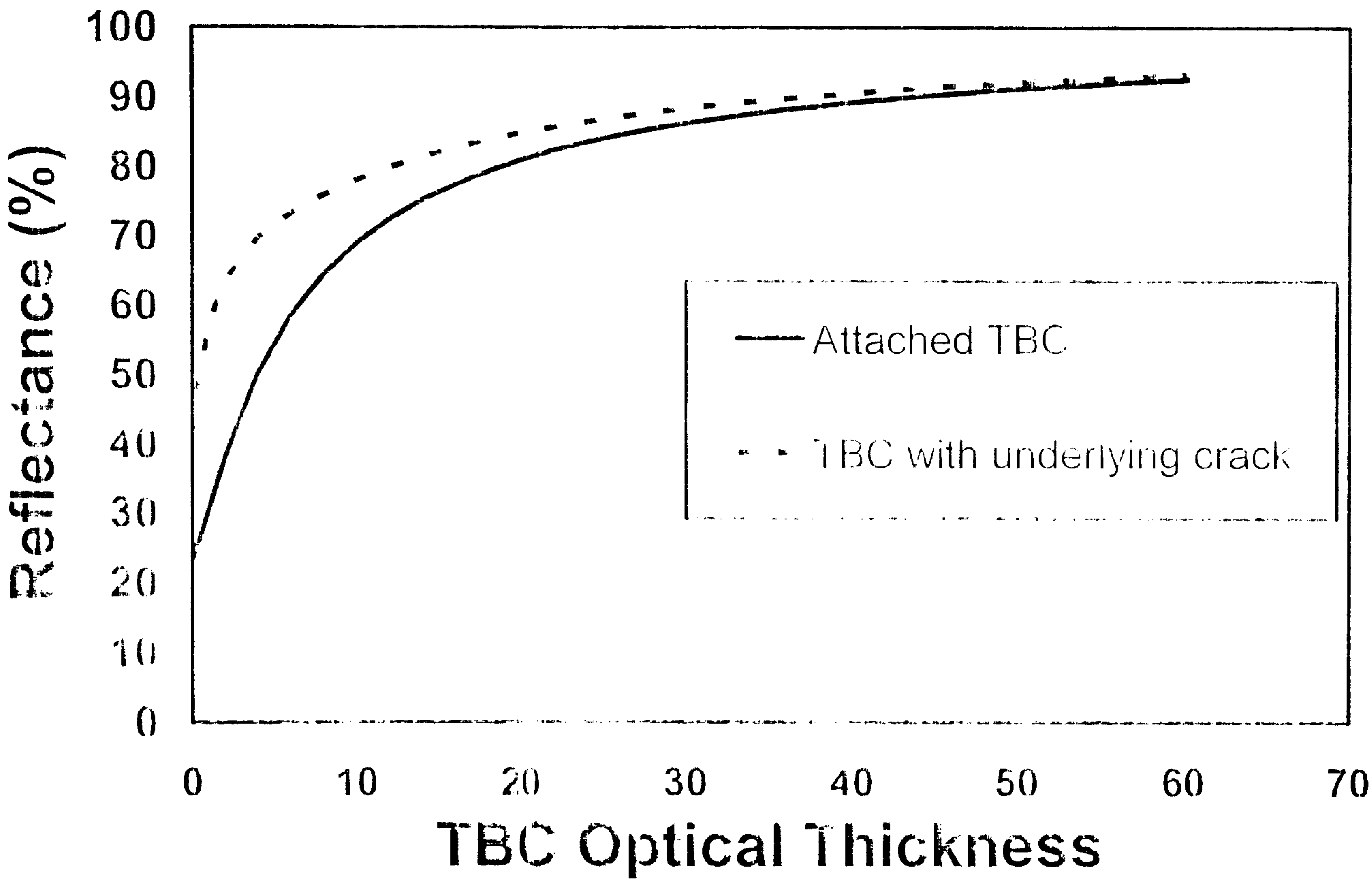
4-Flux (Zero Absorption) Model for Normal Hemispherical Reflectance TBC with underlying crack



Crack introduces high internal reflection due to index of refraction change across TBC/crack interface.

$$q_{reflected} = \rho_c^o q_c^o + (1-\rho_c^i)q_c^-(0) + (1-\rho_d^i)q_d^-(0)$$

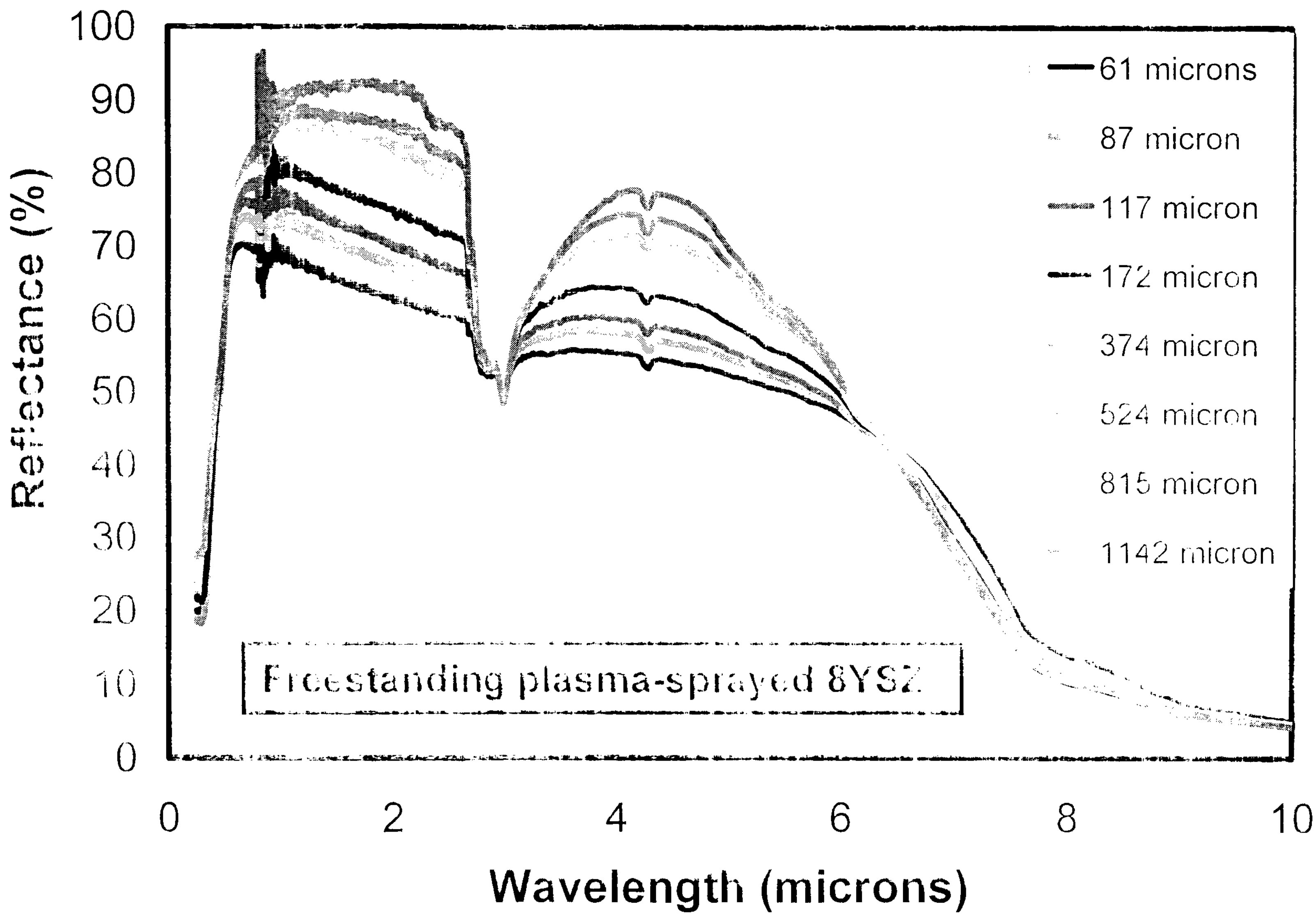
Predicted Effect of Crack on Hemispherical Reflectance
(based on zero-absorption four-flux model)



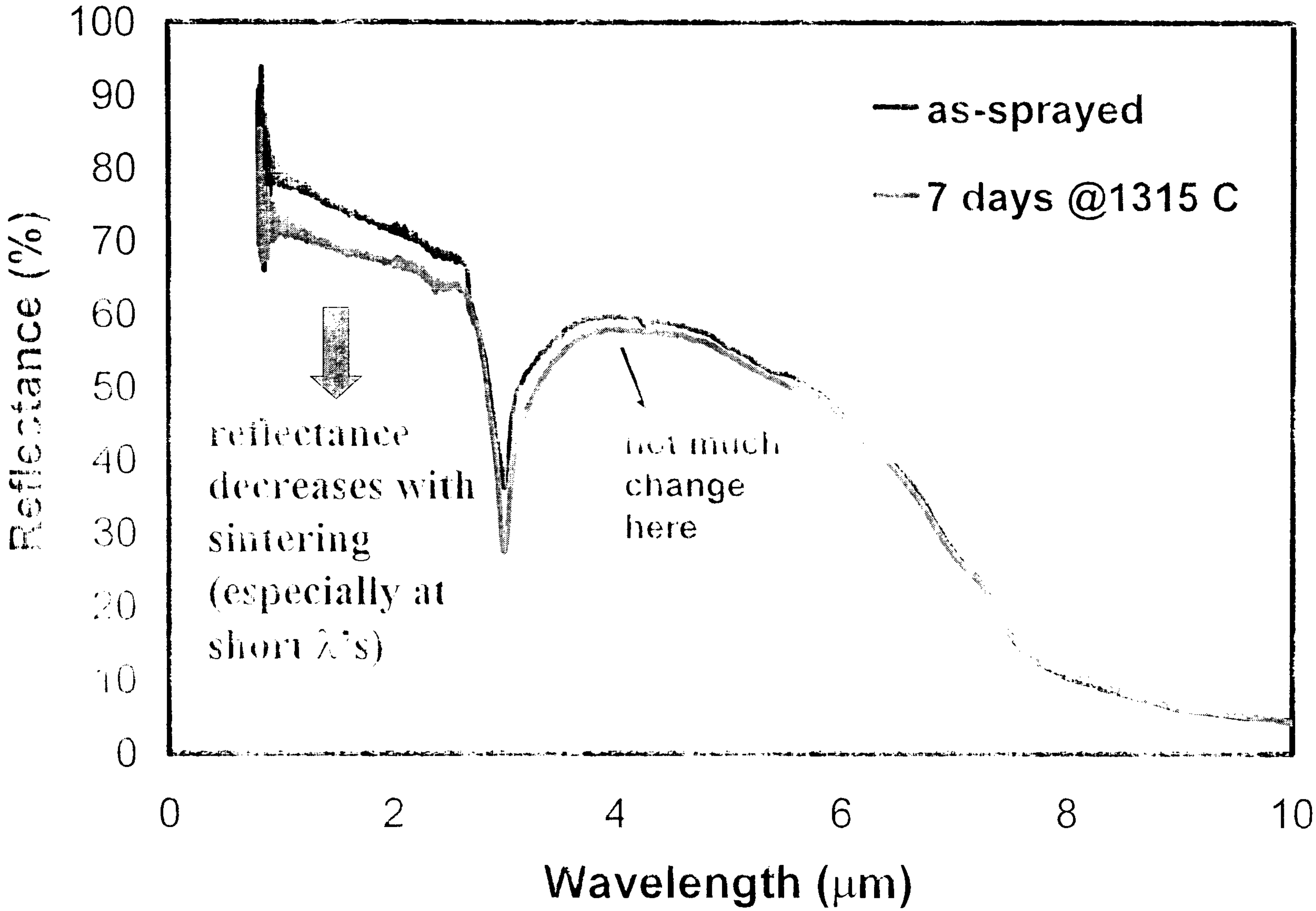
Competing Influences on Hemispherical Reflectance

- OH content in TBC
- TBC thickness variation
- TBC sintering
- Thermally grown oxide (TGO) growth

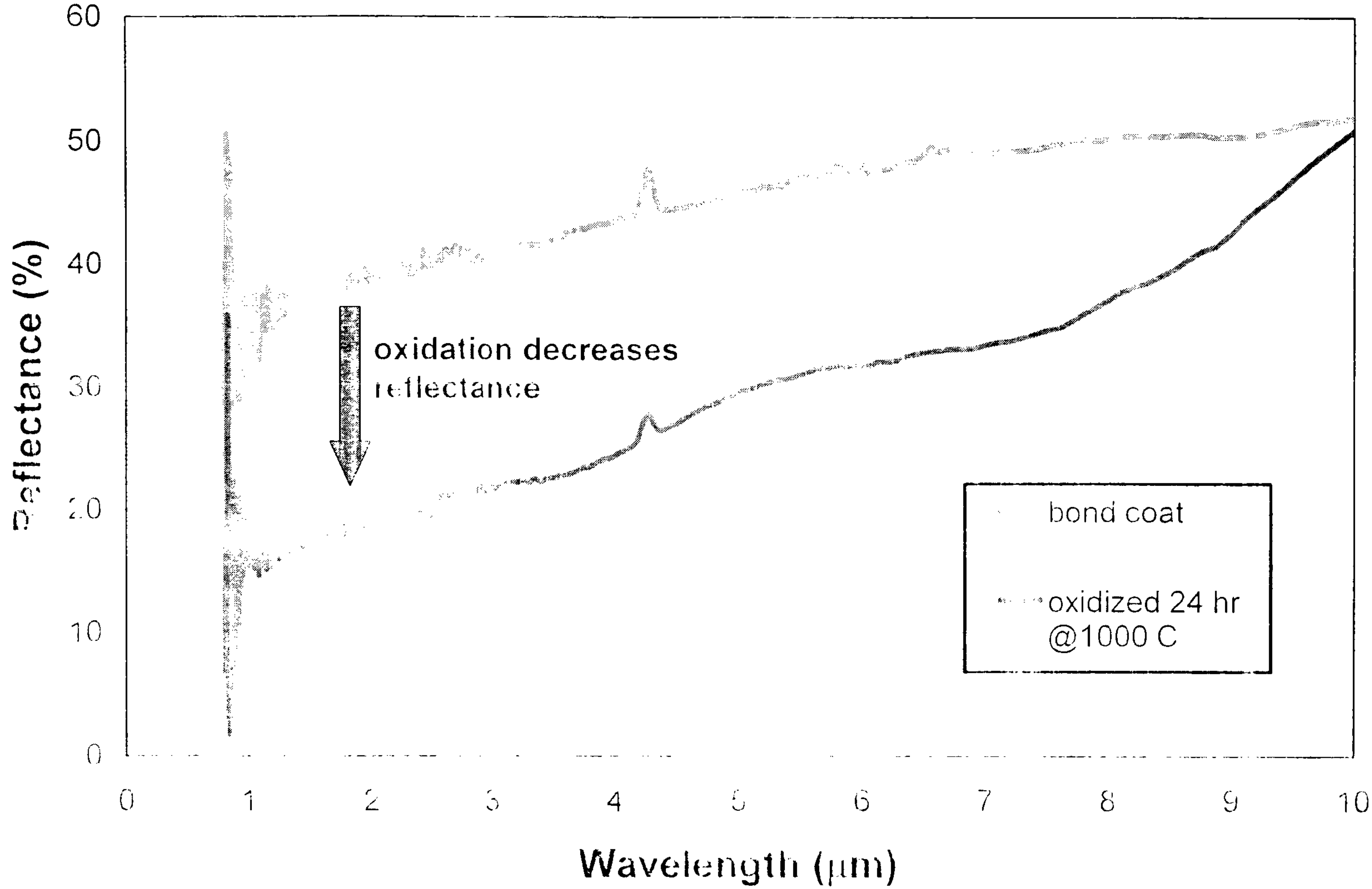
Hemispherical Reflectance Increases with TBC Thickness



Sintering Decreases Hemispherical Reflectance
160-μm-thick freestanding plasma-sprayed 8YSZ



Effect of Thermally Grown Oxide (TGO) on Hemispherical Reflectance



- TGO growth on bare substrate decreases reflectance.
- TGO growth beneath TBC requires further investigation.

Summary of Influences on MIR Hemispherical Reflectance

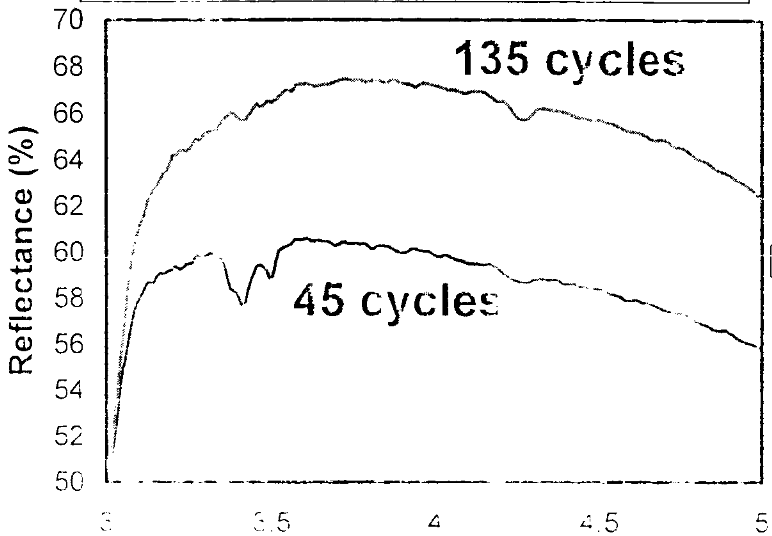
- Increases Reflectance
  - **Progression of delamination crack network**
  - Decrease in OH content (can select wavelengths where effect is minimized)
- Decreases Reflectance
  - Erosion (decrease in TBC thickness)
  - Sintering (preferentially affects shorter wavelengths)
- Requires Further Investigation
  - Effect of buried TGO growth (change in substrate reflectance)

- Sintering & erosion are nonfactors & OH effect is minimized in this study, but need to be considered under less controlled conditions.
  - Competing influences have distinguishing spectral effect "signatures"

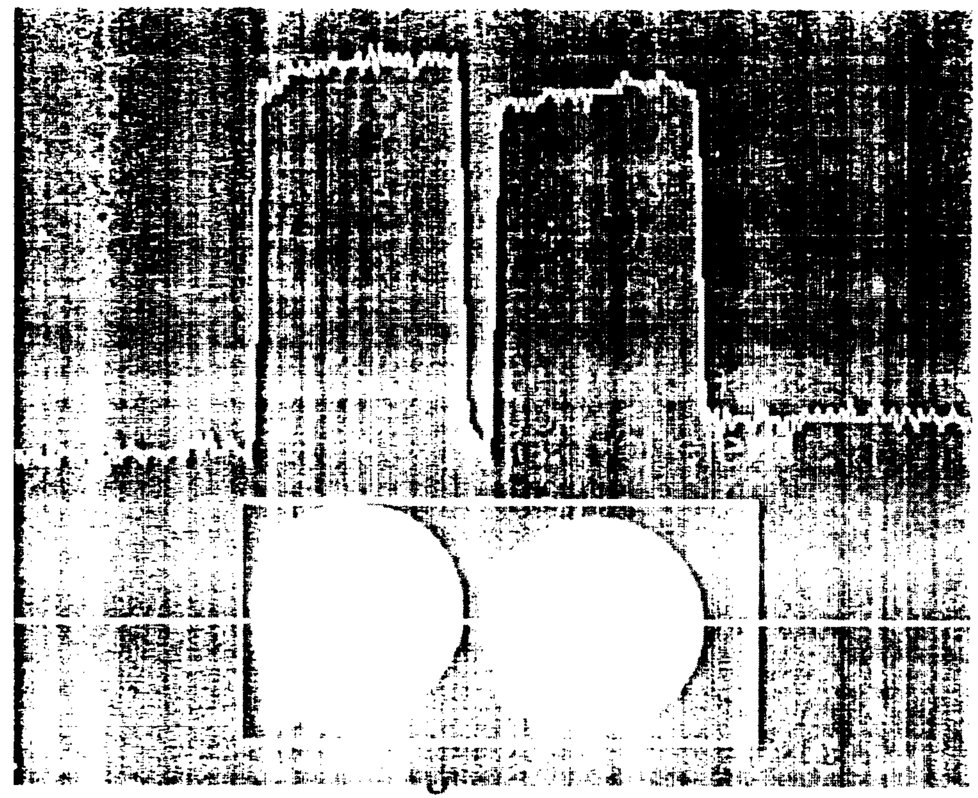
MIR Reflectance Imaging Provides Practical Inspection Capability

(provided by Rich Martin, Cleveland State University)

Hemispherical reflectance



MIR line scans



135 cycles 45 cycles

Furnace cycles to 1163°C

- These are unoptimized, quick & dirty images.
- Imaging provides localized flaw detection capability.
- Visual inspection by MIR reflectance imaging extends technique from lab to practical health-monitoring tool.

Conclusions

- MIR reflectance provides promising approach for TBC health monitoring.
  - MIR wavelengths successfully probe through highly attenuating plasma-sprayed TBCs.
  - MIR reflectance is sensitive to early stages of TBC failure.
  - Gradual progression of delamination crack network allows early warning.
  - Competing influences on MIR reflectance have distinguishing spectral effects.
  - Visual inspection by MIR reflectance imaging will extend technique from lab to practical health monitoring tool.

Acknowledgments

- Chuck Barrett – furnace cycling
- George Leissler & Sandy Leissler – spraying TBC specimens
- Rich Martin – MIR reflectance images