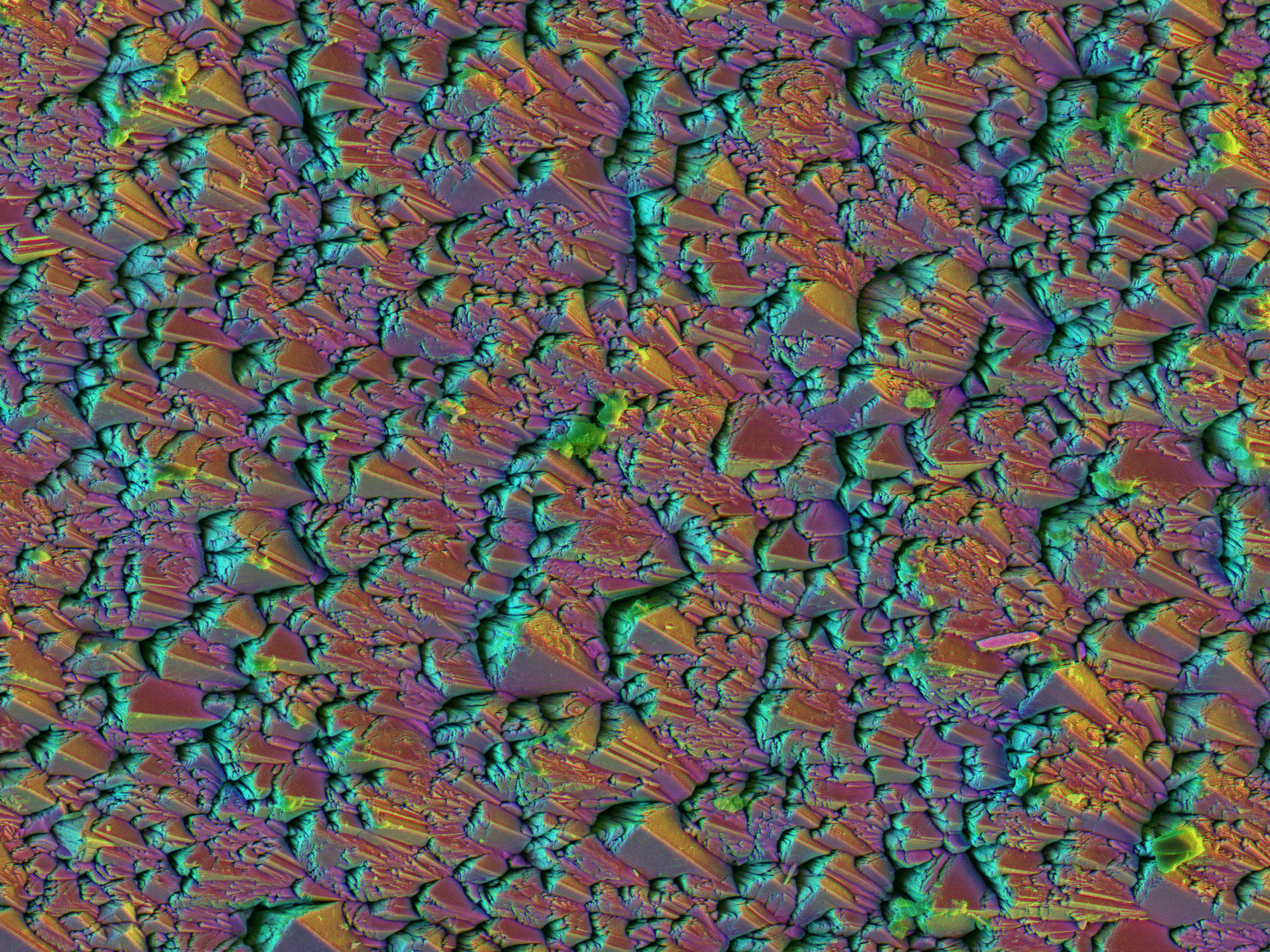


HARVARD
School of Engineering
and Applied Sciences

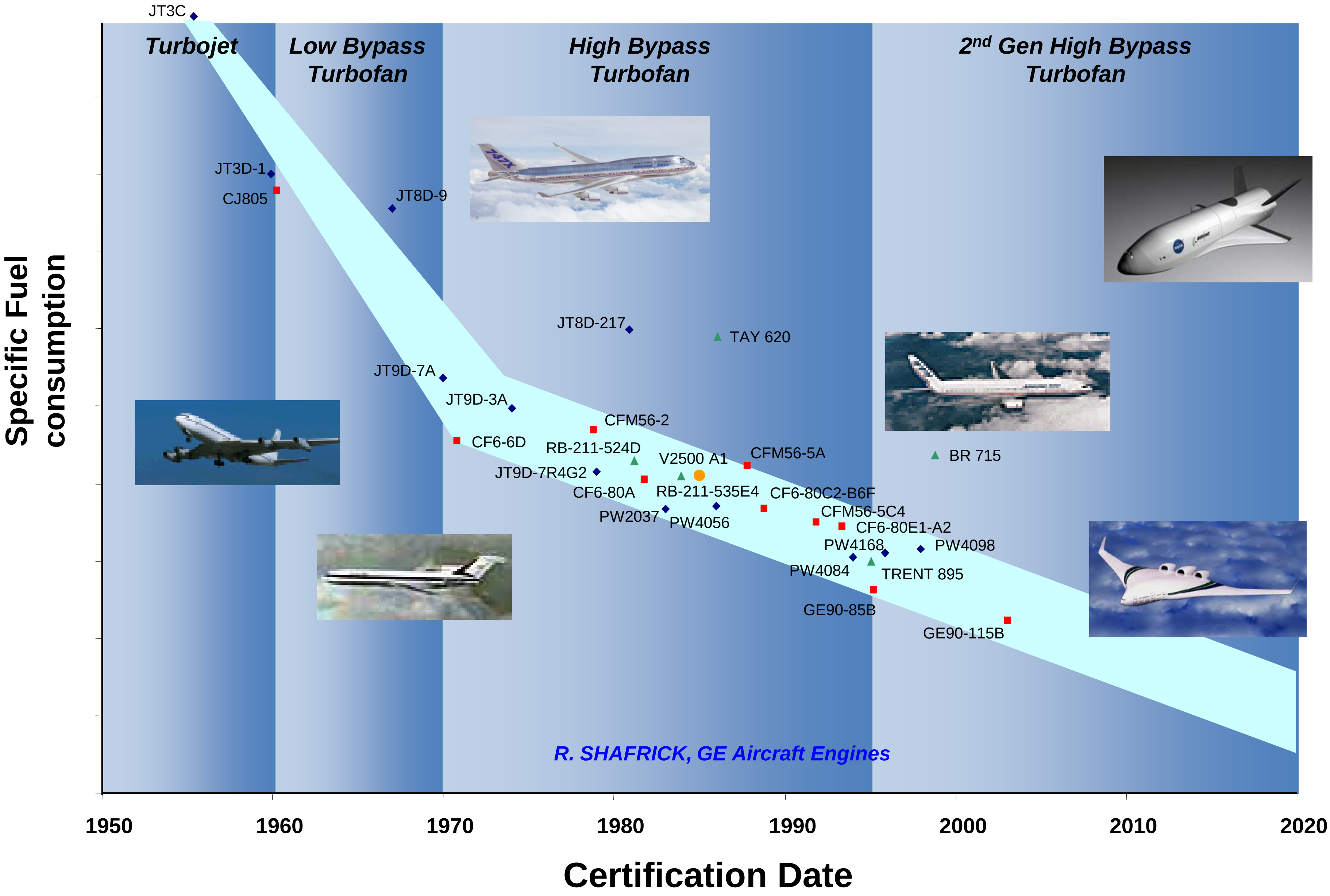
Materials Discovery and Applications Group
Professor David R. Clarke
clarke@seas.harvard.edu

Thermal Barrier Coatings for Gas Turbines

Institute of Advanced Studies,
Hong Kong University of Science and Technology

Hong Kong Institute of Engineers,   January 2015

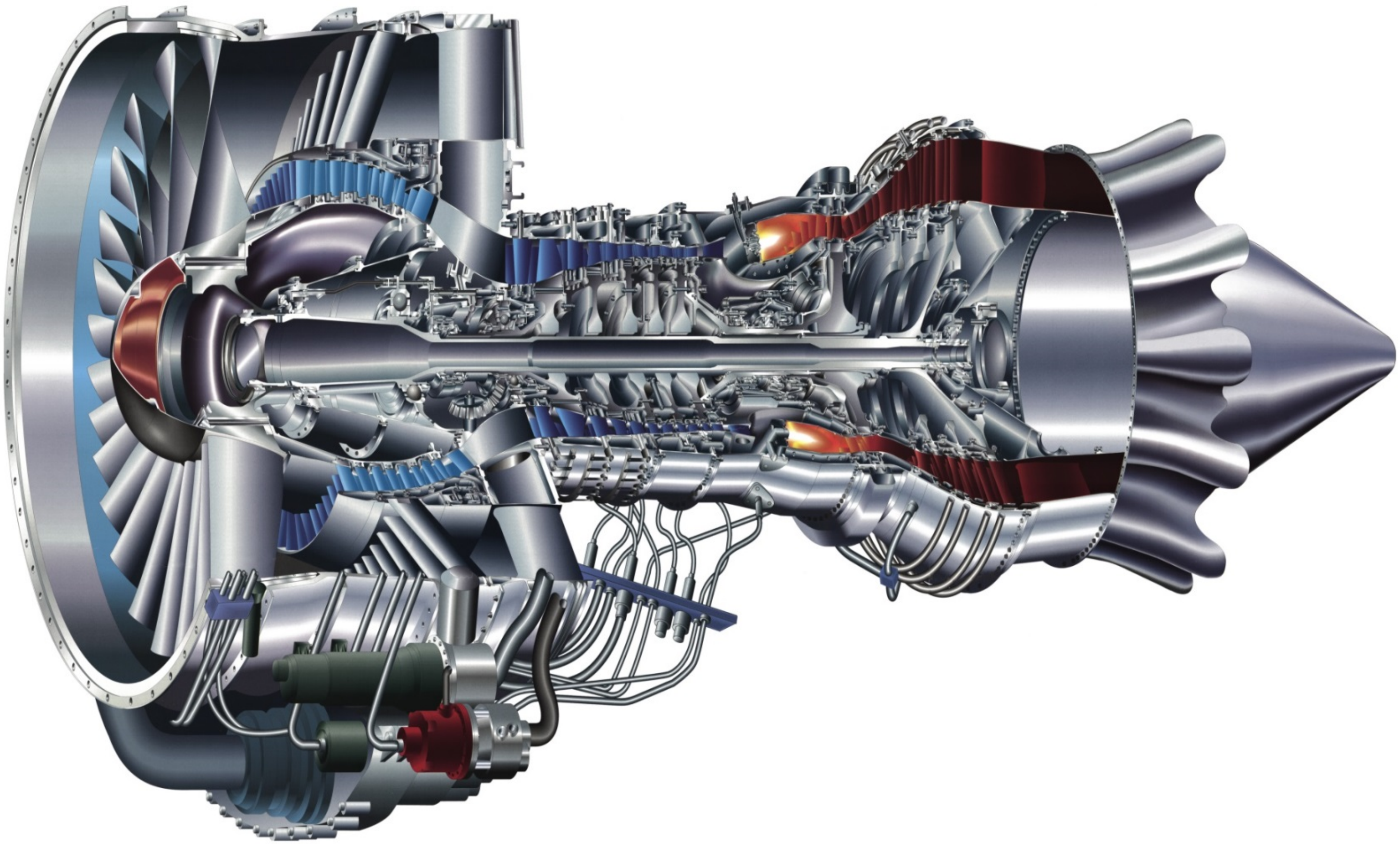
Fuel Efficiency in the Aeroturbine Industry



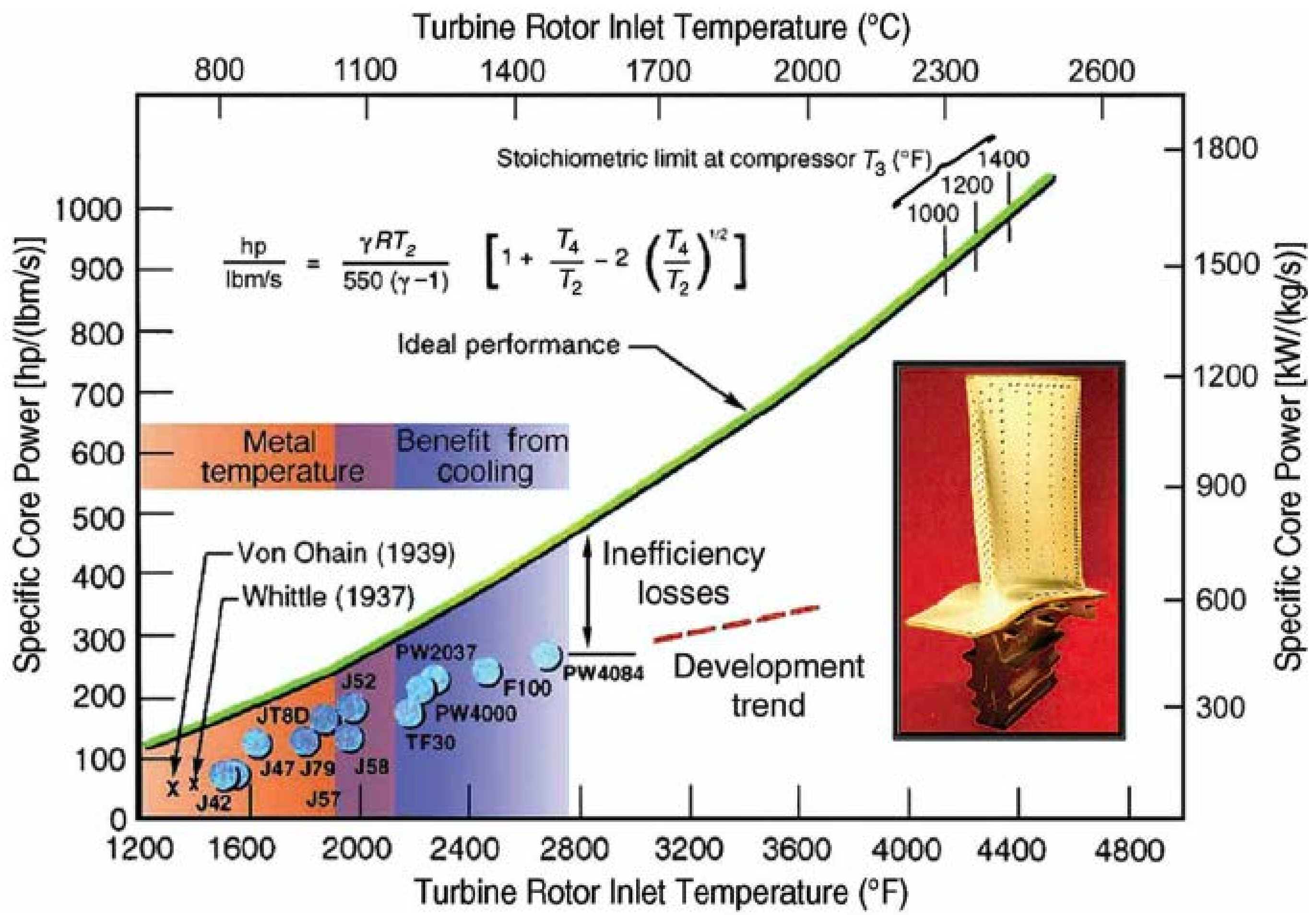
R. SHAFRICK, GE Aircraft Engines


ROLLS
RR
ROYCE

High By-pass Aeroturbine

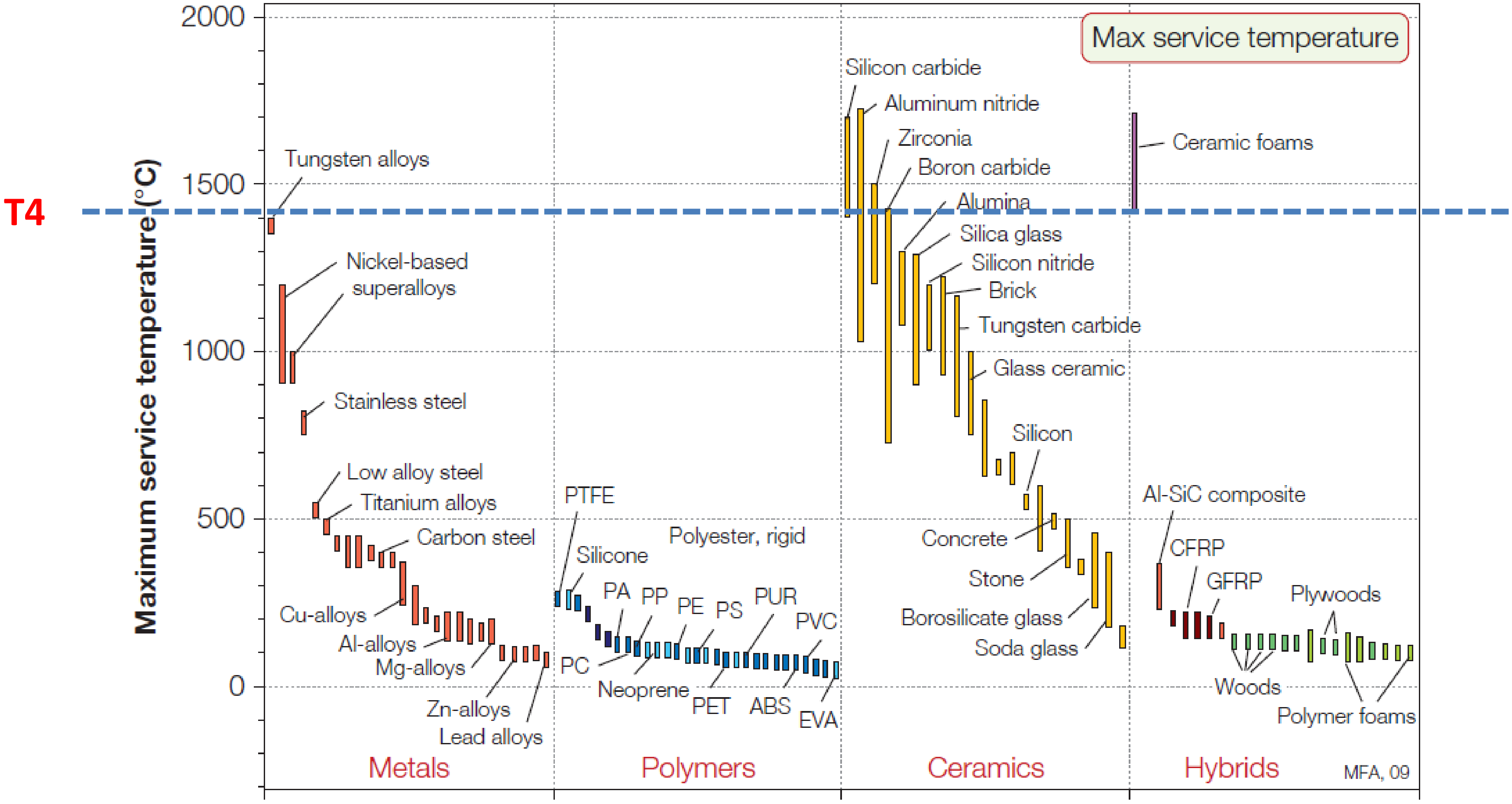


Output Power Depends on Rotor Inlet (T4) Temperature



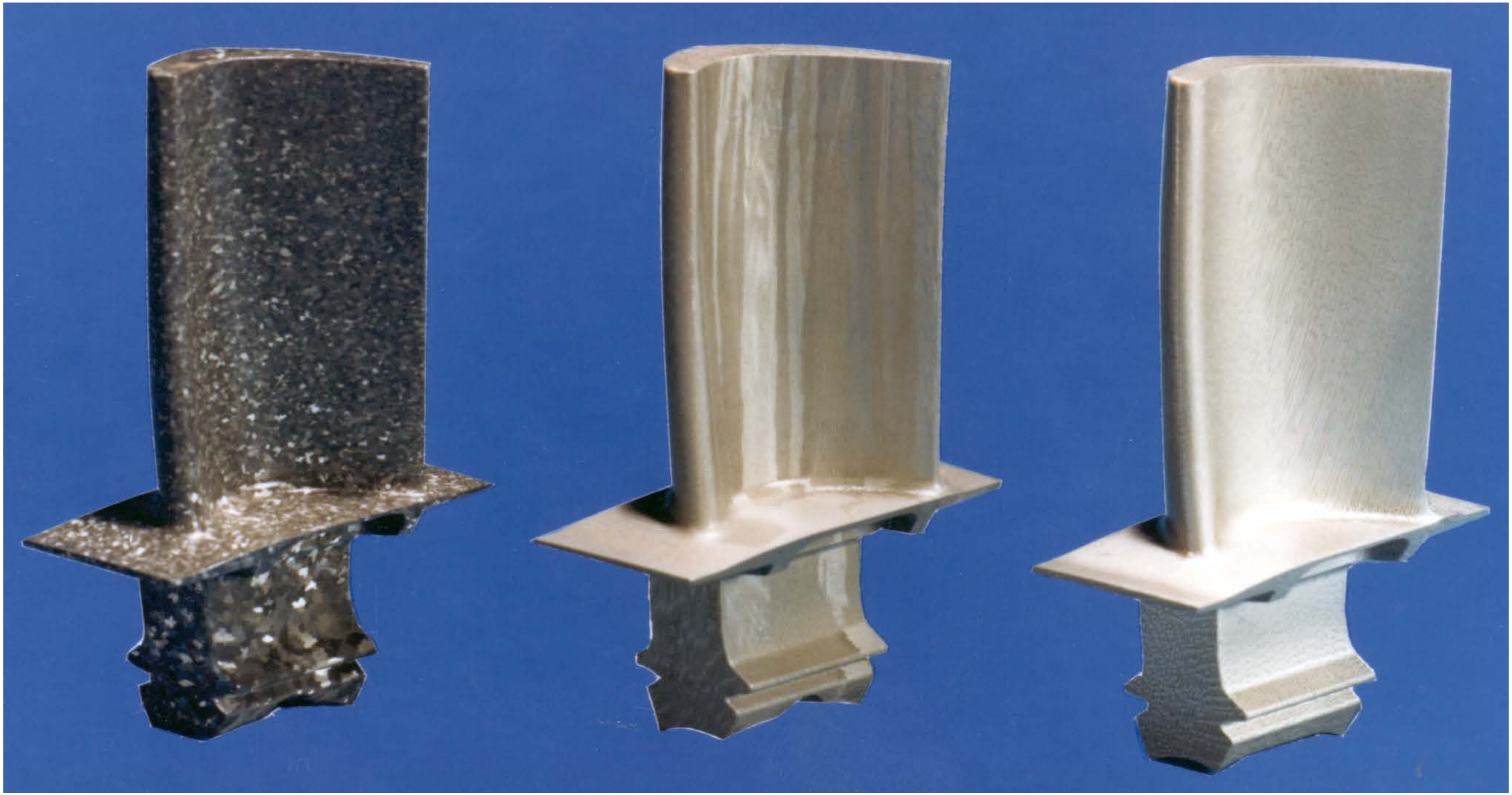
Dimiduk and Perepezko, MRS Bull 639 2003

Maximum Service Temperatures of Materials



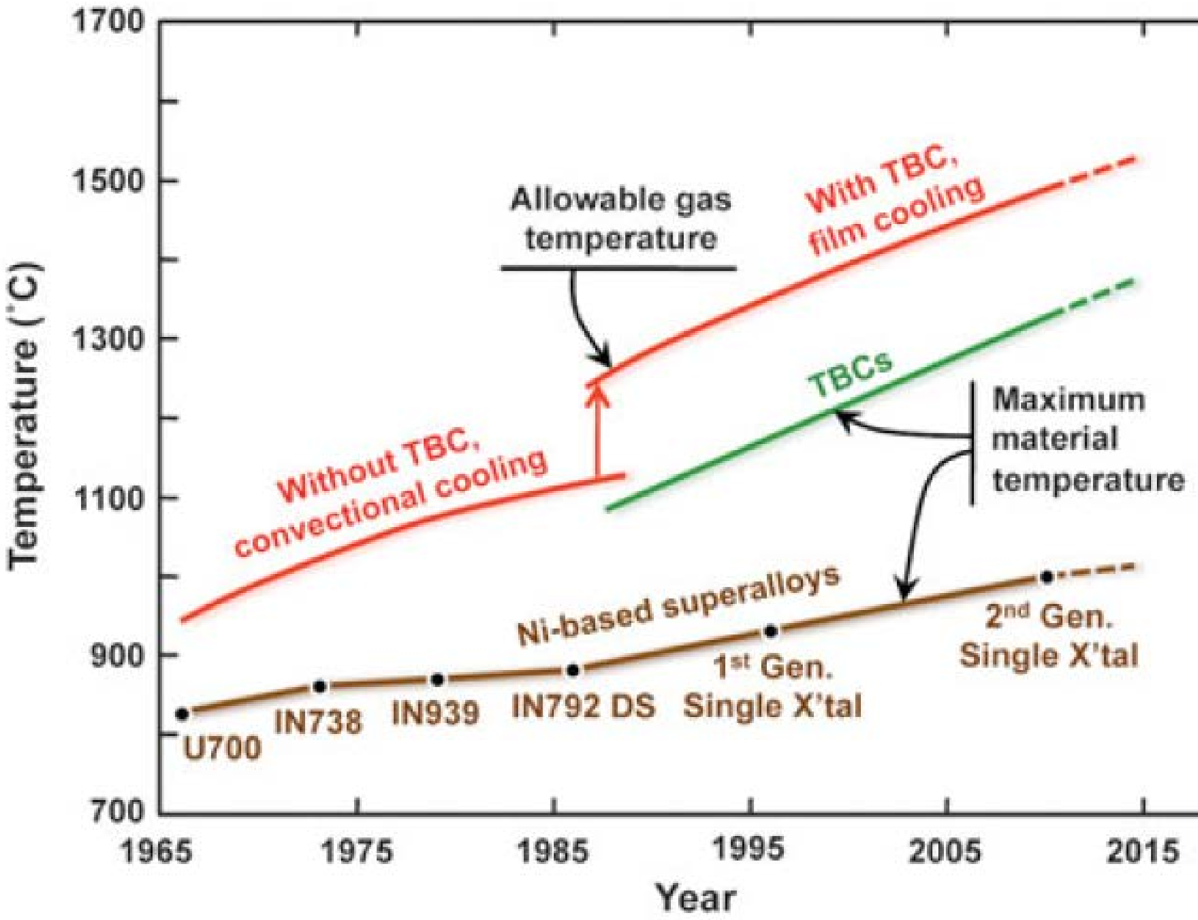
Current T4 temperature exceeds melting temperature of the superalloys !

Superalloy Turbine Airfoils



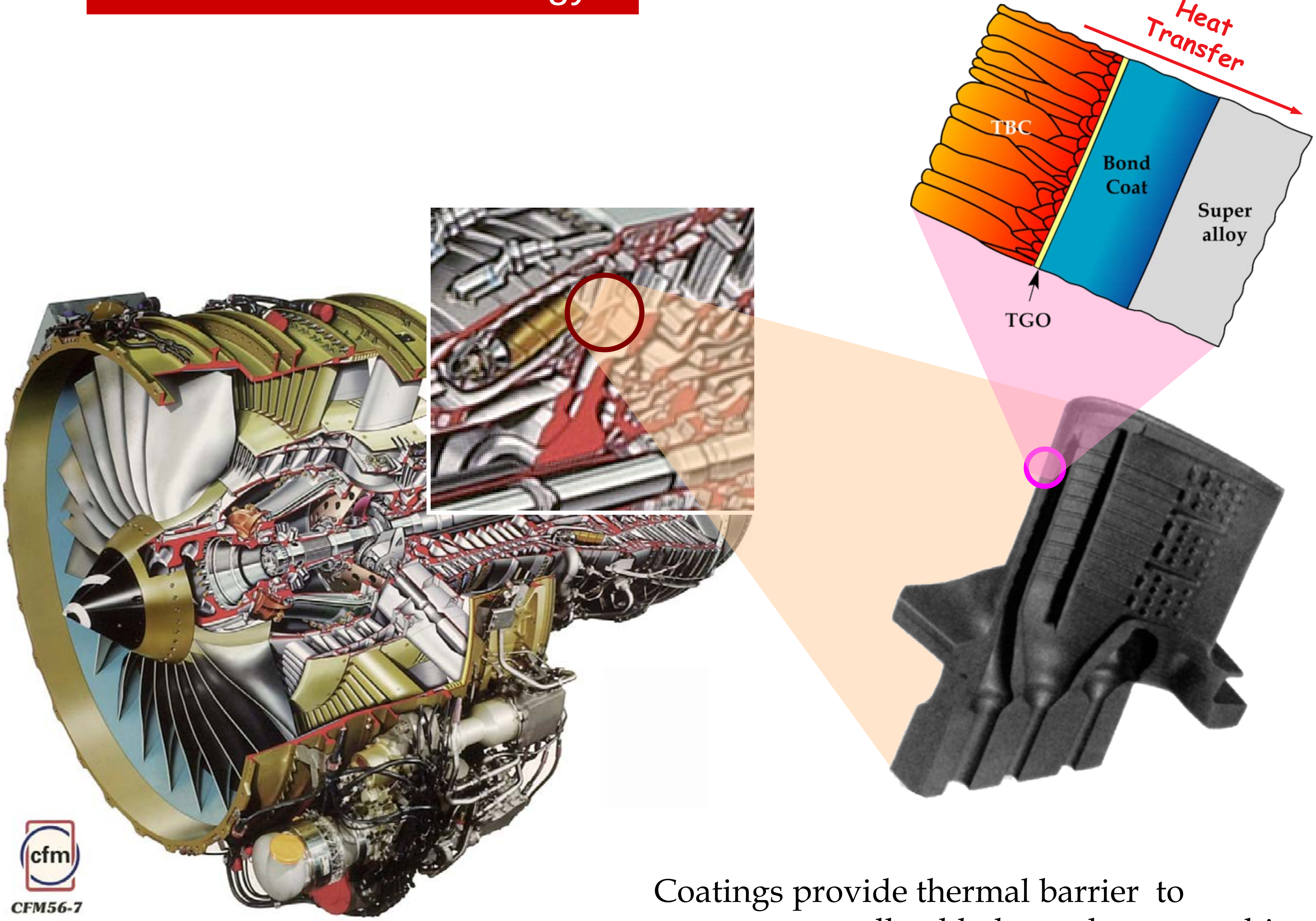
Equiaxed (EQ) **Dir. Sol. (DS)** **Single Xtal (SX)**

Increase in Turbine (T4) Temperatures over Fifty Years



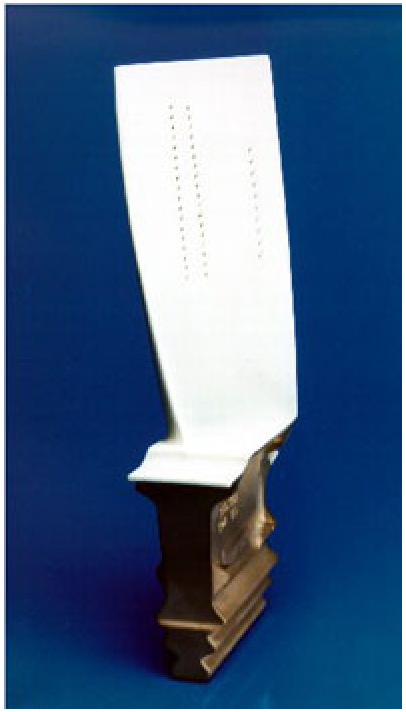
Combination of advances in cooling and materials have enabled
Increases in turbine temperatures and energy efficiencies

Coated Airfoil Technology



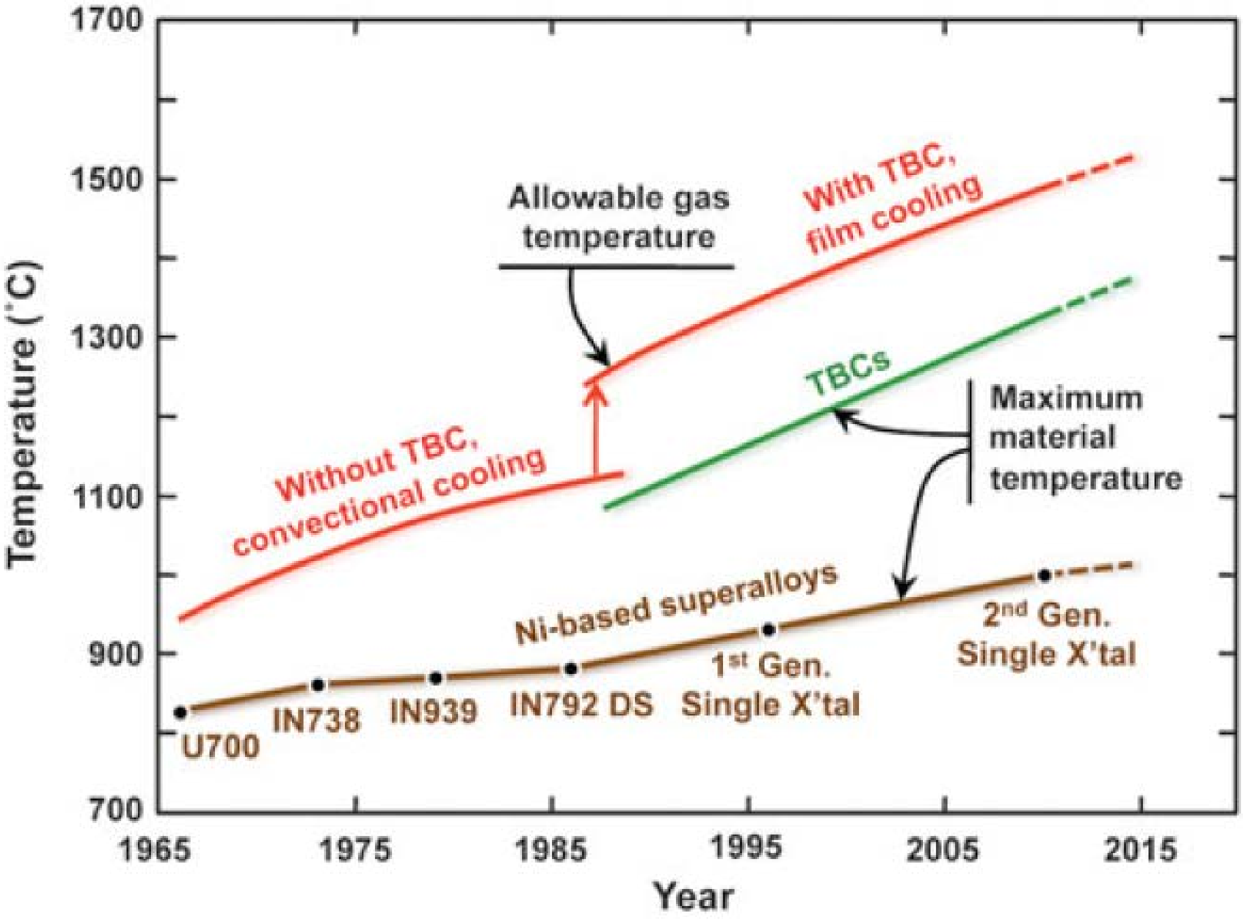
Coatings provide thermal barrier to prevent superalloy blades and vanes melting

Increase in Turbine (T4) Temperatures over Fifty Years



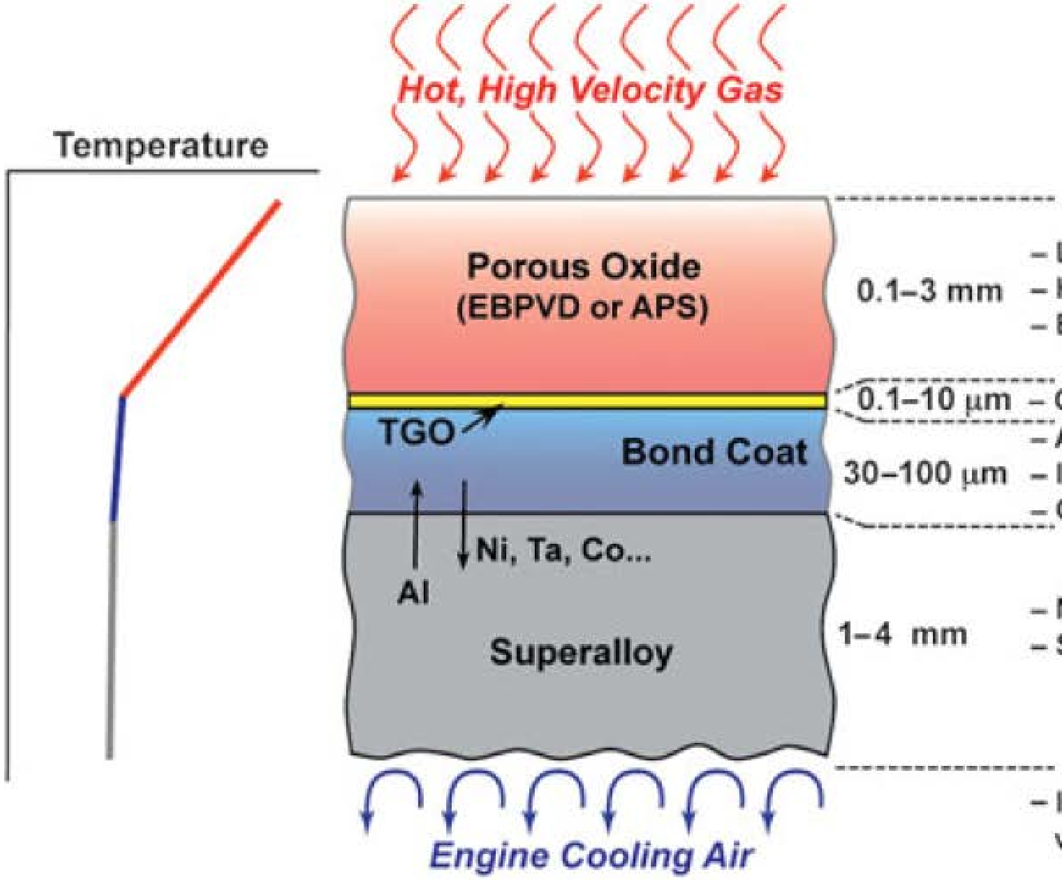
Yttria-stabilized
zirconia coatings
~ 150 – 500 micron thick

Thermal gradient
~ 150-200 K/mm



Thermal barrier coatings have enabled a jump in turbine temperatures and energy efficiencies

The Thermal Barrier Coating System



0.1–3 mm
- Low thermal conductivity
- High strain compliance
- Extreme temperature gradient (~1°C/μm)

0.1–10 μm
- Oxidation product. Large growth strain

30–100 μm
- Al reservoir for forming protective Al_2O_3
- Interdiffusion with superalloy
- Capable of creep and plastic deformation

1–4 mm
- Ni-based superalloy structural component
- Susceptible to creep and cyclic fatigue

- Internal surfaces of superalloy blade or vane cooled with air from engine

Rationale for Using Thermal Barrier Coatings for Turbine Components

- Original motivation was to extend the life of existing aero-turbine engines
- Additional benefits:
  - operate at higher gas temperature than melting point of superalloy
  - Minimize distortions due to transients

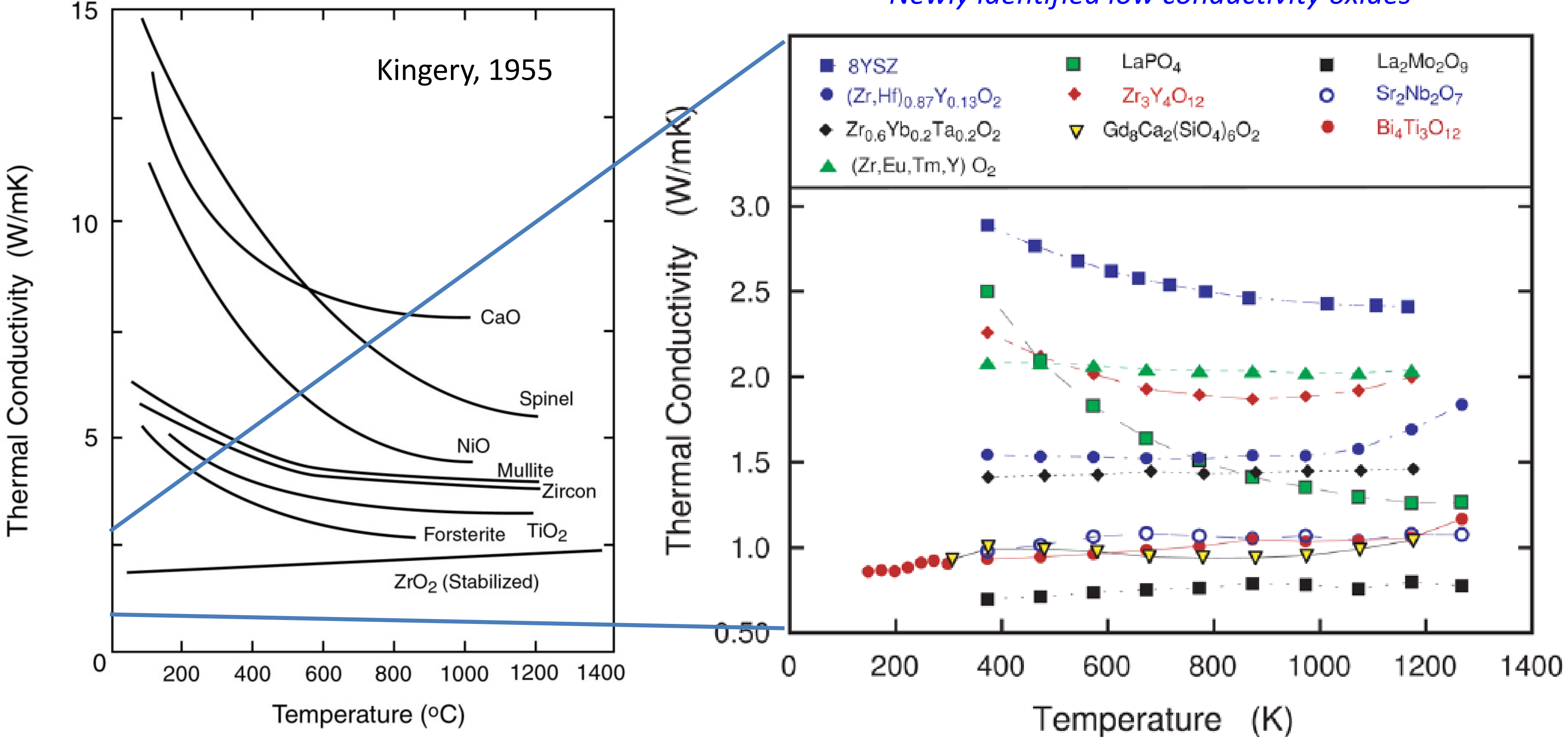
Rationale for Using Zirconia for Thermal Barrier Coatings

- Stabilized zirconia had the lowest thermal conductivities of any oxide @ 1985
- Demonstrated technology for refractory coatings – plasma-spraying – already existed
- Later experiments at NASA demonstrated that 7YSZ exhibited longest thermal cycle life

Some Requirements for a TBC

- Stable in air at temperatures in excess of 1400°C for long times
- Low thermal conductivity *at high temperatures*
  - Current 7YSZ coatings have conductivities < 1.5 W/mK
  - Need even lower thermal conductivity
- Negligible optical absorption
  - To avoid radiative heating by absorption from hot gases and surrounding parts
- Short optical scattering lengths
  - To minimize direct radiative heating
- Coating must stay on !
- High fracture toughness at all temperatures and resistant to thermal shock
  - Fracture toughness equal or greater than 7YSZ
- Chemical stability with alumina (Al2O3), the preferred oxide formed on alloy oxidation
- Coatings must be compliant, conformal and deposited on curved surfaces
- High-rate deposition of 150-250 micron thickness coatings needed

Alternative Oxides --- Thermal Conductivity



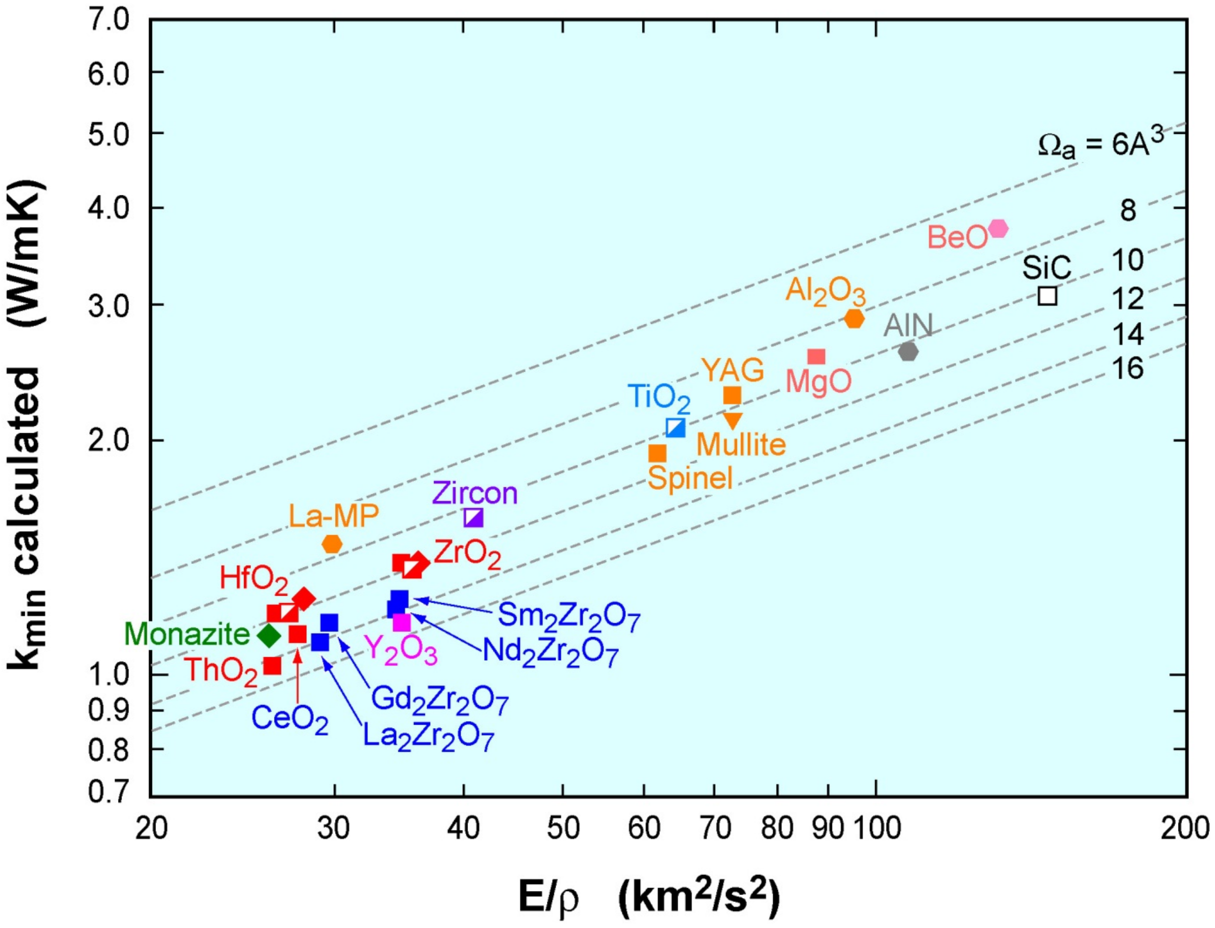
Newly identified low conductivity oxides

At high temperatures, conductivity always asymptotes to minimum value, K_{min}

NB. Some oxides have a temperature independent conductivity above room temperature

NB. Data shown from fully dense materials so no porosity contribution

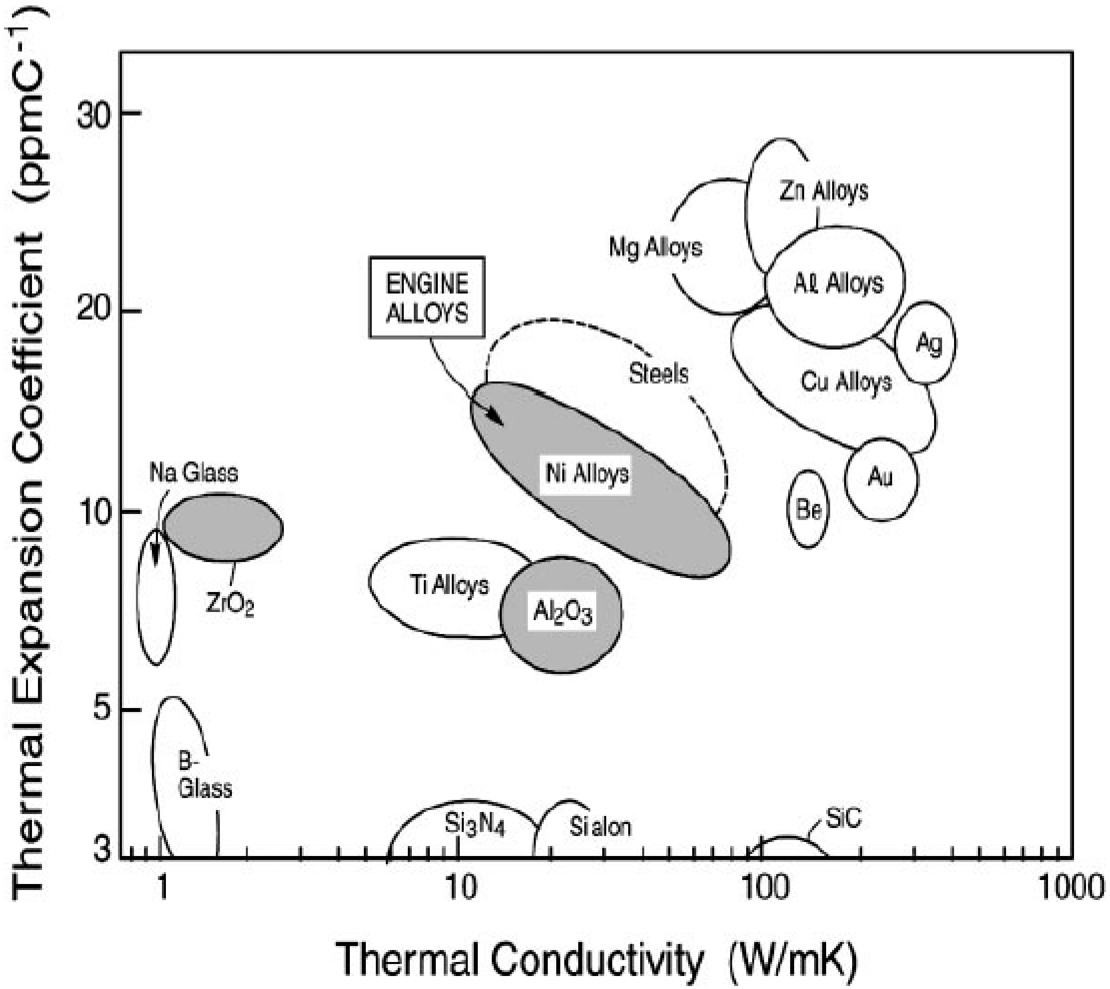
High-Temperature Thermal Conductivity Scaling



$$\boxed{\kappa_{\min} = k_B\, v_m\, \Lambda_{\min} \rightarrow 0.87 k_B \overline{\Omega}_a^{-2/3} \left(E/\rho\right)^{1/2}}$$

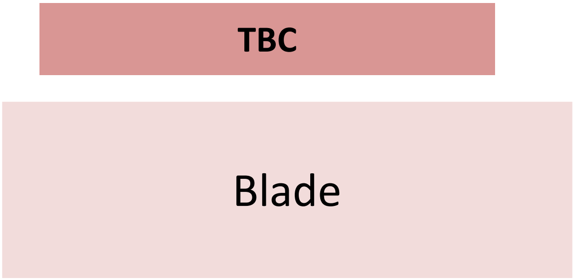
$$\overline{\Omega}_a = \left[M/\left(m\,\rho\, N_A\right)\right]$$

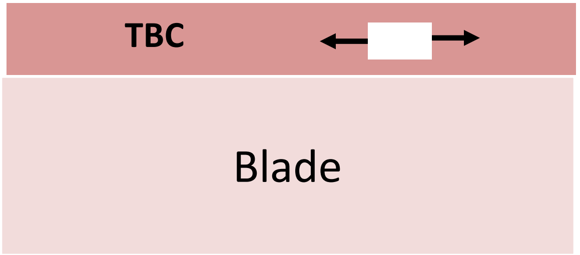
Thermal Expansion Mismatches



Minimization of Thermal Expansion Mismatch Stresses

To remain intact on the blade, the coating must withstand the stresses created by the thermal expansion mismatch strains





Mismatch strain in coating:

$$\varepsilon_{\Delta T} = \Delta\alpha\,\Delta T$$

Elastic strain energy in coating: $$U_{elastic} = \frac{\sigma^2 h}{2E_{coat}} = \frac{E_{coat}^2\,\varepsilon_{\Delta T}^2\,h}{2} = \frac{h\left(\Delta\alpha\,\Delta T\right)^2 E_{coat}^2}{2}$$

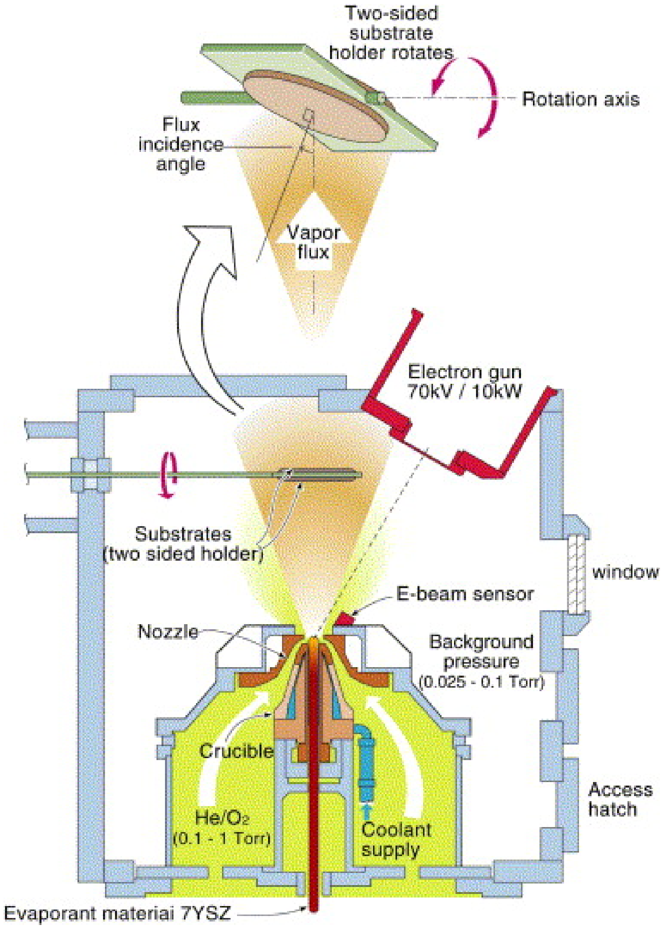
Condition for failure: strain energy release rate, G > fracture toughness of interface, Γ

The only way to reduce elastic strain energy is to lower the elastic modulus of the coating
How ?

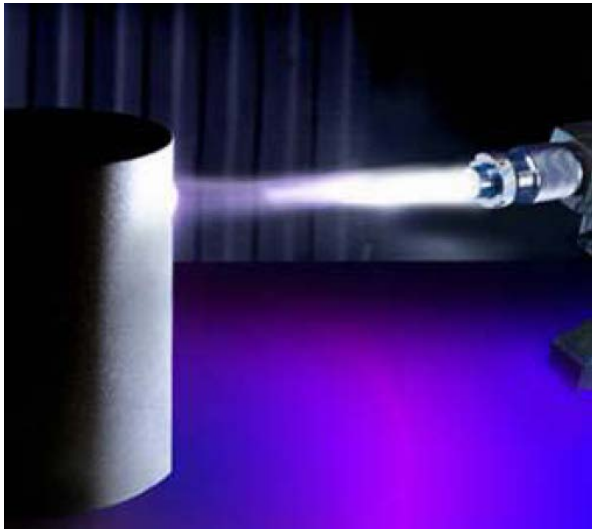
Introduce a “shape factor” into the performance index, ie porosity/gaps

Deposition of Thermal Barrier Coatings

- Deposition methods for introducing porosity for strain compliance



EB-PVD

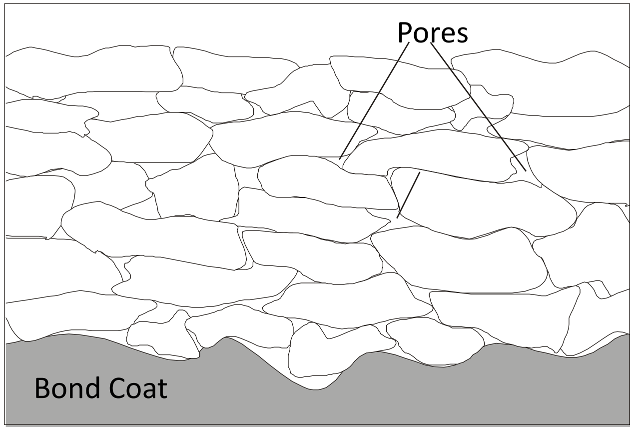


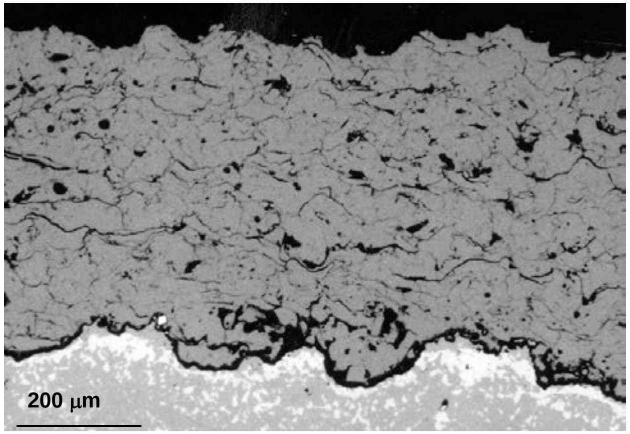
APS

Deposition of Thermal Barrier Coatings

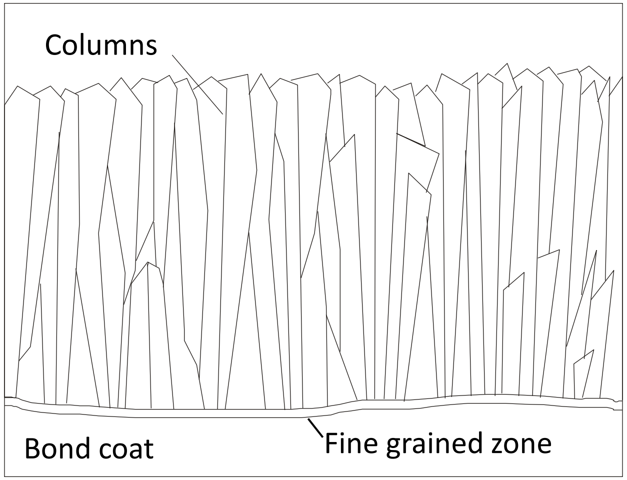
- Deposition methods for introducing porosity for strain compliance

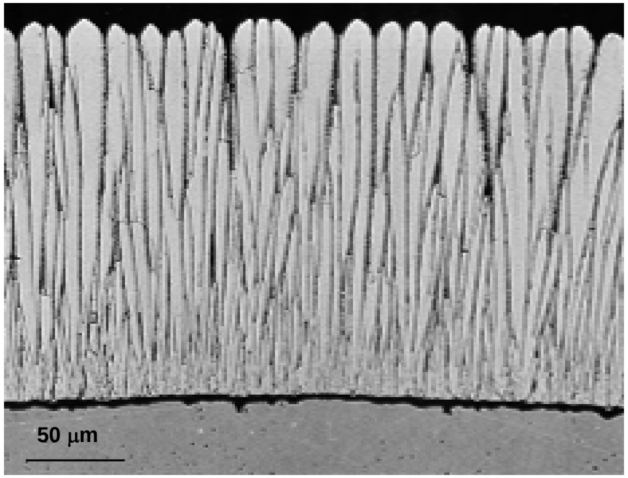
APS
(Atmospheric
Plasma
Sprayed)



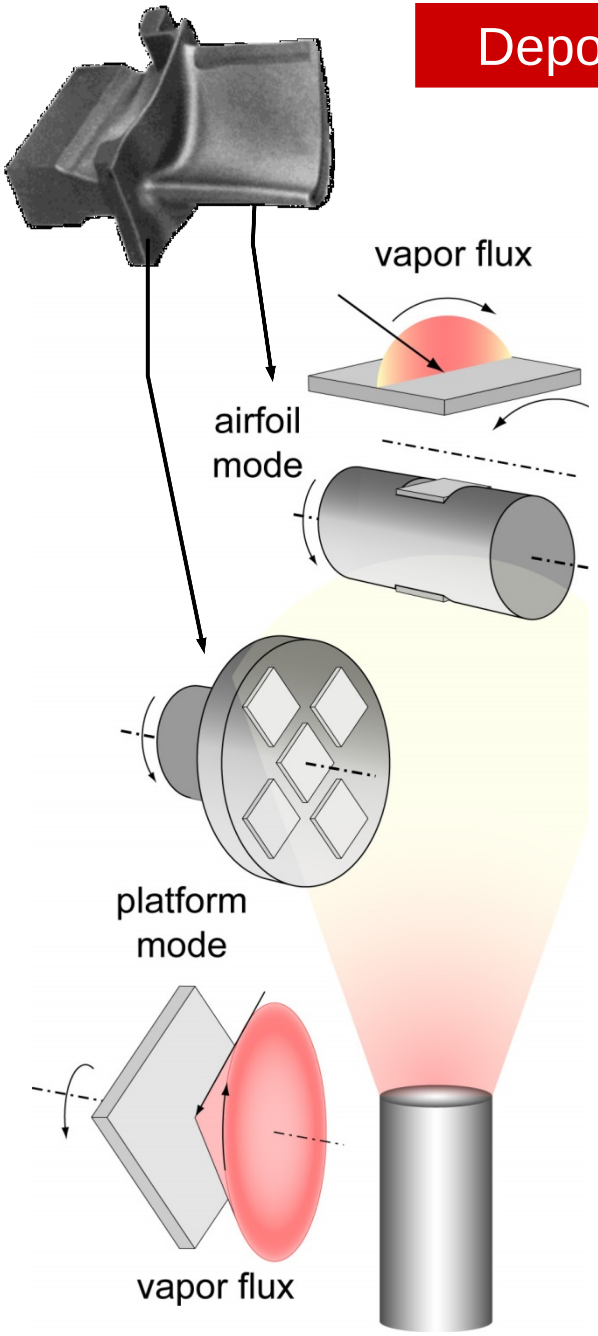


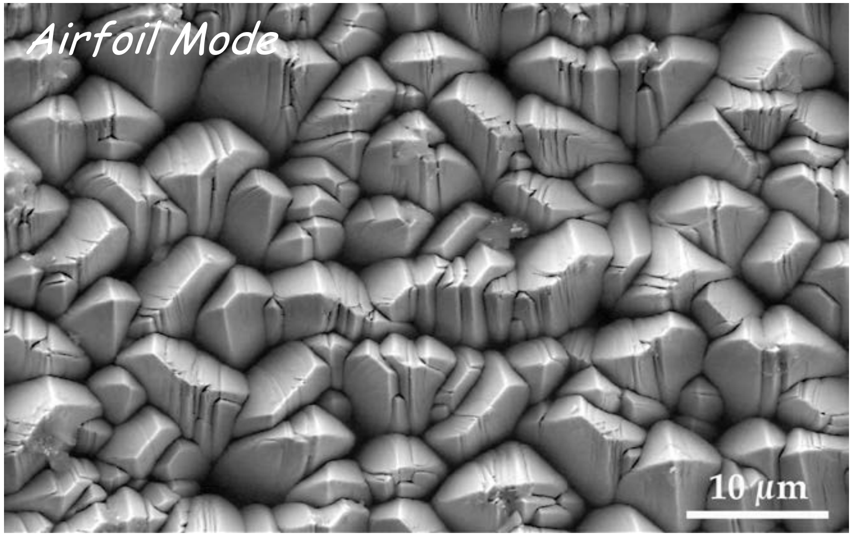
EB-PVD
(Electon Beam -
Physical Vapor
Deposited)

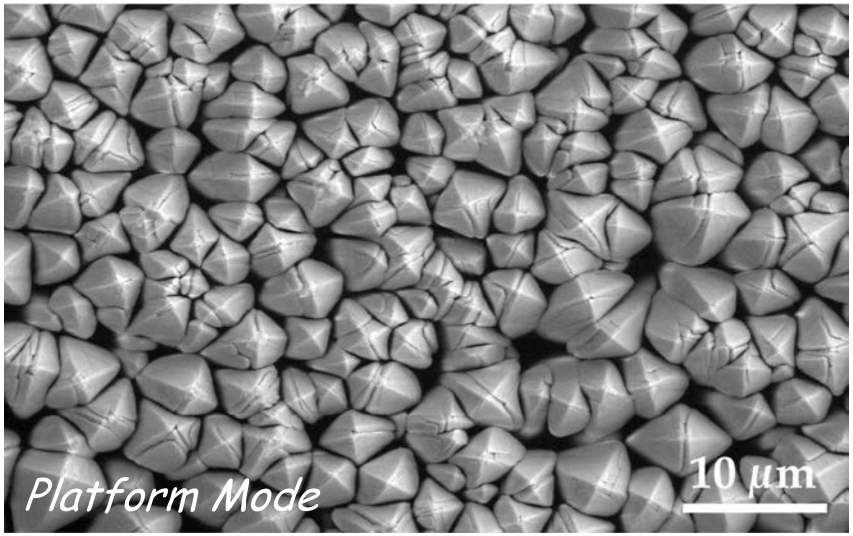




Deposition Effects on Microstructure





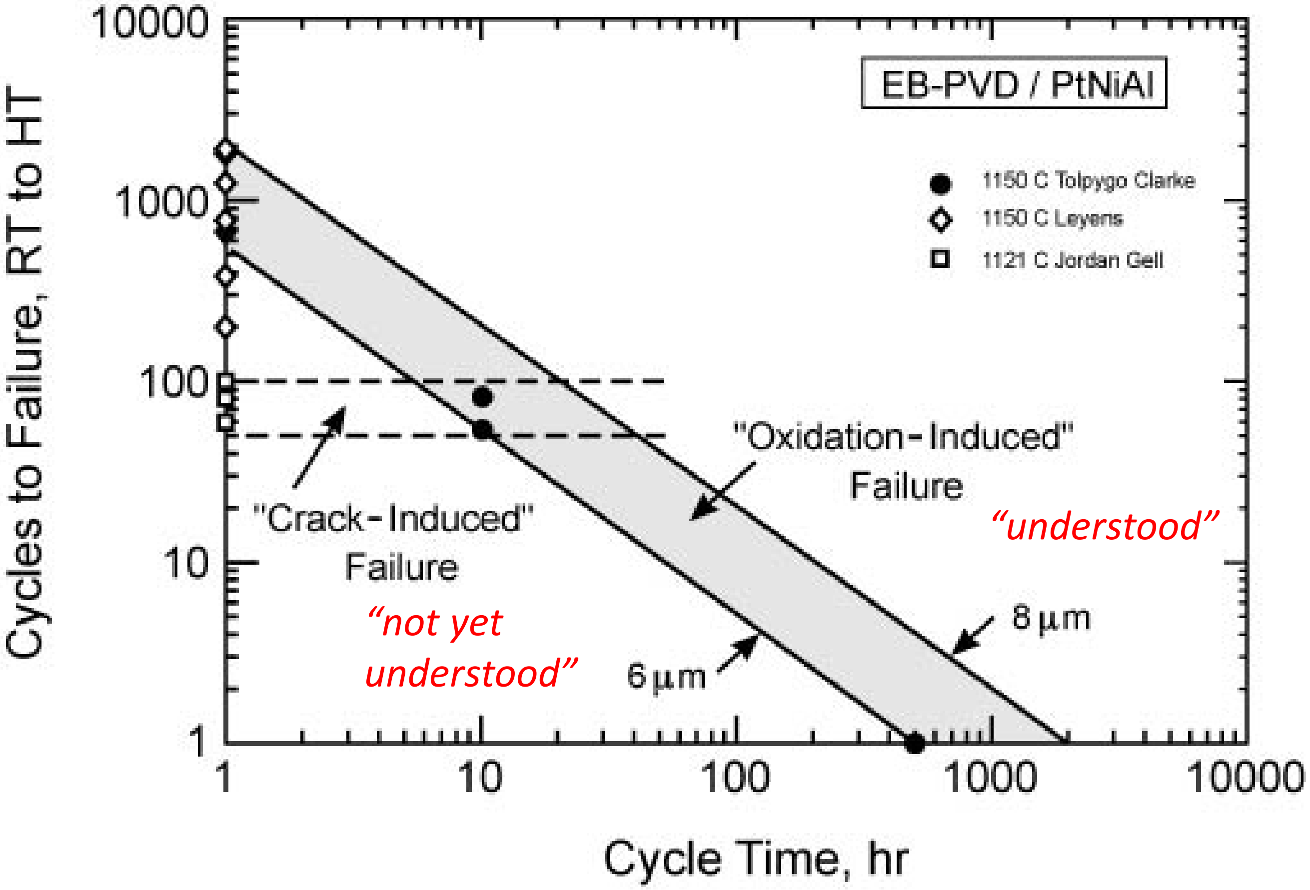


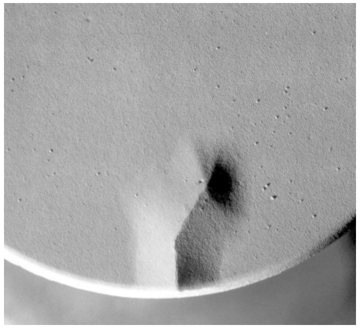
C. Levi, UCSB

Assuring Thermomechanical Reliability – Prime Reliance

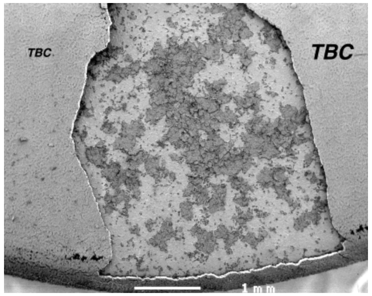
- Coating life usually limited by various fracture processes
- Both low temperature and high temperature failures can occur
- Need high fracture toughness at both low and high temperatures
- Underlying mechanism of coating delamination are poorly understood
- Thermal cycling lives are usually much shorter than constant temperature lives

Effect of Thermal Cycling on Coating Life





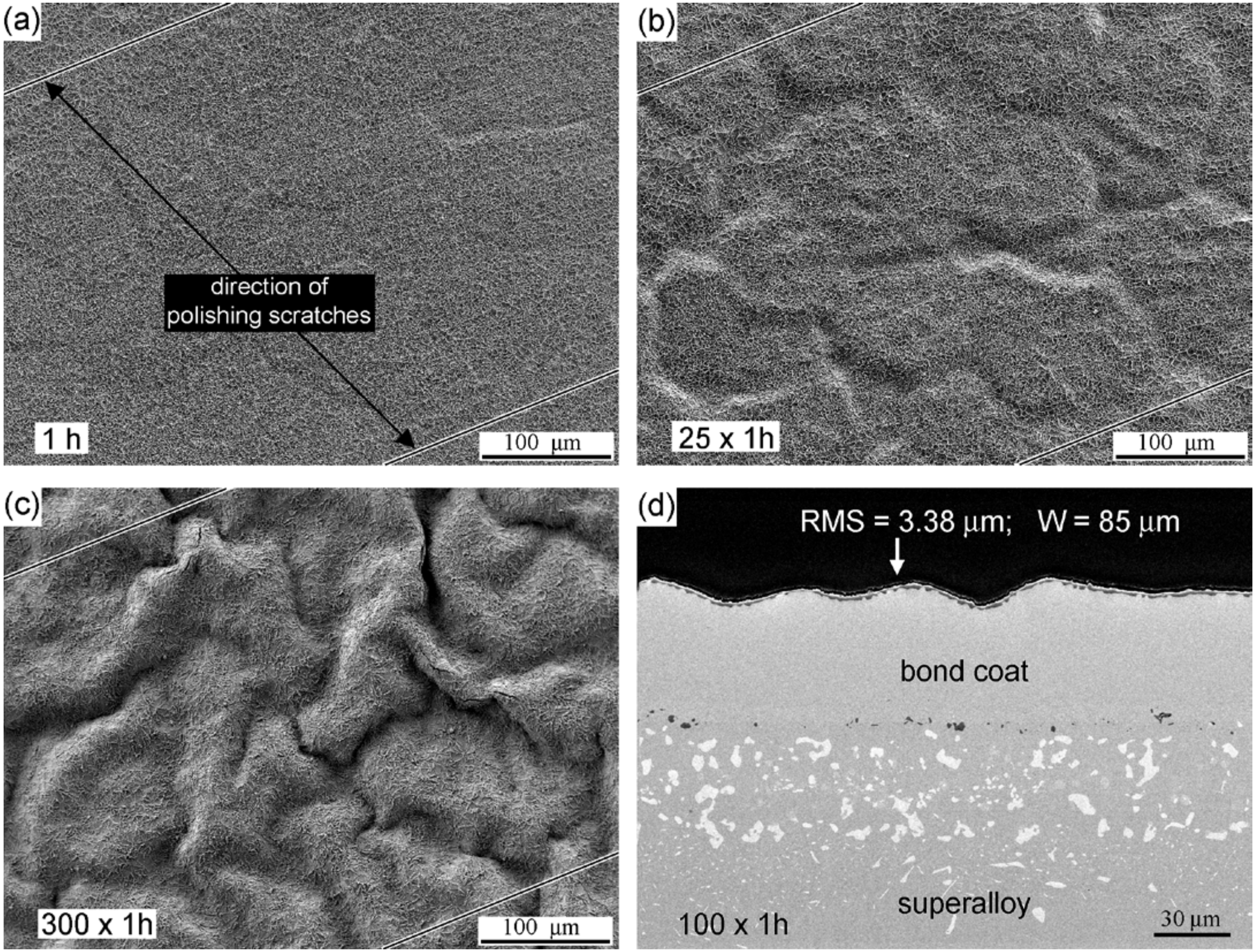
Failure typically by TBC buckling/spallation



SWRI report

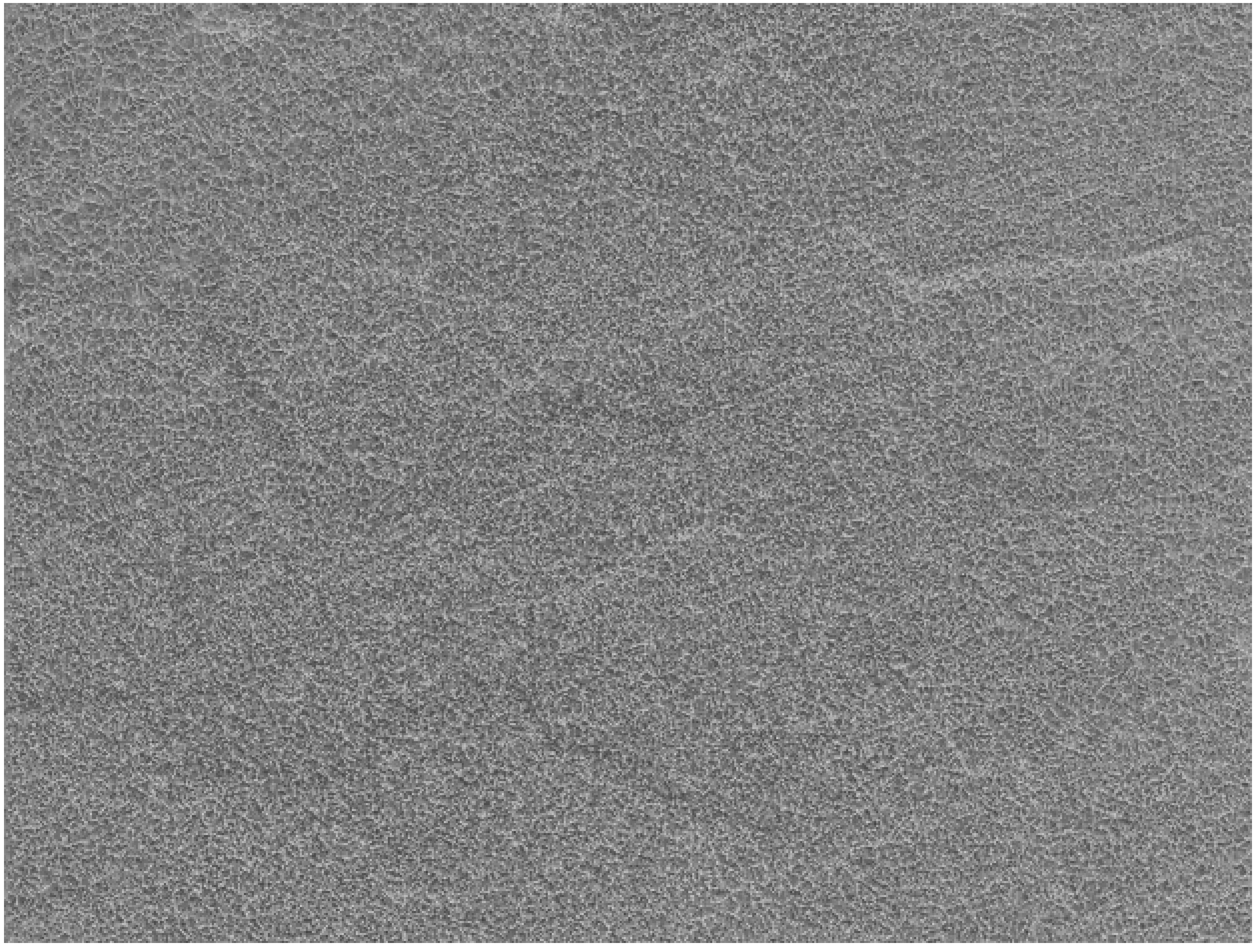
Effect of Thermal Cycling on Bond Coat

Life of TBC is often limited by morphological instability ("rumpling") of the metal bond coat on thermal cycling causing incompatibilities with TBC. More stable alloys needed



Thermal Cycling Instability

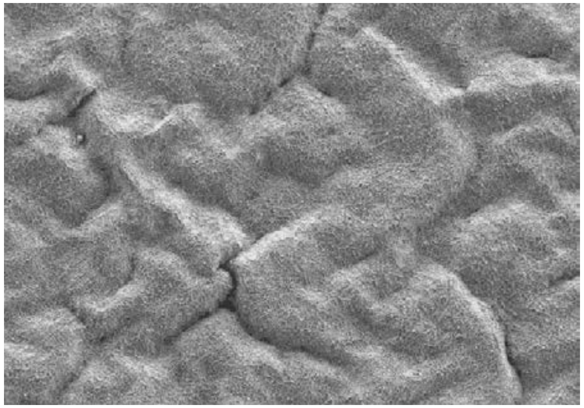
Life of TBC is often limited by morphological instability ("rumpling") of the metal bond coat on thermal cycling causing incompatibilities with TBC. More stable alloys needed



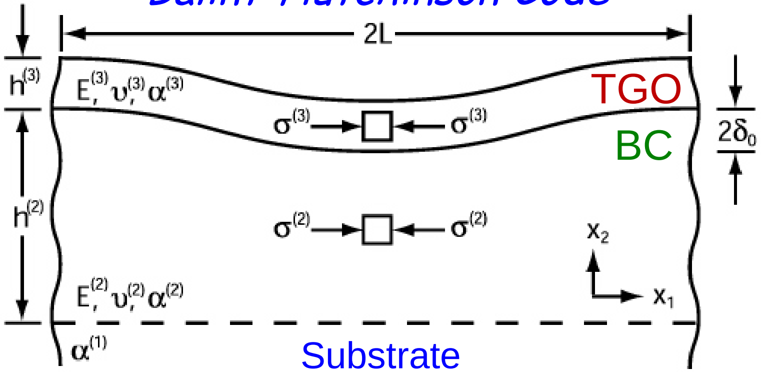
Coating surface on thermal cycling.

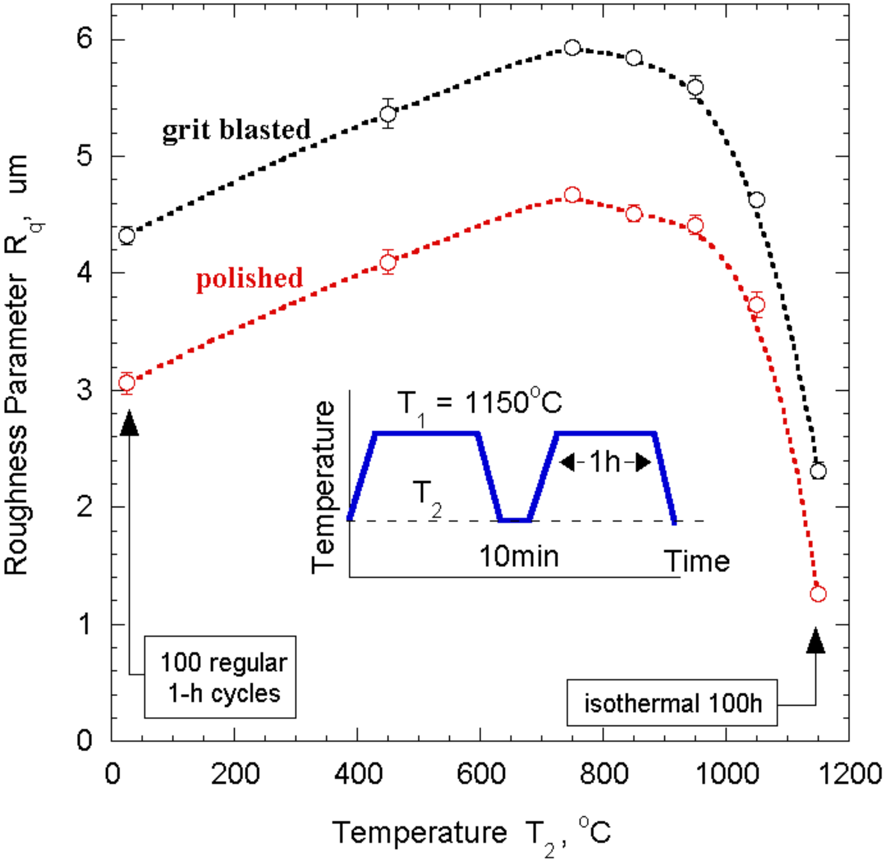
0-300 cycles to 1150^{o}C in air. ~ 400 micron field of view

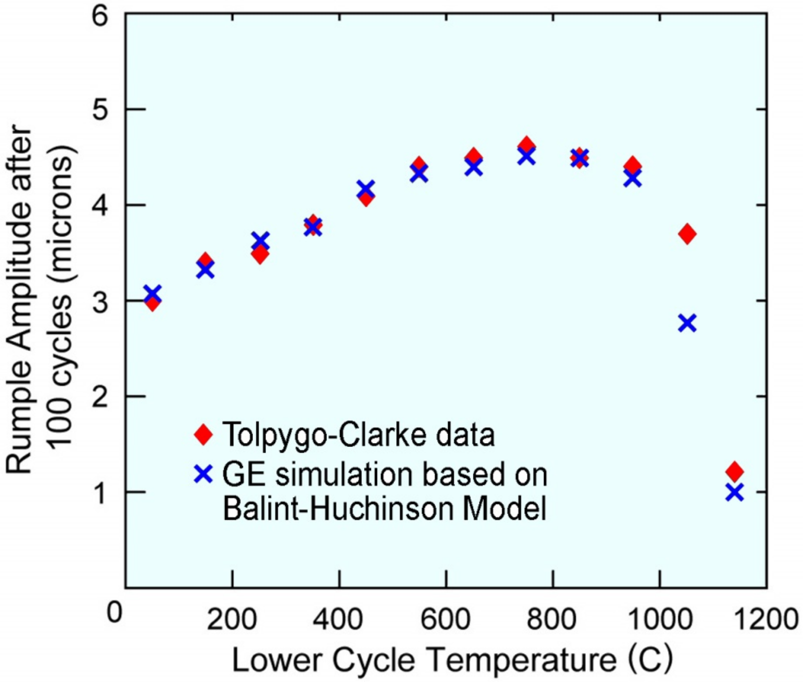
Mechanics Model Validation



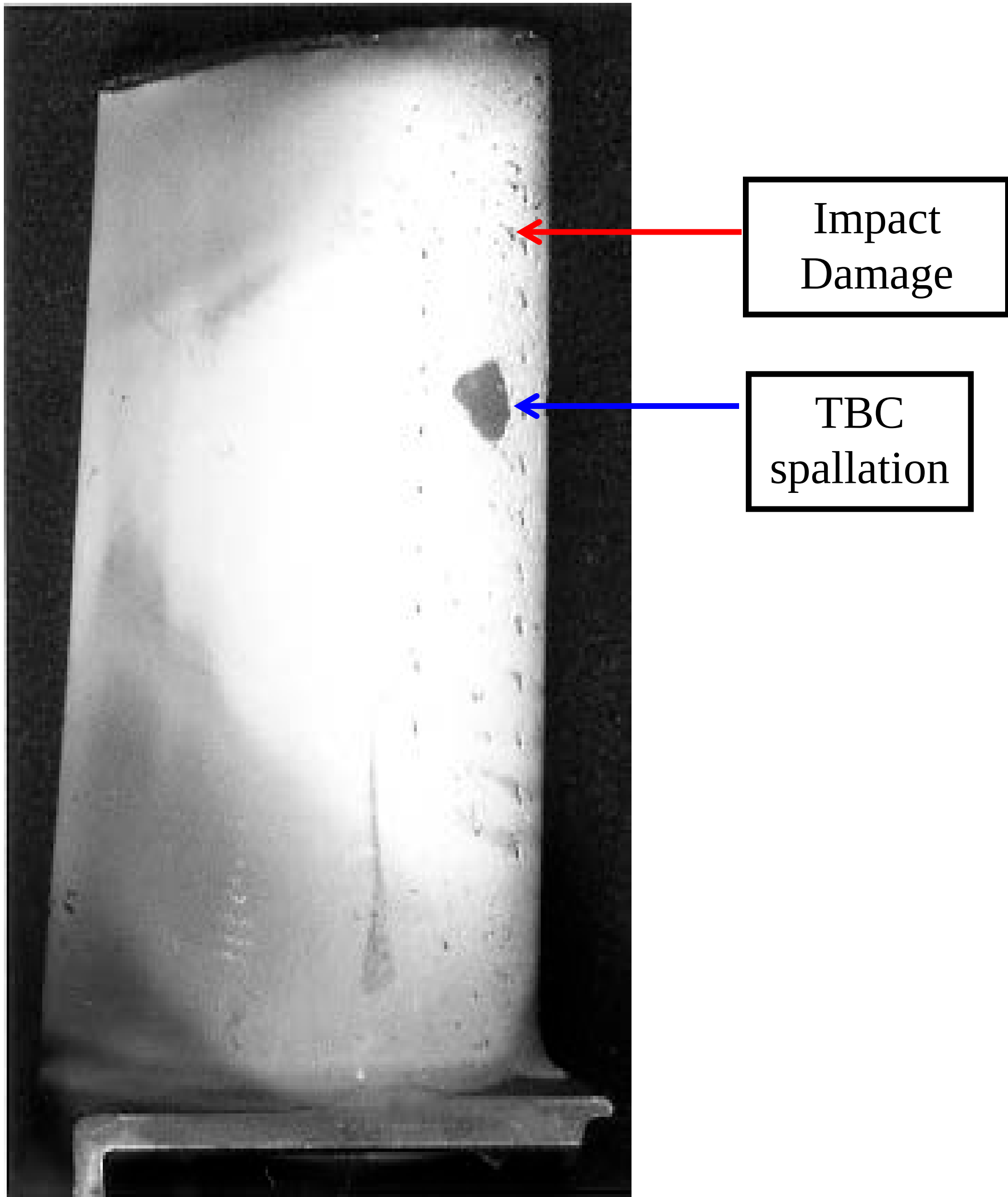
Balint-Hutchinson Code







Impact Resistance Requires High Fracture Toughness



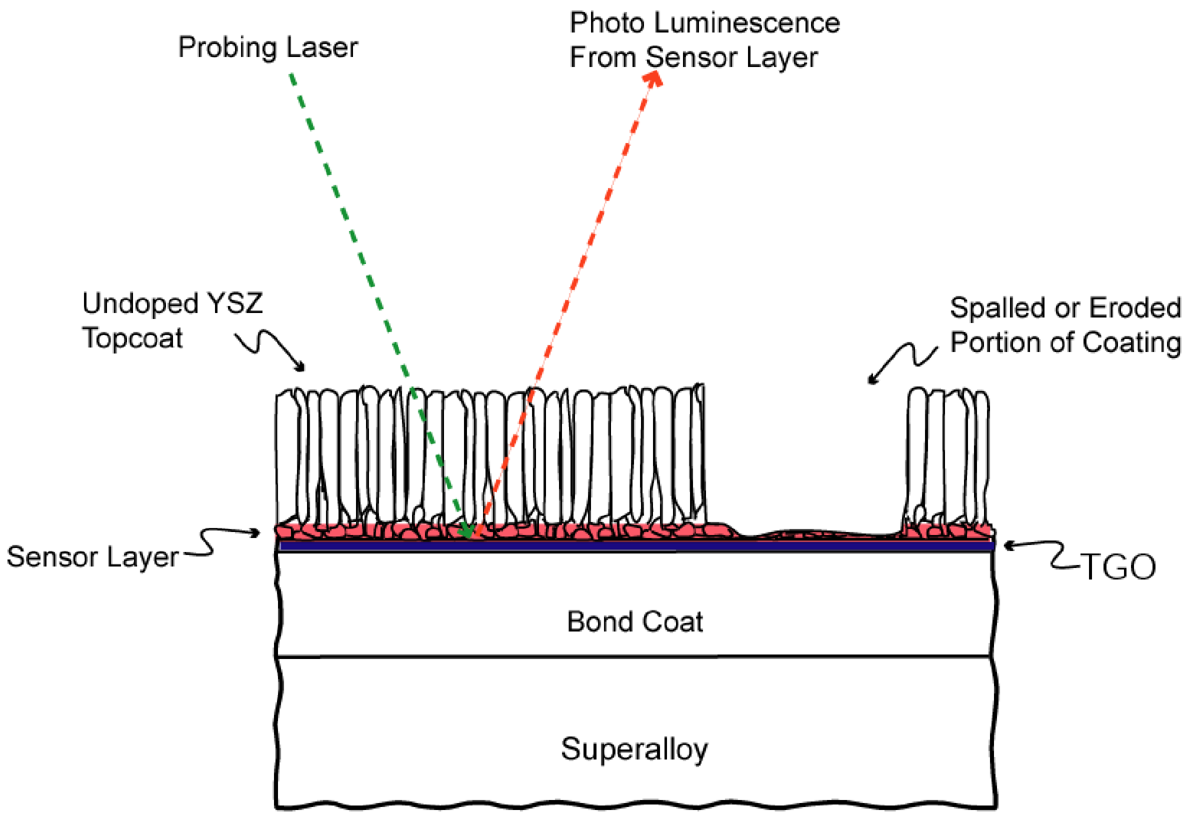
Impact Damage

TBC spallation

1820 engine cycles

Luminescence Based Temperature and Damage Sensor

Non-contact method



- Luminescent ions can be incorporated into crystal structure of the coating material to act as sensors

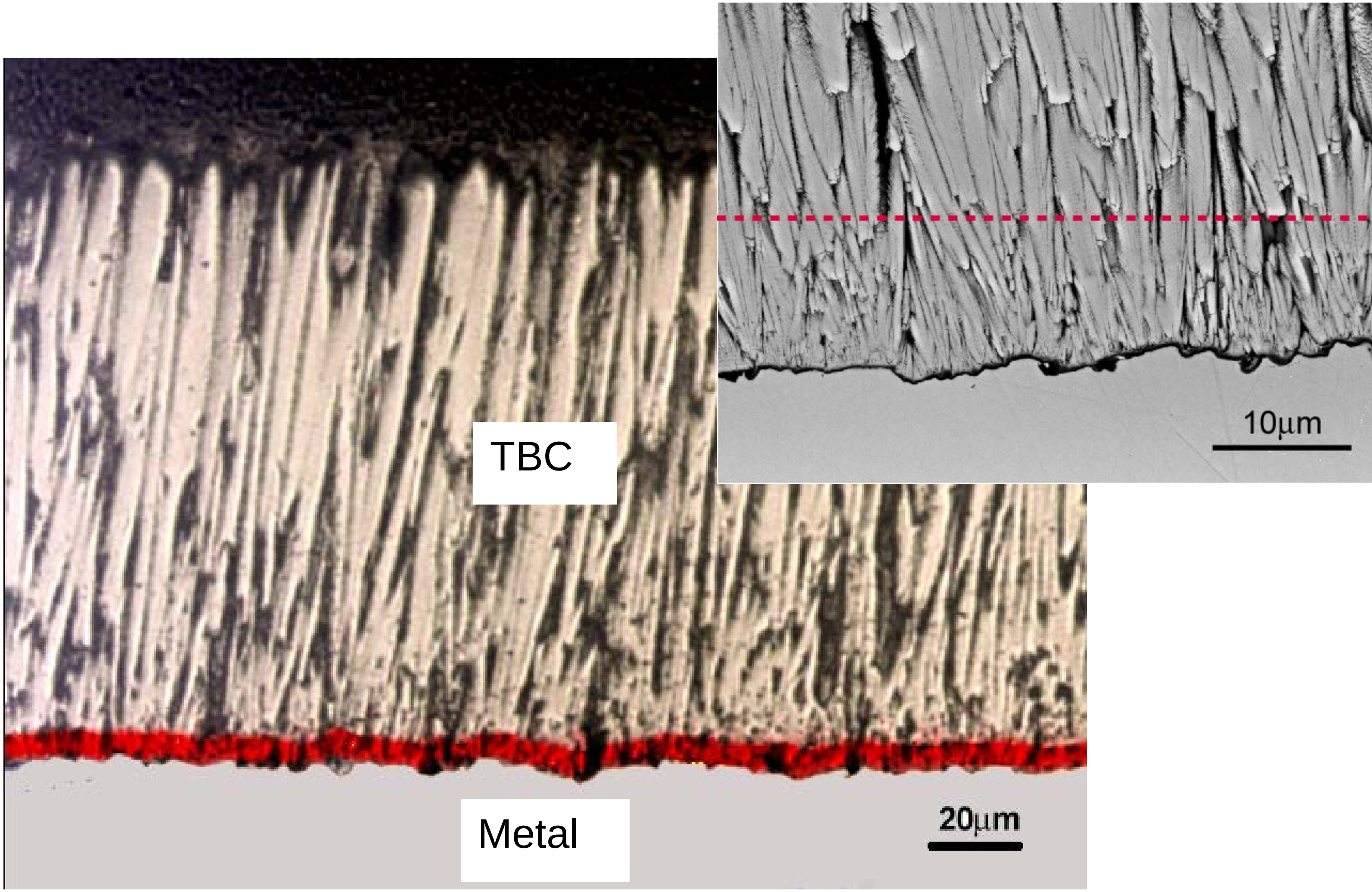
- Luminescence lifetime is known to be temperature sensitive

- Because of translucency of TBC materials, visible lasers and luminescence can be used to measure temperatures of sensors buried in a coating

- Multiple sensor layers can be applied to measure the temperature at any depth

Luminescence decay times can be used measure temperature

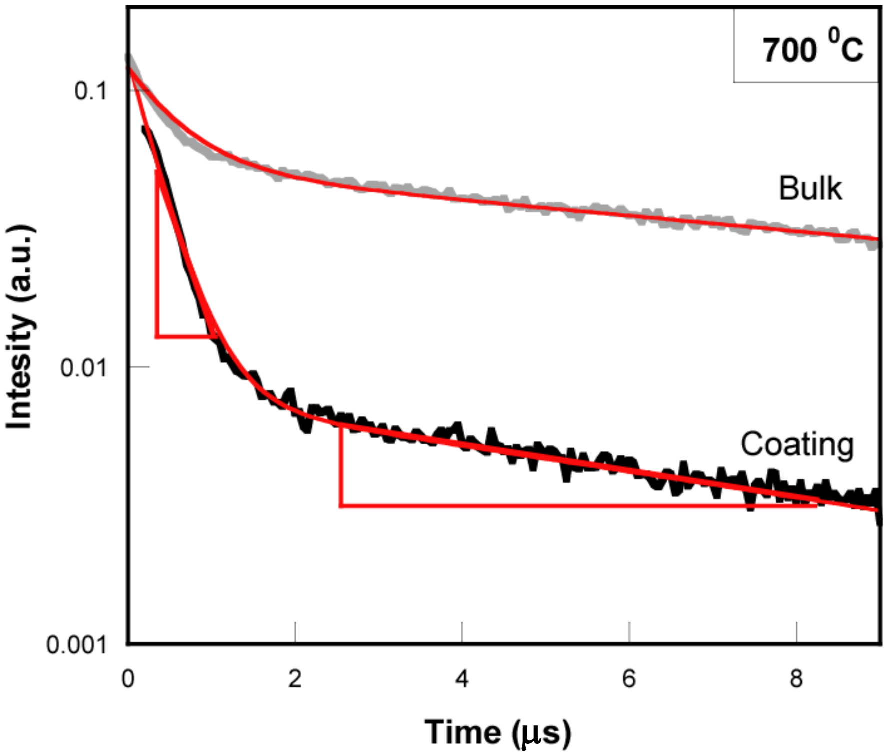
Example: Eu Doped TBC Sensor Layer

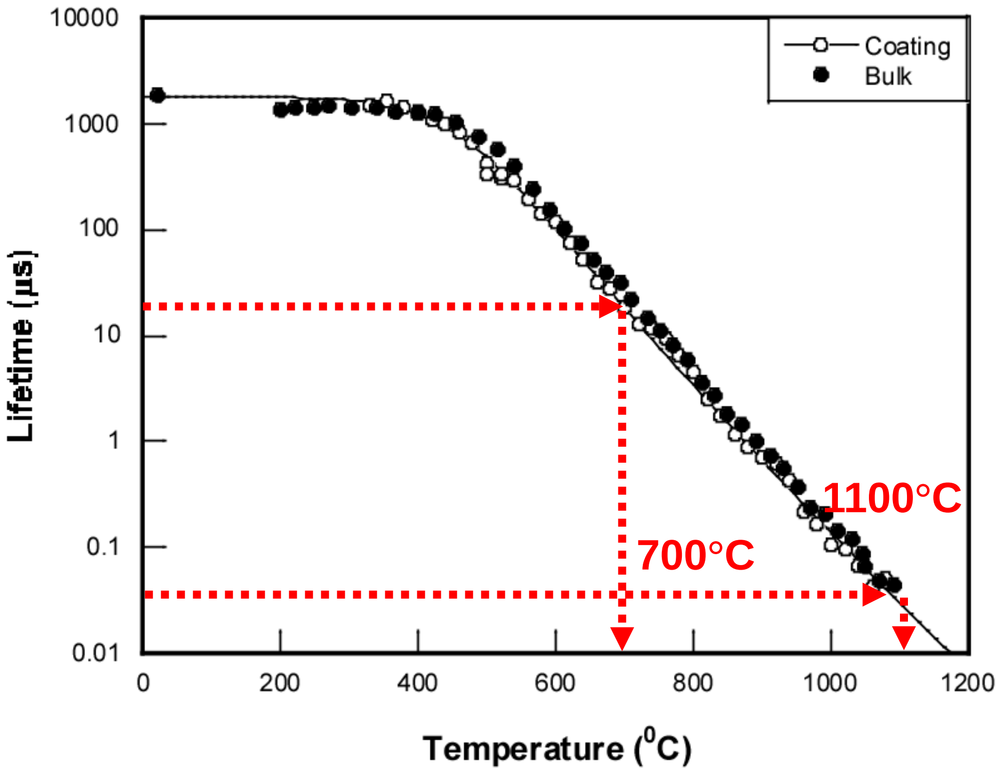


Superimposition of white light and UV luminescence images

Temperature Sensing Using Luminescence Lifetimes

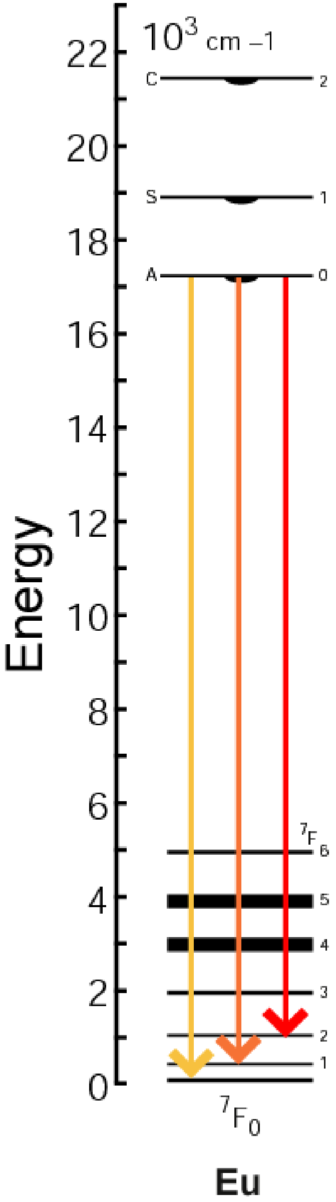
10 micron sensor layer on EB-PVD coating

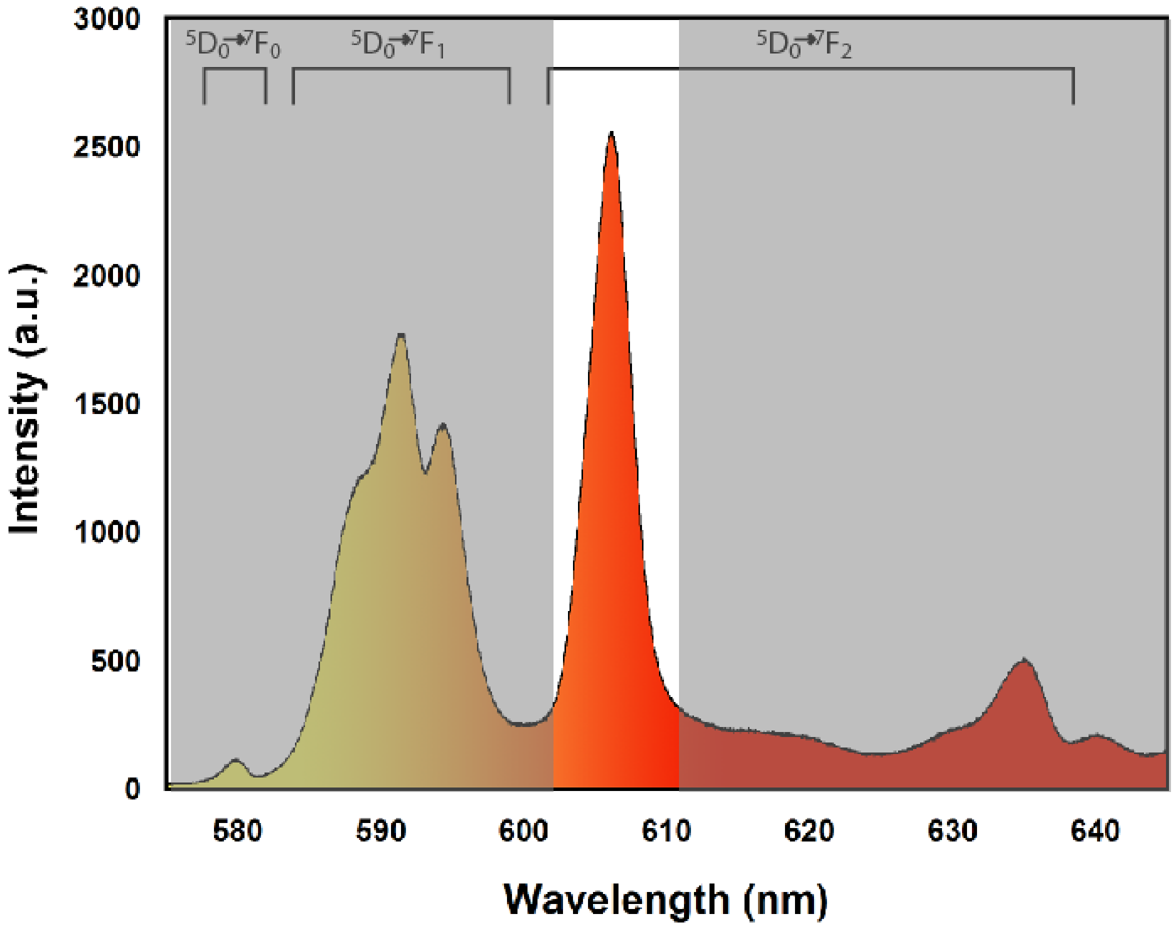




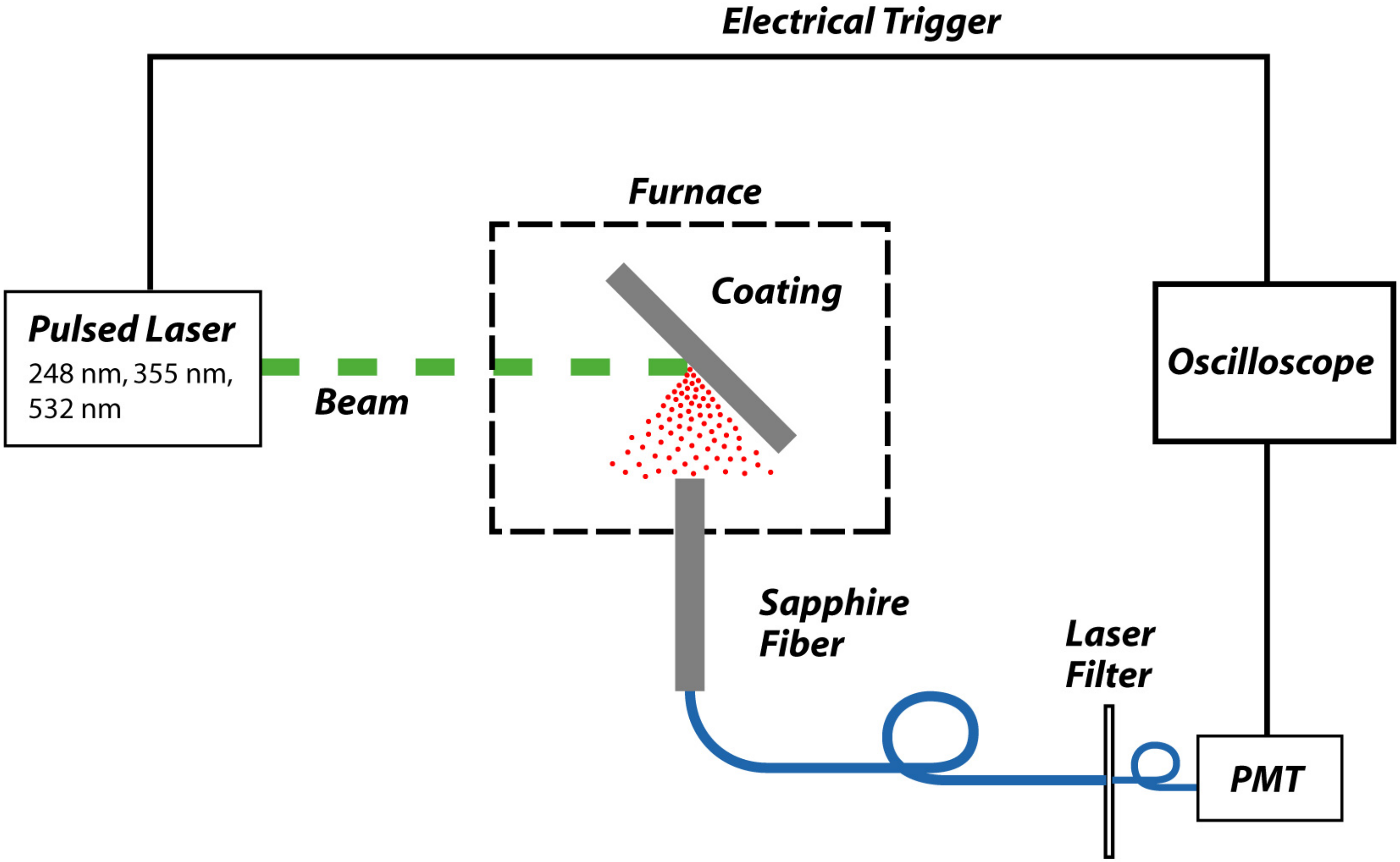
Calibration of luminescence lifetime provides basis for temperature measurements on engine components

Major Luminescence Transitions in Eu^{3+} doped YSZ

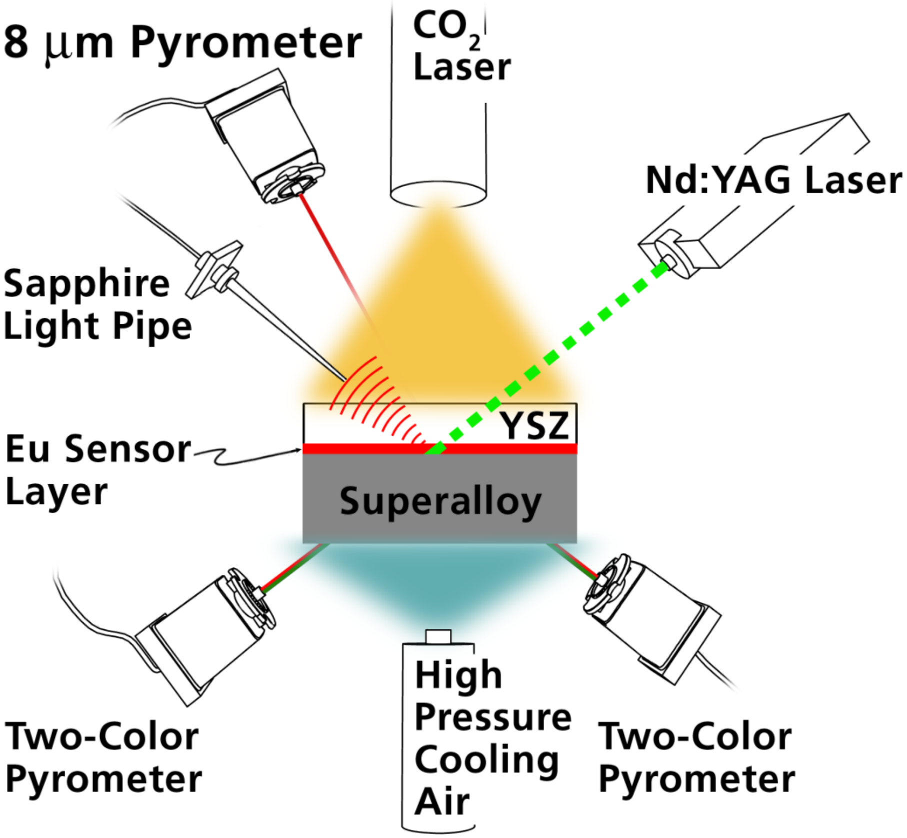


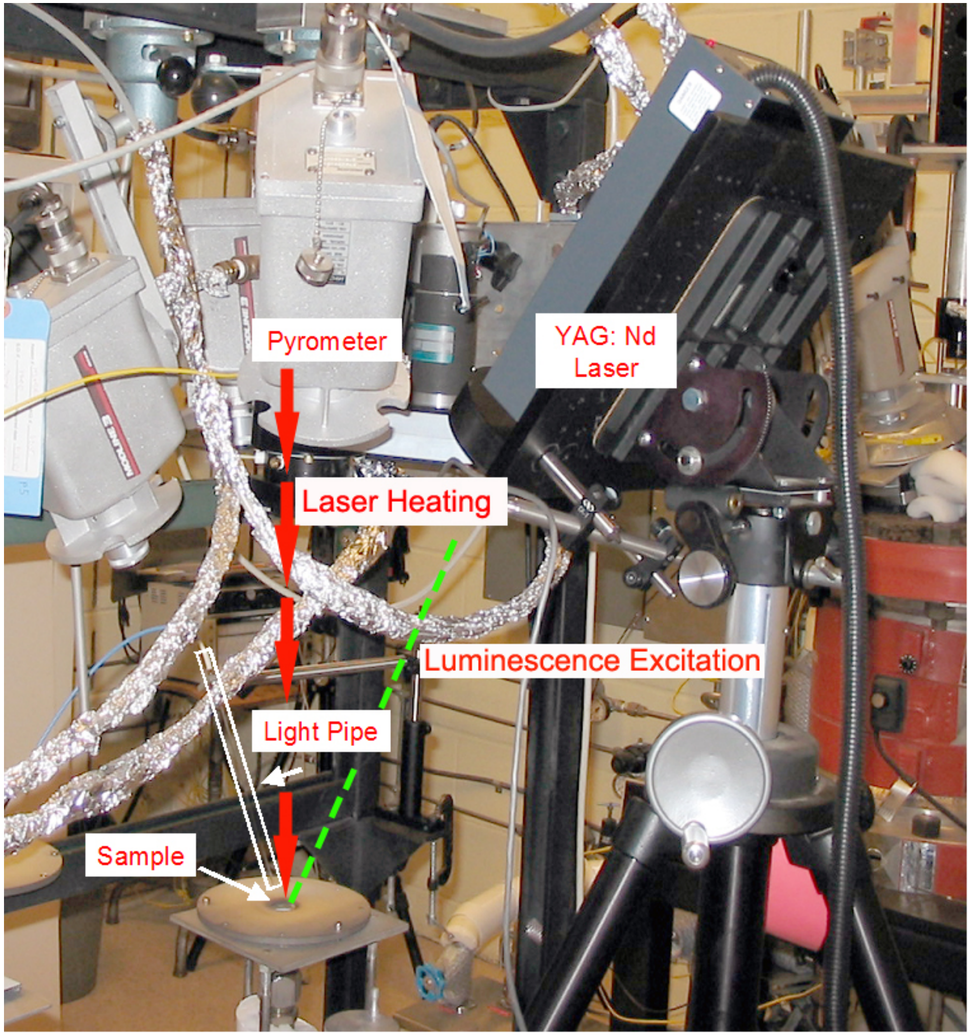


Luminescence Decay Measurement System

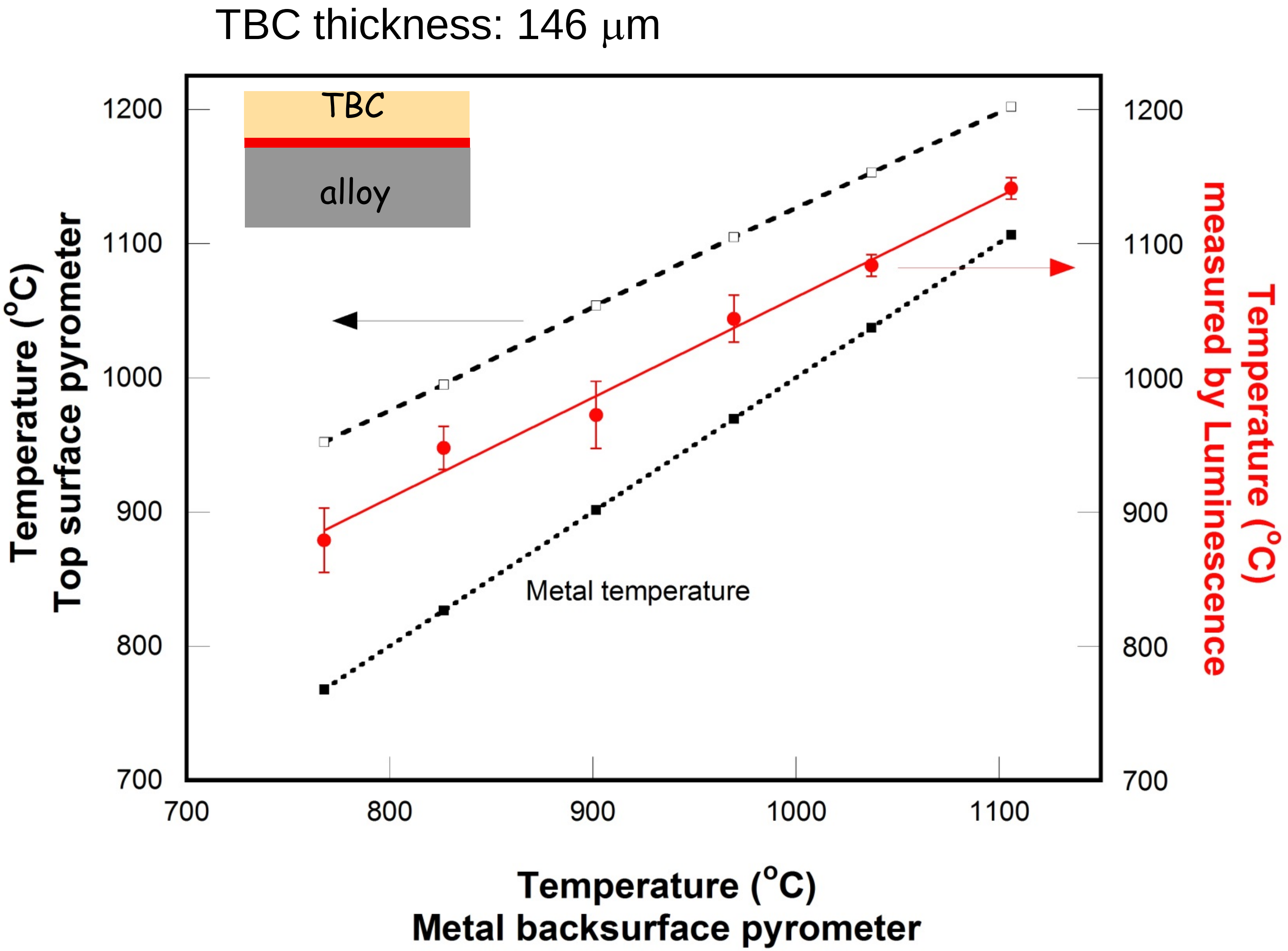


TBC Interface Temperature in a Thermal Gradient

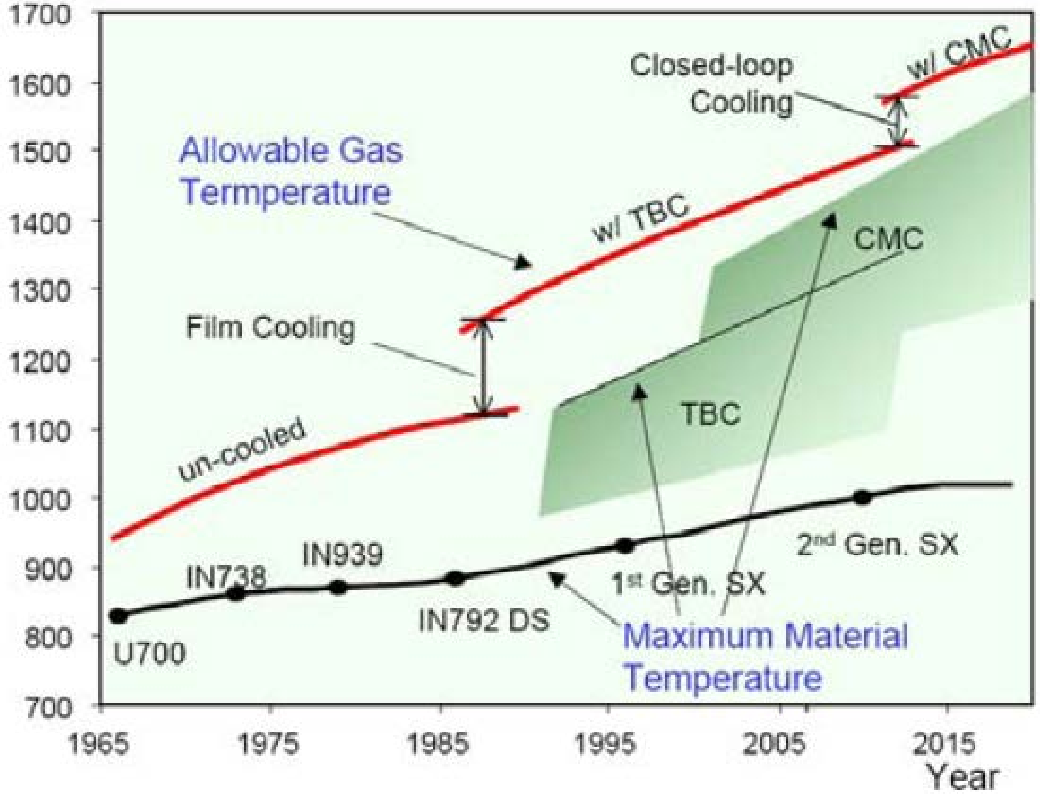




TBC Interface Temperature in a Thermal Gradient



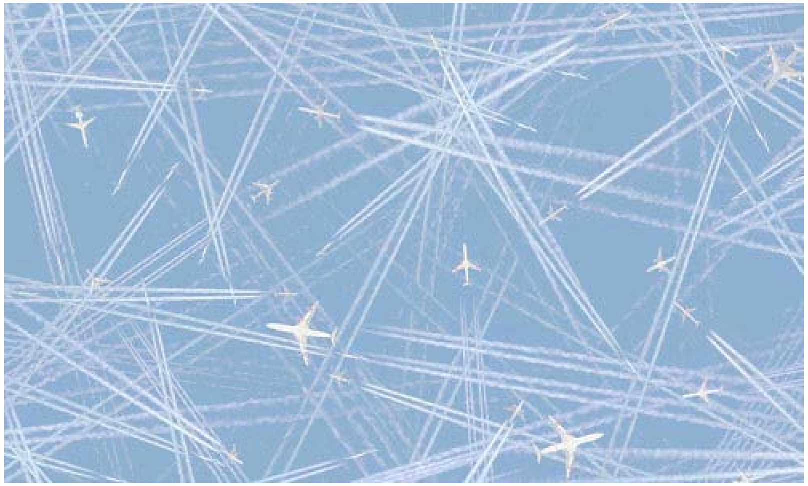
The Next Materials Frontier: Ceramic Matrix Composites



- **High temperature capability**
- **High corrosion resistance**
- **Toughening mechanisms:**
    - **- Microcracking**
    - **- Fiber pull out**
    - **- Crack bridging**
- **90% cooling air reduction**
- **Reduced emissions**

Future Limits To Gas Turbines: Unresolved Challenges

- Atmospheric pollution from engine exhausts
  - Chemical reactions produce NOx -- will limit max combustion temperature



- Melting of ingested sand can erode TBC

- Corrosion of GT components from pollution in the atmosphere, eg SO_2
  - Many of the metallic alloys in the engine were not designed to resist SO_2 corrosion

Combustion Creates NOx Pollution

Combustion Reaction

$$CH_4 + 2O_2 + N_2 \rightarrow CO_2 + 2H_2O + N_2 + CO + NO_x + \text{heat}$$

Zeldovich Mechanism for NOx Formation

- The chemical reactions that lead to thermal NOx formation are:

$$N_2 + O \leftrightarrow NO + N$$

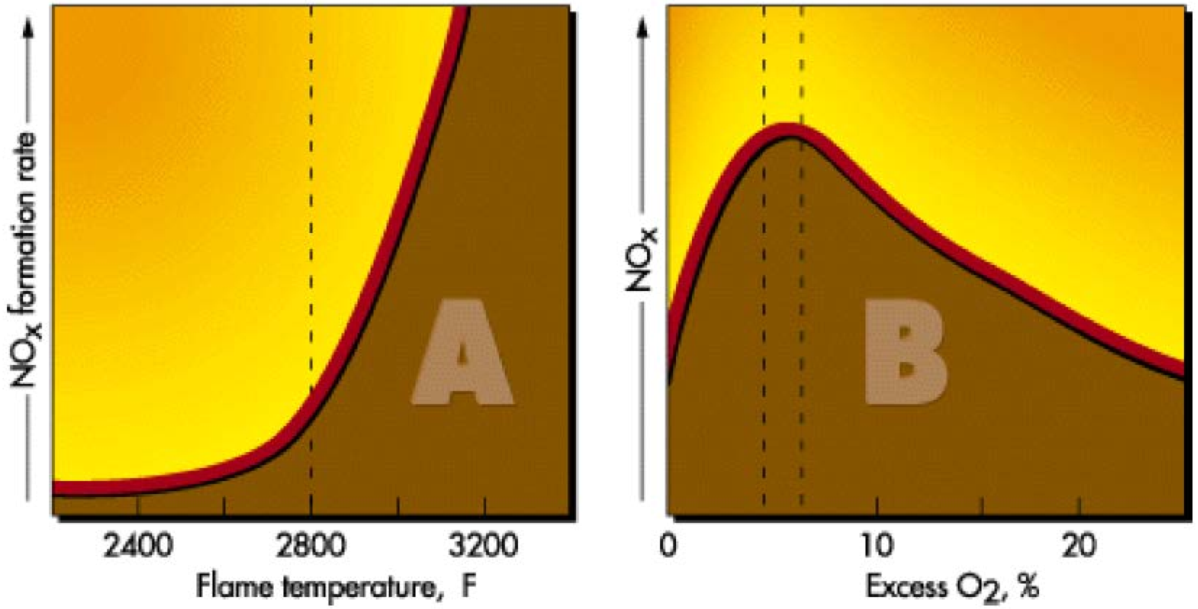
$$N + O_2 \leftrightarrow NO + O$$

- In the first reaction di-nitrogen is attacked by O to form NO and a nitrogen radical
- The nitrogen radical then attacks O_2 to form another NO and regenerates the oxygen radical
- The overall reaction is given by, $N_2 + O_2 \leftrightarrow 2(NO)$
-

Highly endothermic: $\Delta H_F = +90.4$ kJ/mol

NB. The formation rate of NOx is primarily a function of temperature and the residence time of nitrogen at that temperature.

NOx Emissions Depend on Combustion Temperature



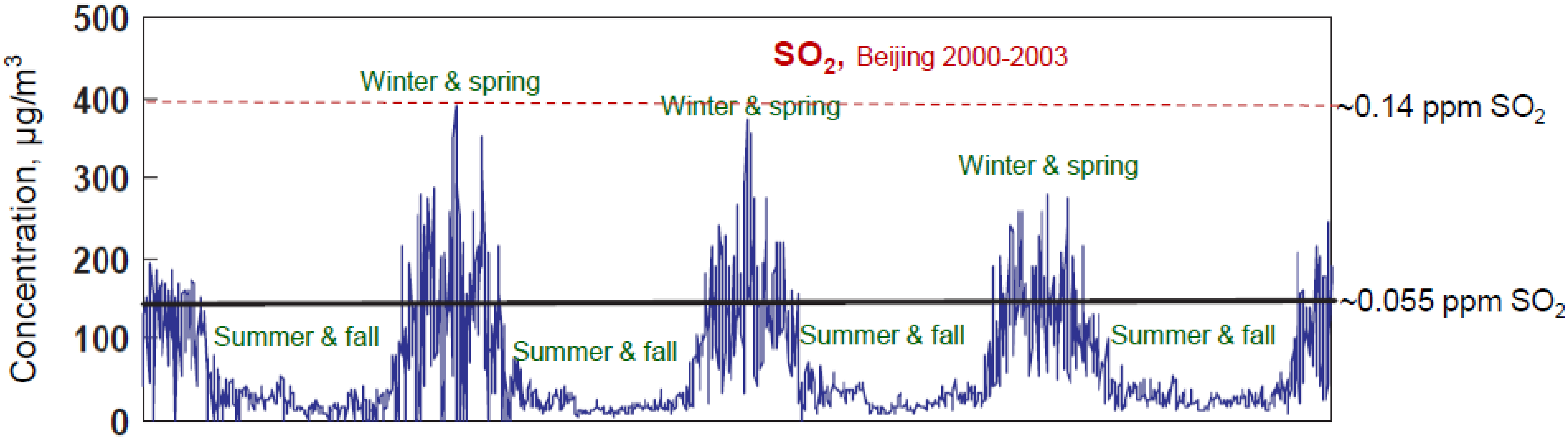
Wikipedia

On land-based turbines, *NOx* can be reduced by steam injection into combustor

Aerospace turbines might need their own high-temperature catalytic convertor

SO2 Corrosion Resistance

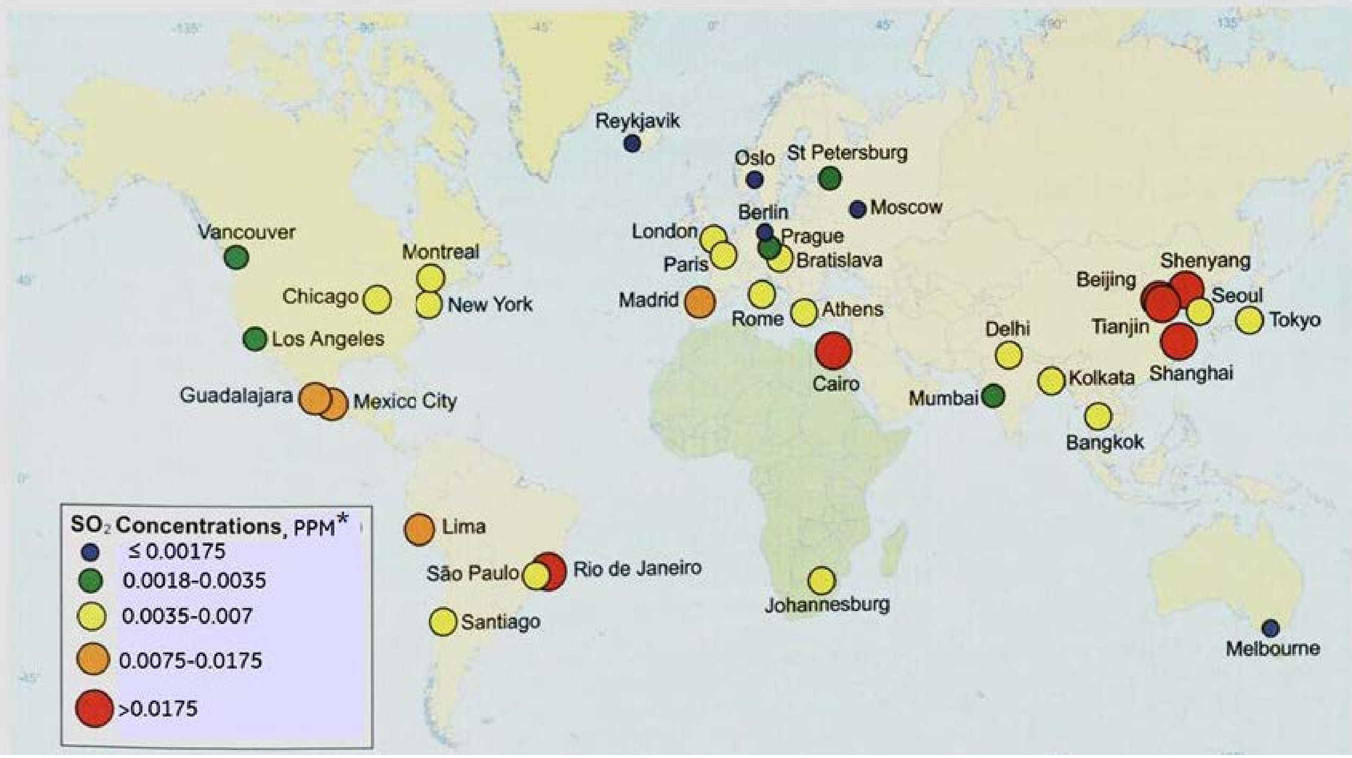
Growing problem: rising SO2 levels in air in many cities around the world
Probably will require extensive modification of bond-coat alloys.



SO_2 Corrosion Resistance

Growing problem: rising SO2 levels in air in many cities around the world.
Current bond-coat alloys were designed for much lower SO2 levels.
Solution: probably will require extensive modification of bond-coat alloys.

Source: R. Sokhi, World Atlas of Atmospheric Pollution, Anthem Press, New York, 2008



Summary and Future Directions

Identifying the next generation thermal barrier coatings remains a major challenge

- Low thermal conductivity at high temperatures is a *necessary but not sufficient* criterion.
- Thermal conductivity at low temperatures is relatively un-important and not a good guide to high-temperature conductivity
- High fracture toughness at high temperatures is also a necessary requirement.
- Thermal barrier coatings are part of a dynamically evolving and interacting system.
- Bond-coat and superalloy must also be morphologically stable, especially on thermal cycling

Future Directions

- Development of *in-situ* monitoring, particularly of coating temperatures and damage.
- Operation in air containing higher SO2 concentrations.
- Coatings for turbines using alternative fuels.
- Plenty of inter-disciplinary research and development opportunities
- Success will require a large scale, multidisciplinary approach and extensive collaborations

Want to Know More ?

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MRS Bulletin

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Advancing materials. Improving the quality of life.

Thermal-barrier coatings for more efficient gas-turbine engines

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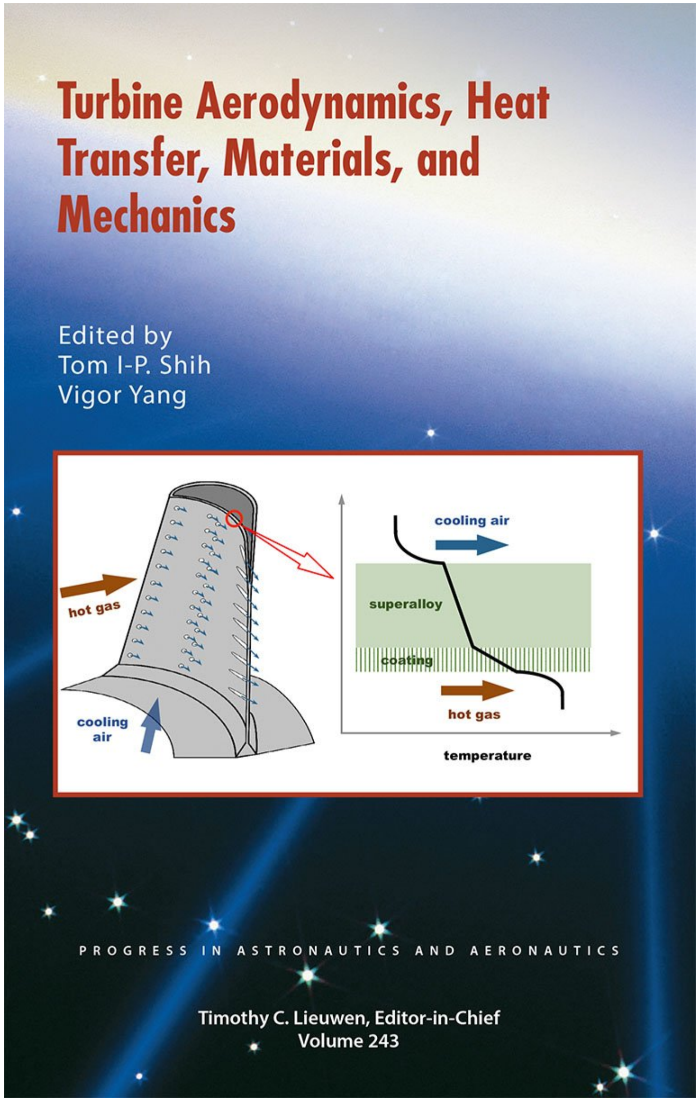

Turbine Aerodynamics, Heat Transfer, Materials, and Mechanics

Edited by
Tom I-P. Shih
Vigor Yang

PROGRESS IN ASTRONAUTICS AND AERONAUTICS

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