Manufacturing Science of Layered Multifunctional coatings

Sanjay Sampath, Gopal Dwivedi, Vaishak Viswanathan

DOE UTSR Meeting, Nov 2015

Center for Thermal Spray Research
AT STONY BROOK UNIVERSITY

Hot section coatings having been critical enablers in recent years

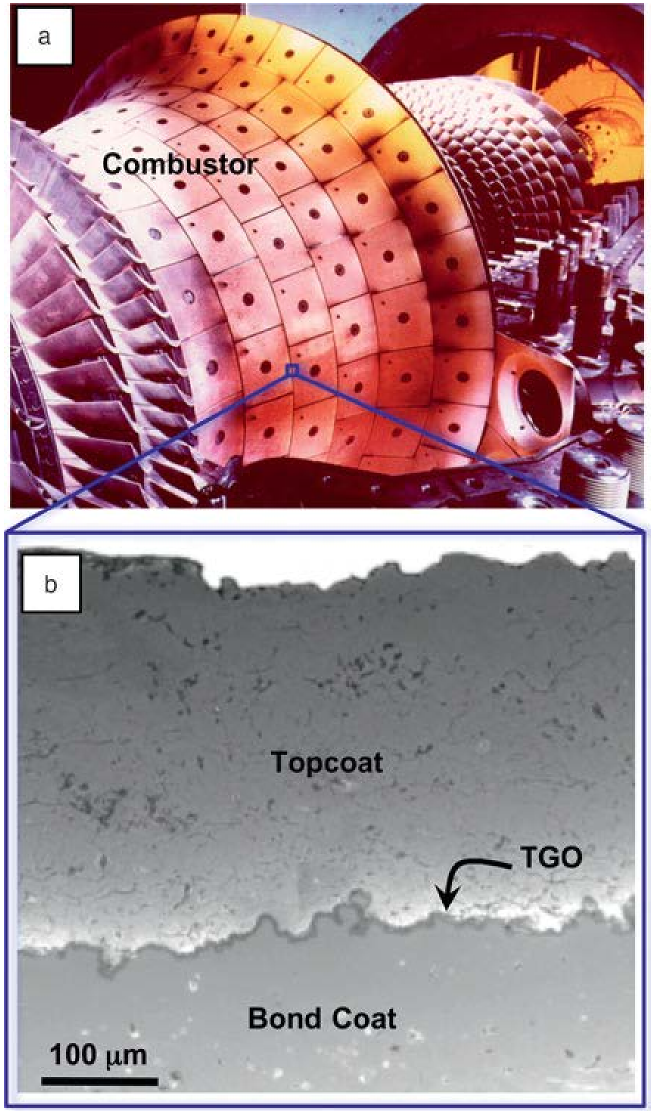
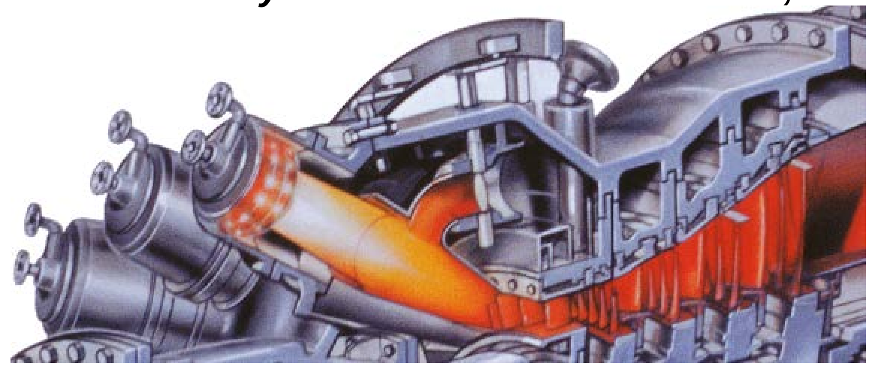
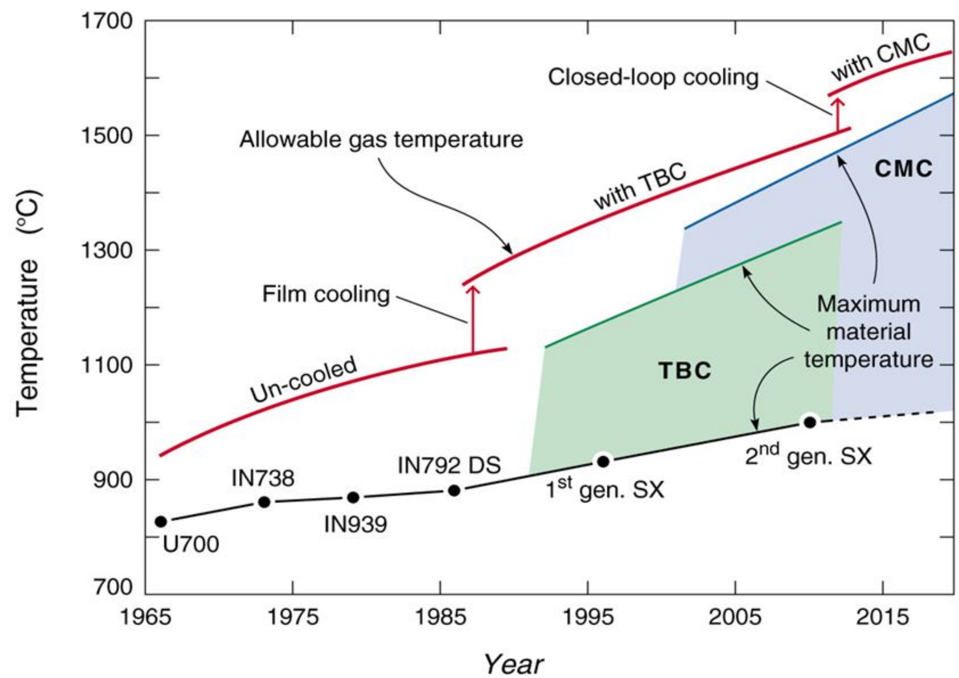


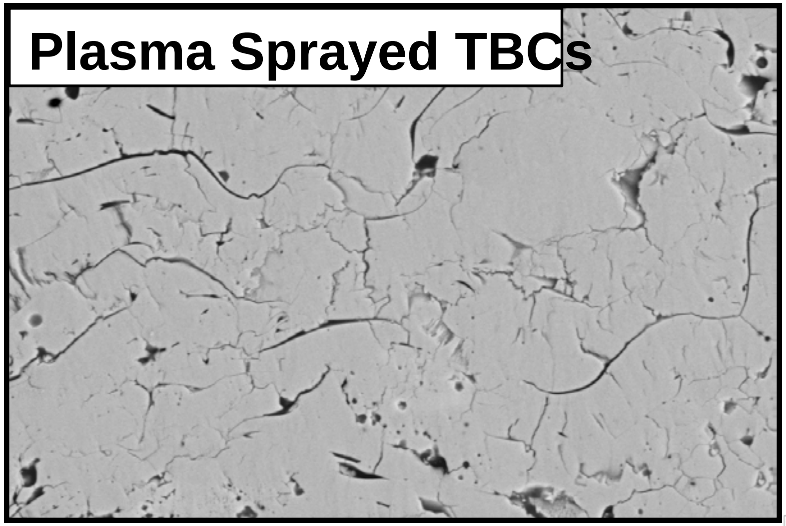
Photo Courtesy – Dr. Ramesh Subramanian, Siemens

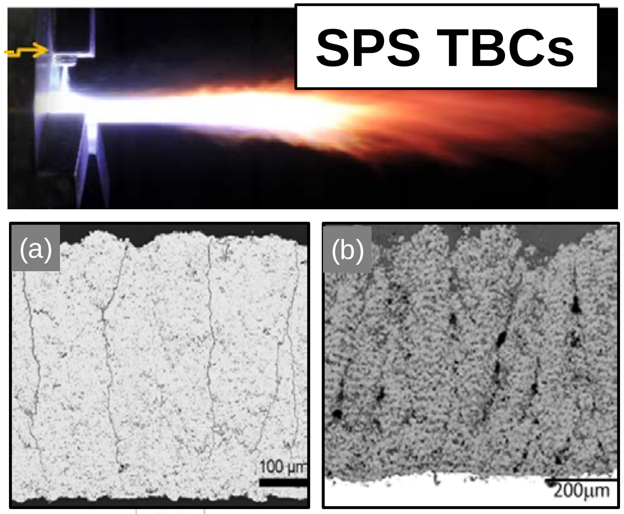


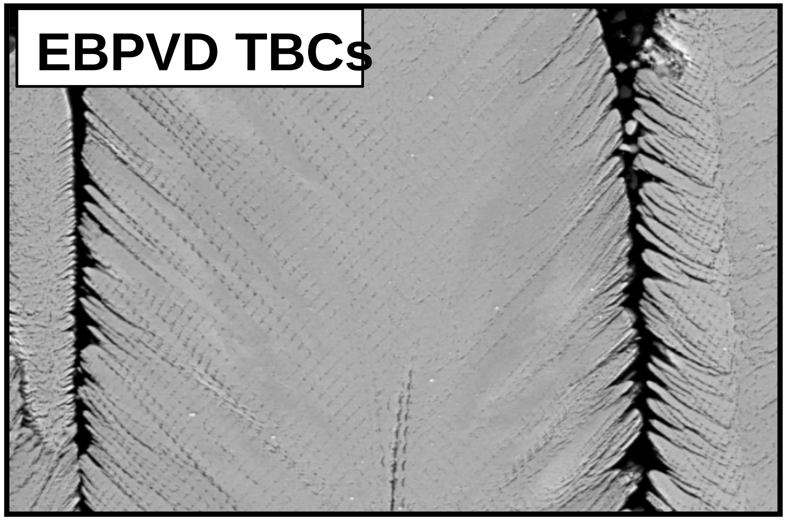


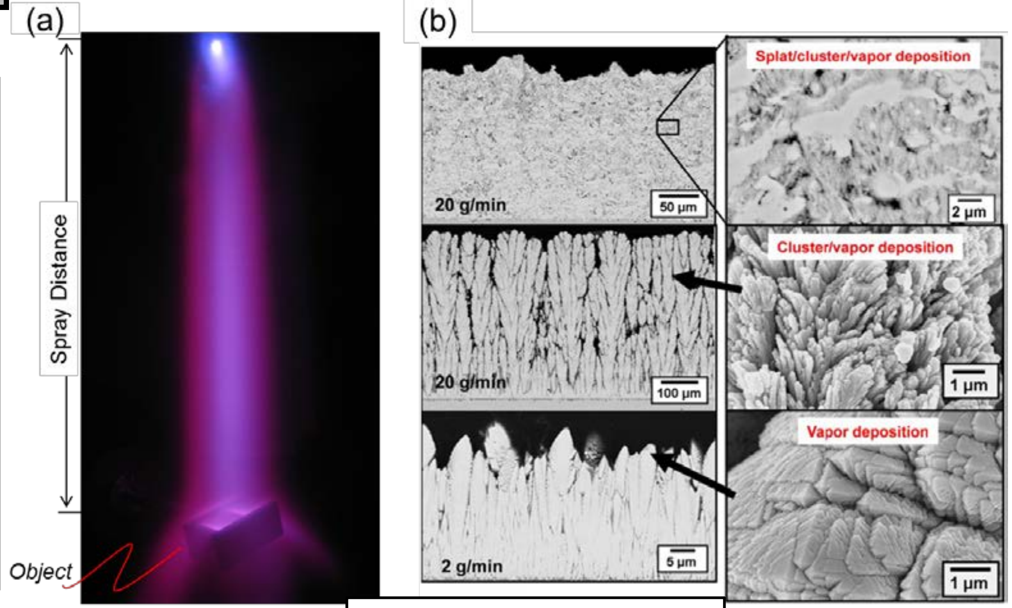
These are complex Dynamically Evolving Structures

TBC Manufacturing Technologies



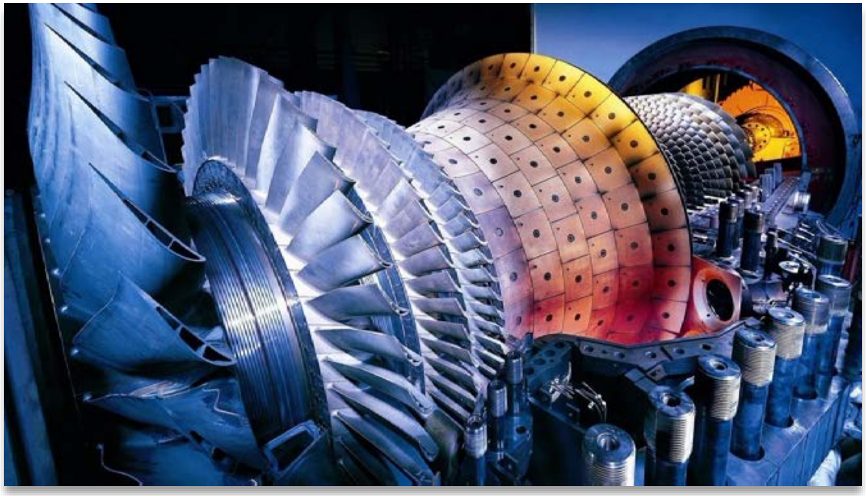


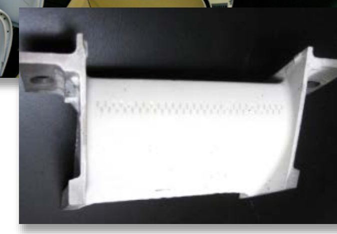


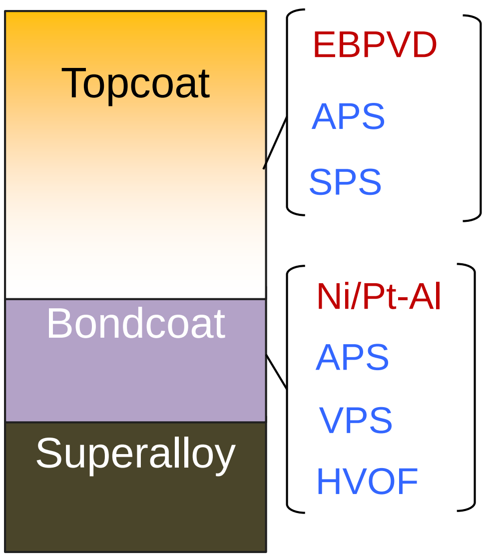


PSPVD TBCs

Thermal spray manufacturing variants





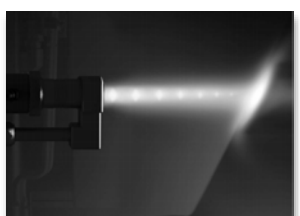



LPPS


APS

SPS

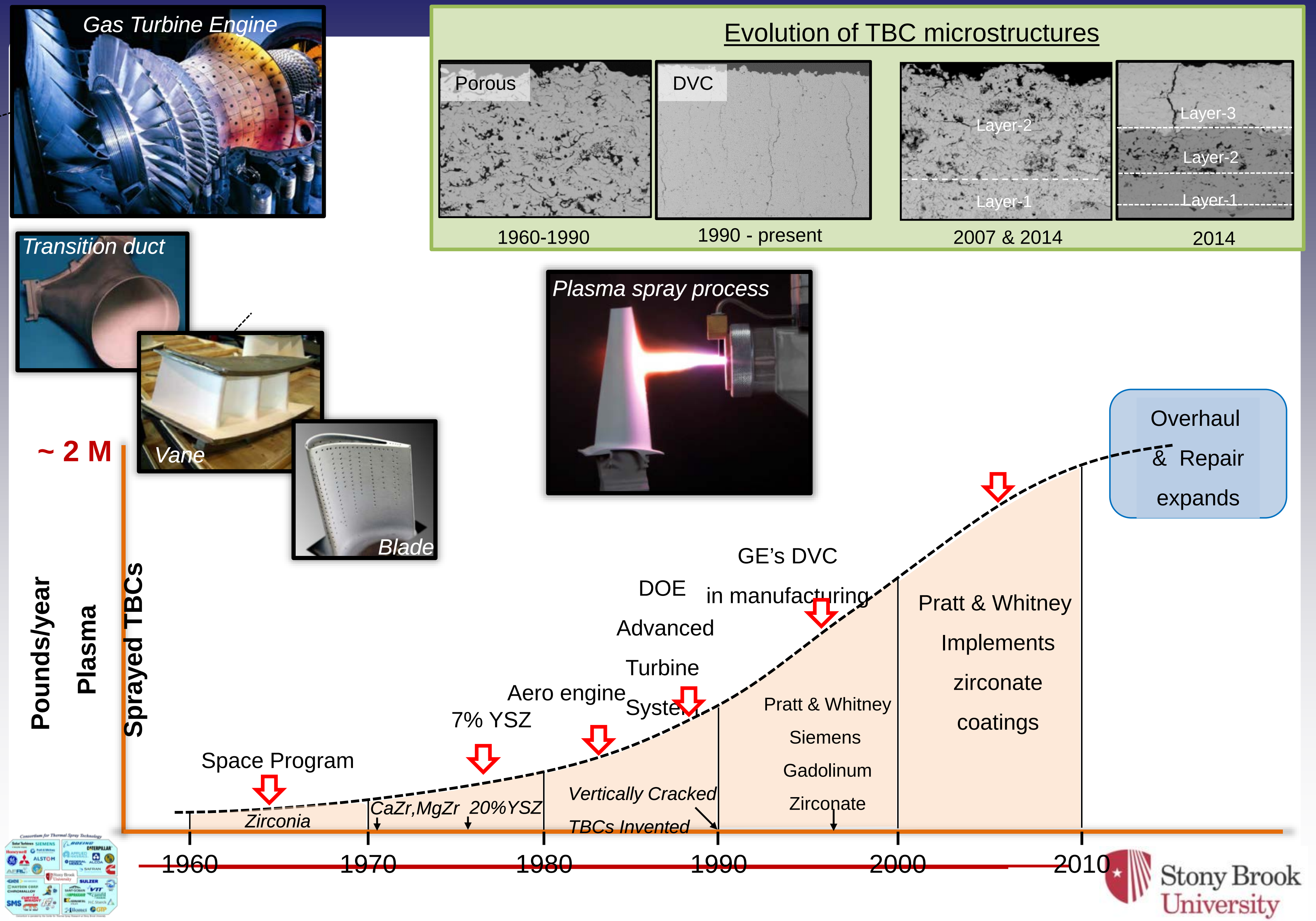

High Through-put APS


Liquid Fuel HVOF


Gas Fuel HVOF


VPS

Evolution of TBC Materials and Thermal Spray Manufacturing



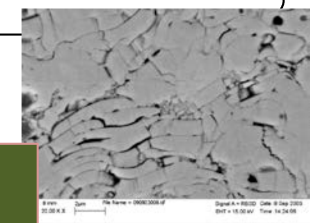
APS TBC fabrication involves numerous variables

- Composition
- Morphology
- Size Distribution

- Plume Orientation
- Plume Spread
- Particle State

- Feed rate
- Raster / Rotation Rate
- Angle of Deposition

- Defect (Cracks & Pores)
- Crystal (Phase & Composition)
- Layering (Splat Characteristics)
- Grain (Size)
- Anisotropy



Feedstock Characteristics

Component Performance

Process Variables

Implications

Extreme variability – local and global

Infant mortality and poor reliability

Difficult to incorporate into life models

Residual Stress,
Stiffness, Elastic Modulus

- Functional
Electrical / Thermal transport,
Wear / Erosion / Corrosion Resistance

- Equipment related
(Gun, Gases, Power)
- Particle Injection

- Chemistry
- Adsorbates
- Temperature
- Roughness

Multitude of applicators locations

Multitude of spray devices & parameters

Multitude of evaluation Criteria and variants

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TBC Processing Reliability/Quality is becoming increasingly important

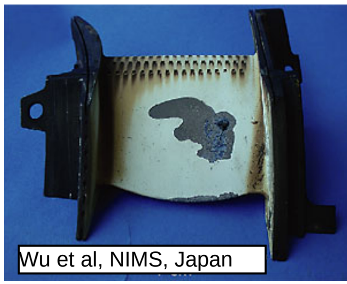
Traditional Role of TBC ⇒ Life Extension

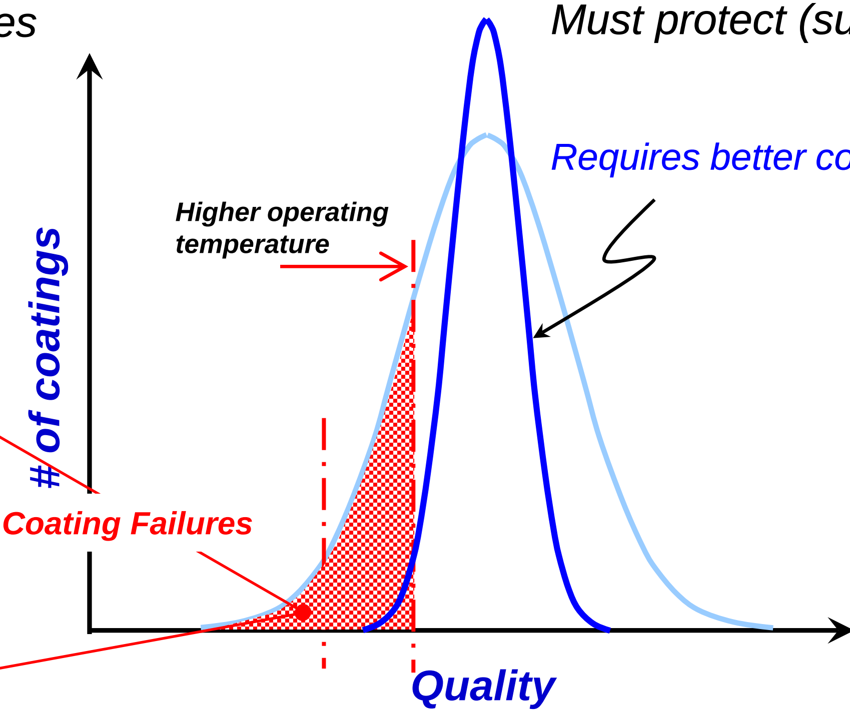
Extra protection on substrates

Future Role of TBC ⇒ Prime Reliant

Must protect (super-alloy) substrates

Requires better control of quality variability





Requires ….

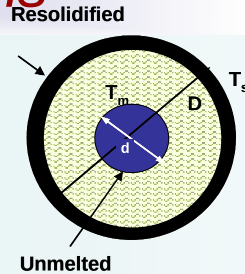
- *Robust scientific understanding of manufacturing process*
- *Effective tool to* ***assess coating quality*** *and* ***process/coating reliability***

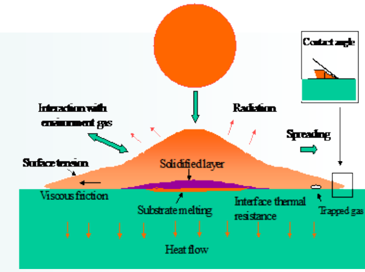
(both from development and manufacturing point of view)

Plasma spray is a highly complex deposition process: Materials Synthesized from Extreme Conditions

NON-EQUILIBRIUM PROCESSING

- Ultra rapid heating and phase change
- Rapid cooling and solidification
- Impact pressure induced transformations

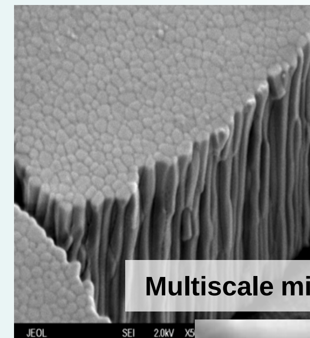


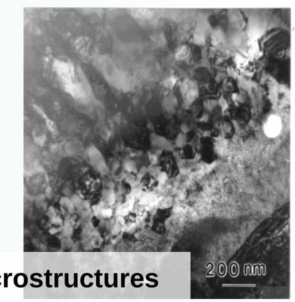


Microsecond time scales

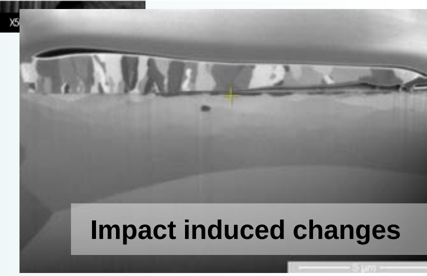
MULTI-SCALE STRUCTURE AND PROPERTIES

- Nano-, micro-, meso- and macro-scales
- Defect-dominated attributes





Multiscale microstructures

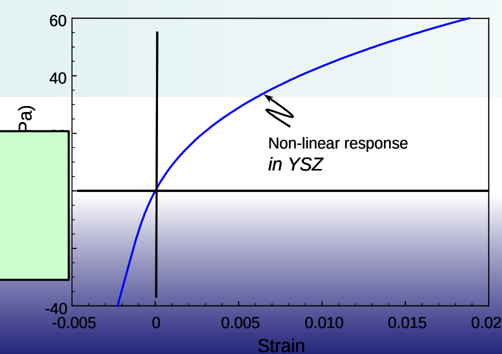


Impact induced changes

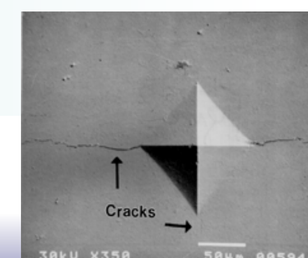
HIGHLY ANISOTROPIC BEHAVIOR

- Process-induced residual stresses
- Anisotropic properties across length scales
- Non-linear elastic behavior

Non-linear response ceramics

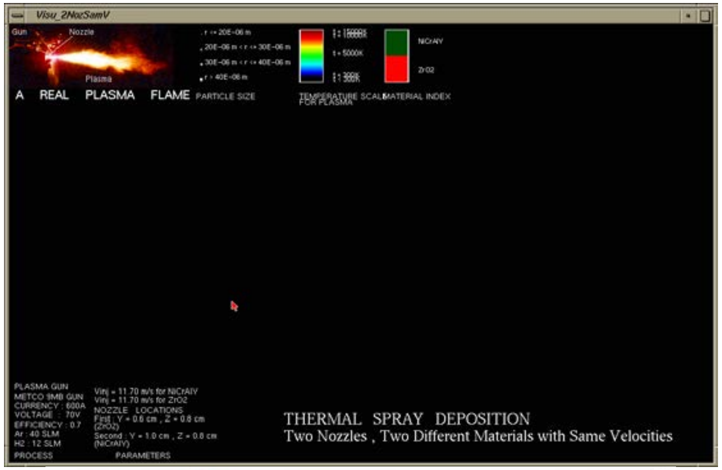


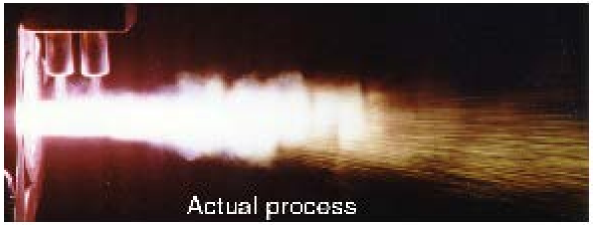
Anisotropy

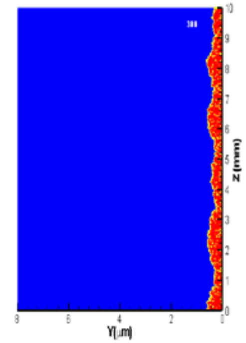


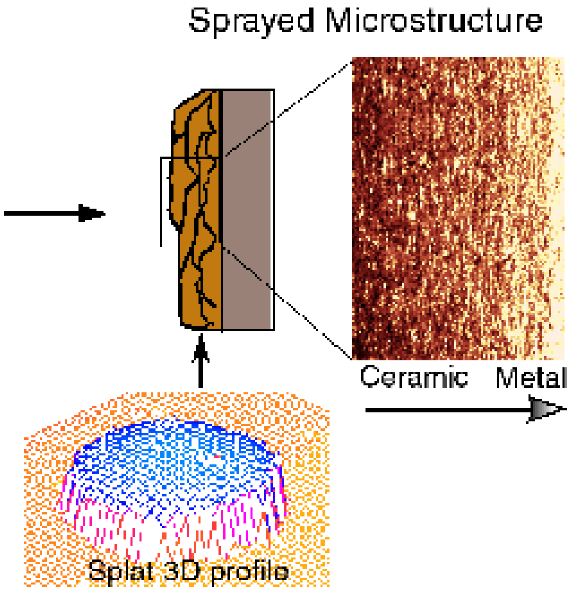
Need to develop interdisciplinary Processing/Manufacturing Science

Center for Thermal Spray Research at Stony Brook University





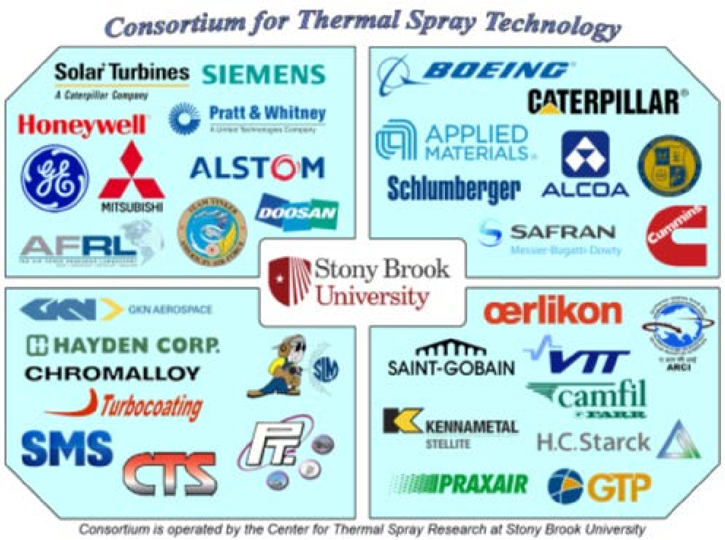




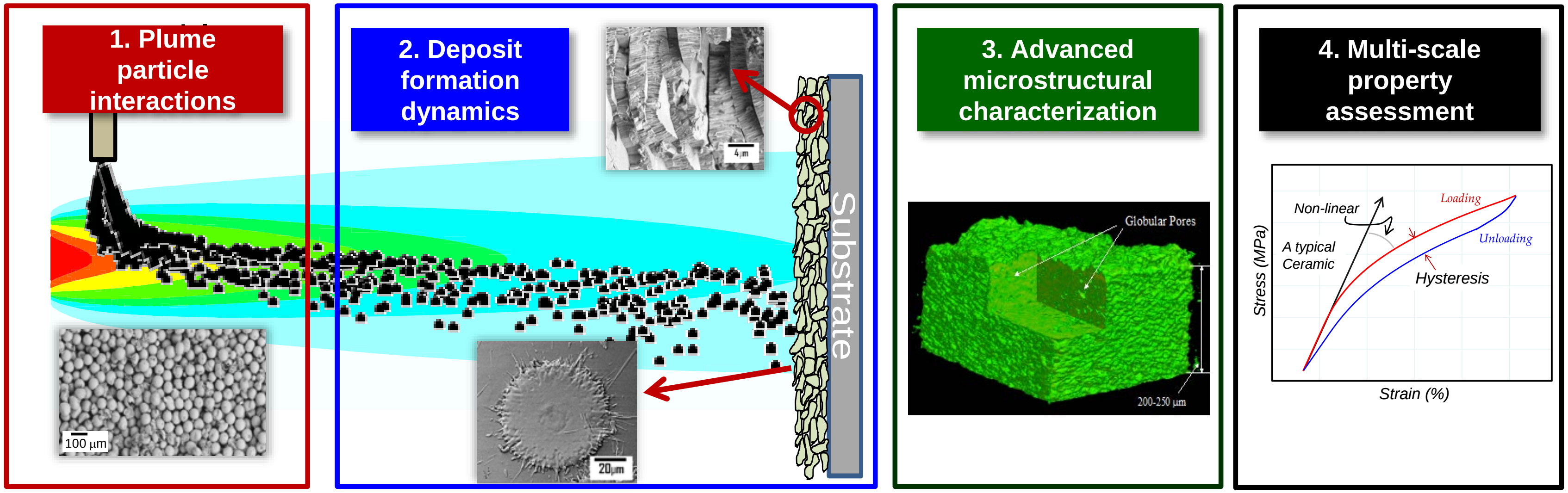
Established as an NSF MRSEC in 1996

Integrated Interdisciplinary Research Aimed at Advancing Science, Technology and Outreach for Thermal Spray Technology

Linking Research to Practice



Tools, Technologies and Models are now available at each step



Industry has started to adopt these capabilities for manufacturing control,

Enhanced new processes, novel designs, models and applications

Article in Integrating Materials and Manufacturing Innovation

PAINT: Partnership for Accelerated Insertion of New Technology:

Case Study for Thermal Spray

http://www.immijournal.com/content/pdf/2193-9772-2-1.pdf

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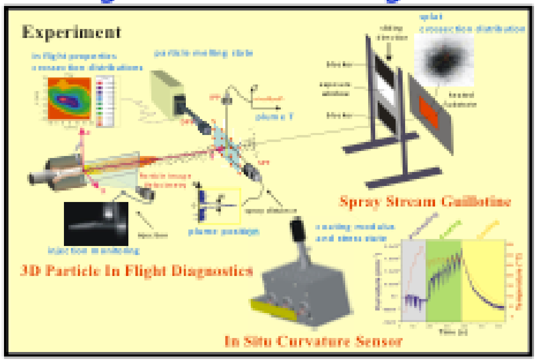
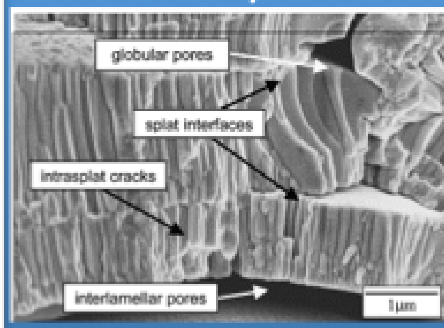
A large portfolio of scientific information has been developed manufacturing science of TBCs

Integrated Process Diagnostics

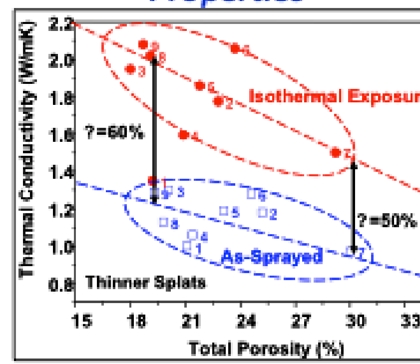


Neutron-based Assessment of Pore Distribution (3D)

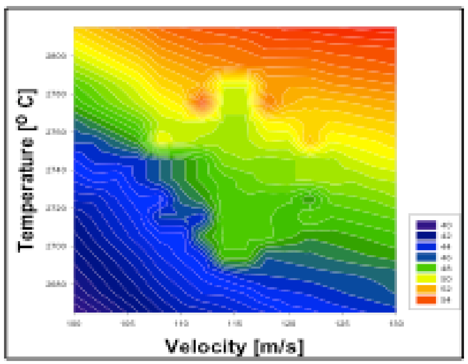
Properties dominated by defects, nanoscale grains, splats interfaces and interphases



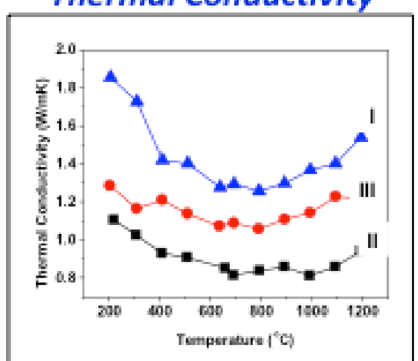
Thermal Aging Effects on Properties



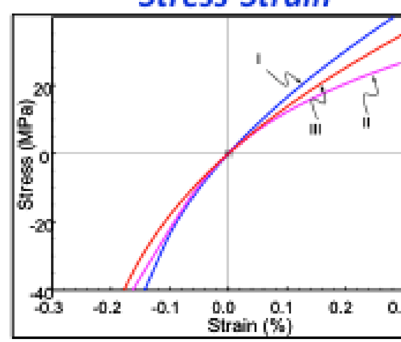
2nd Order Process Map Elastic Modulus Contours



Temperature-Dependent Thermal Conductivity



Nonlinear Stress-Strain



1999- Present

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Demonstrated Industrial Benefits of Advanced Manufacturing Science through Joint Experiments: 32 Field Trips in the Last 7 Years

Post-docs and students facilitate ***effective knowledge transfer to industrial workforce through cooperative experimentation*** using advanced technologies and scientific methodologies developed in academia.

Simultaneously, they benefit from the industrial insight and priorities

Stony Brook-Caterpillar Team

Volvo Sweden Field Trip

- Residual Stress and Evolution
- Coating Modulus Evaluation
- Diagnostics
- Coatings Characterization

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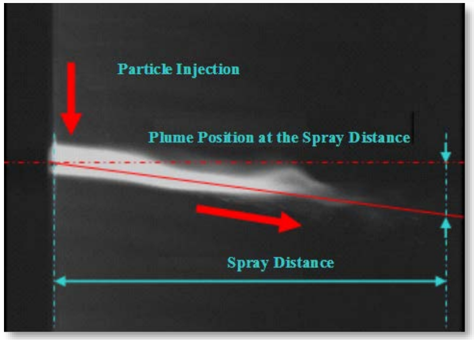
Companies involved in field trips

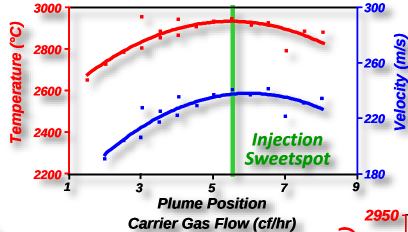
University West · CHROMALLOY NEW YORK · Universität Stuttgart Germany · HAYDEN CORP. · CATERPILLAR · CTS · SULZER · JÜLICH FORSCHUNGSZENTRUM · PRAXAIR TAFA · Alcoa Howmet ALCOA · PRAXAIR · VOLVO AERO · FEDERAL MOGUL · Deloro Stellite · ALSTOM · MITSUBISHI POWER SYSTEMS

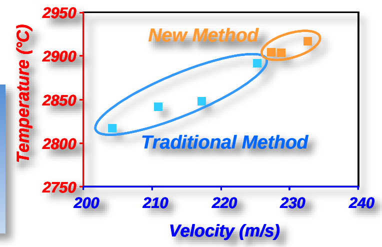
Advanced science impacts both efficiency and reliability

Observation

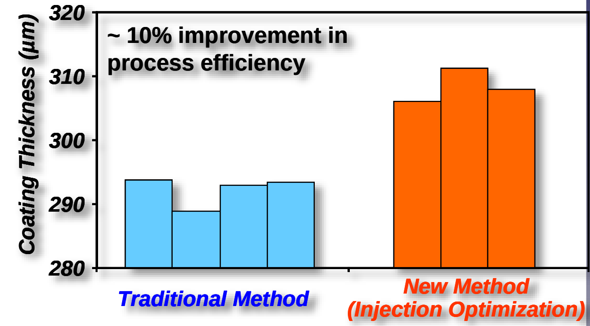
Observations of novel phenomena in thermal plasmas (injection sweet spot)







Successful testing of hypothesis in field: Tinker AF Base & Plasma Technology Inc.



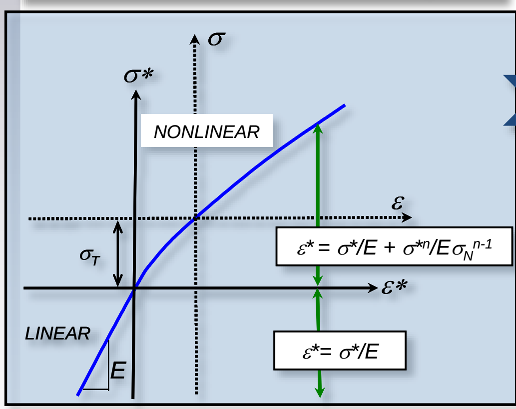
Proof of Concept Demo

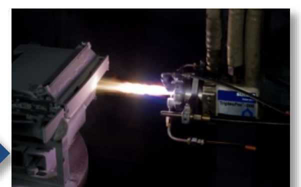
OUTCOME:

Procedures for simultaneously enhancing process efficiencies and reliability

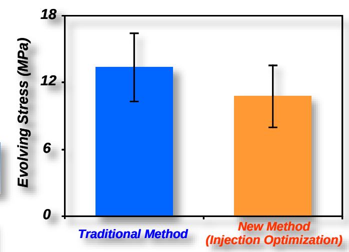
Fundamental Science

Observations and quantification of non-linear properties of ceramic coatings

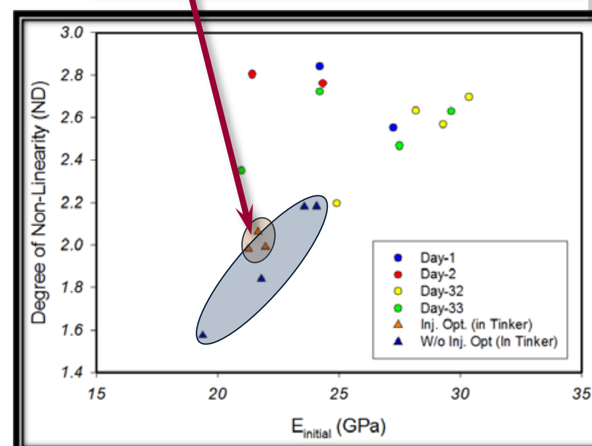




In situ process diagnostics



In situ & ex situ extraction of non-linear properties

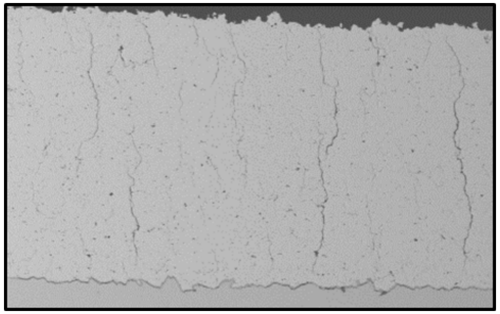


The Past and Future

Industrial perception of APS manufacturing as a constraint

- Lack of understanding of the scientific nuances
- Perception of poor Repeatability, Reproducibility and Reliability
- In effective control and metrology tools
- Lack of integrated understanding
- Disconnect between design, materials and processes

=> Implication: Manufacturing is a “burden”



With advanced science <u>manufacturing can be an enabler</u>

- Implemention of Segmented or Dense Vertically Cracked Coatings
  - (Directionally solidified, in-plane compliant coatings)
- Understanding the importance of toughness of metastable t” YSZ on durability
- Advanced process control through insitu sensor based feedback
- Predictive microstructures through maps, correlations and models
- Process-property guided layered engineering

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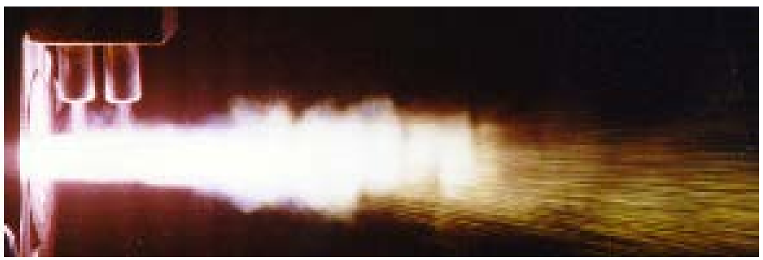
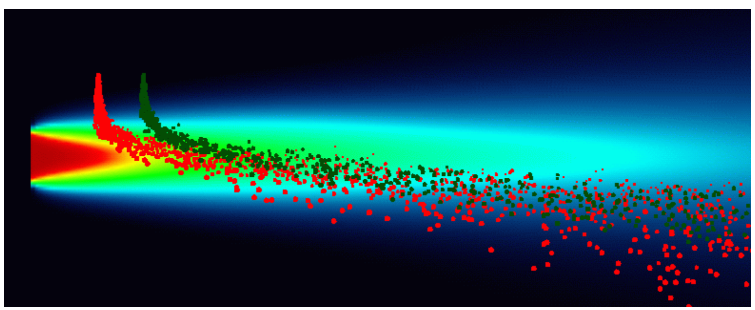
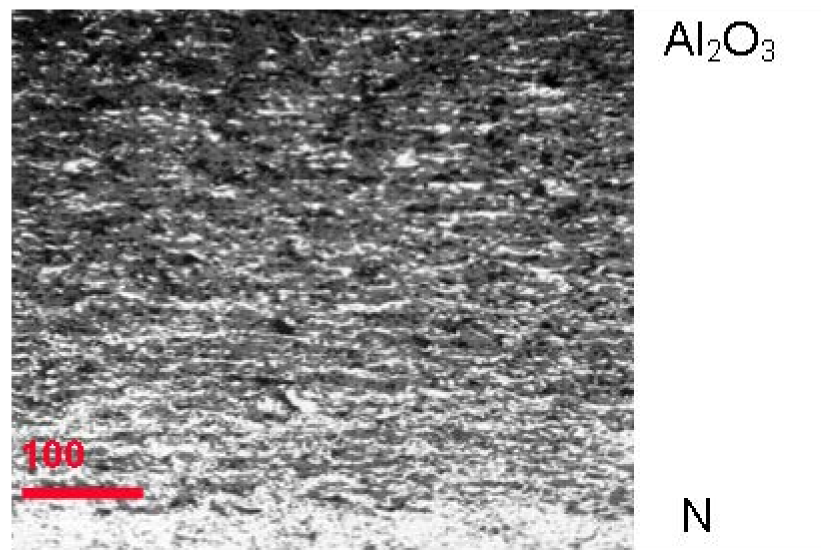
Thermal spray as an additive and layered manufacturing technology



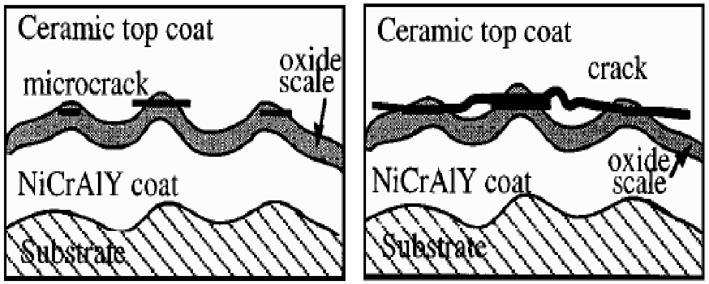




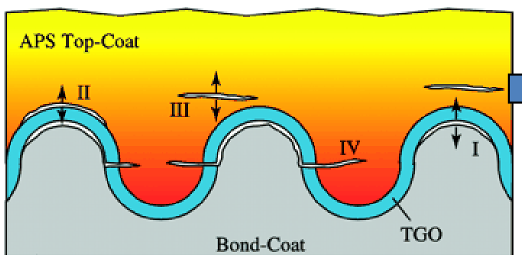
Bring Manufacturing Science and Novel Capabilities

to Expand Design and Materials Options

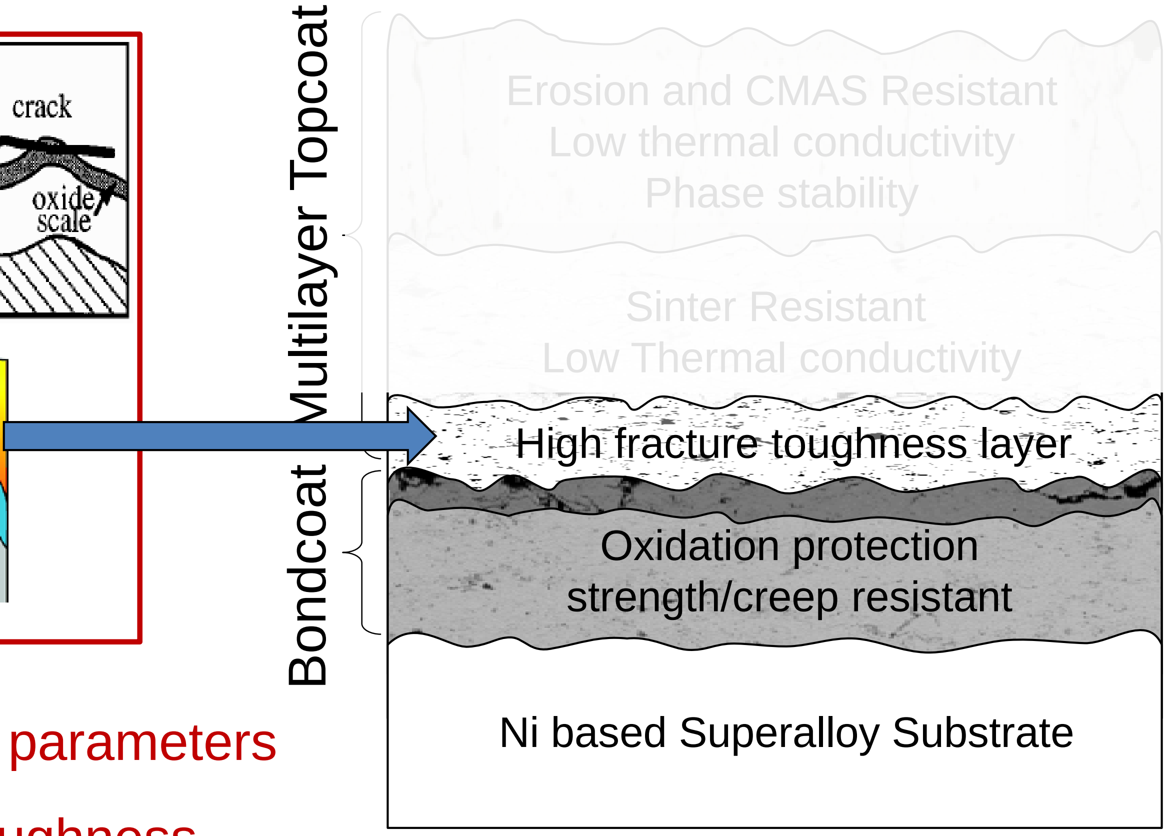
E.g. Optimal Layer Design for Improved Durability



Teixeira et al., JTST, 9(2), 2000—191



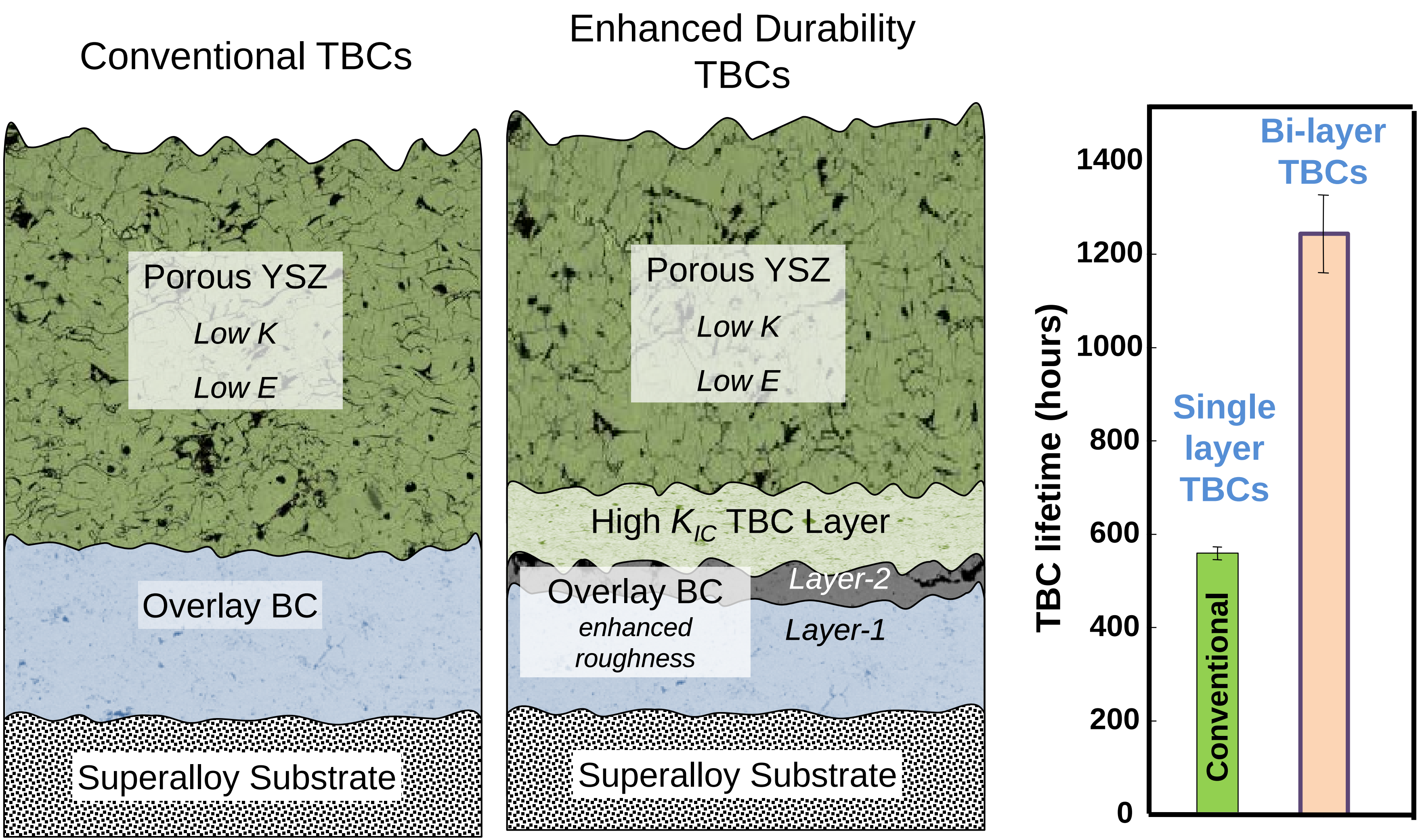
Padture et al., vol. 296,Science, 280, 2002



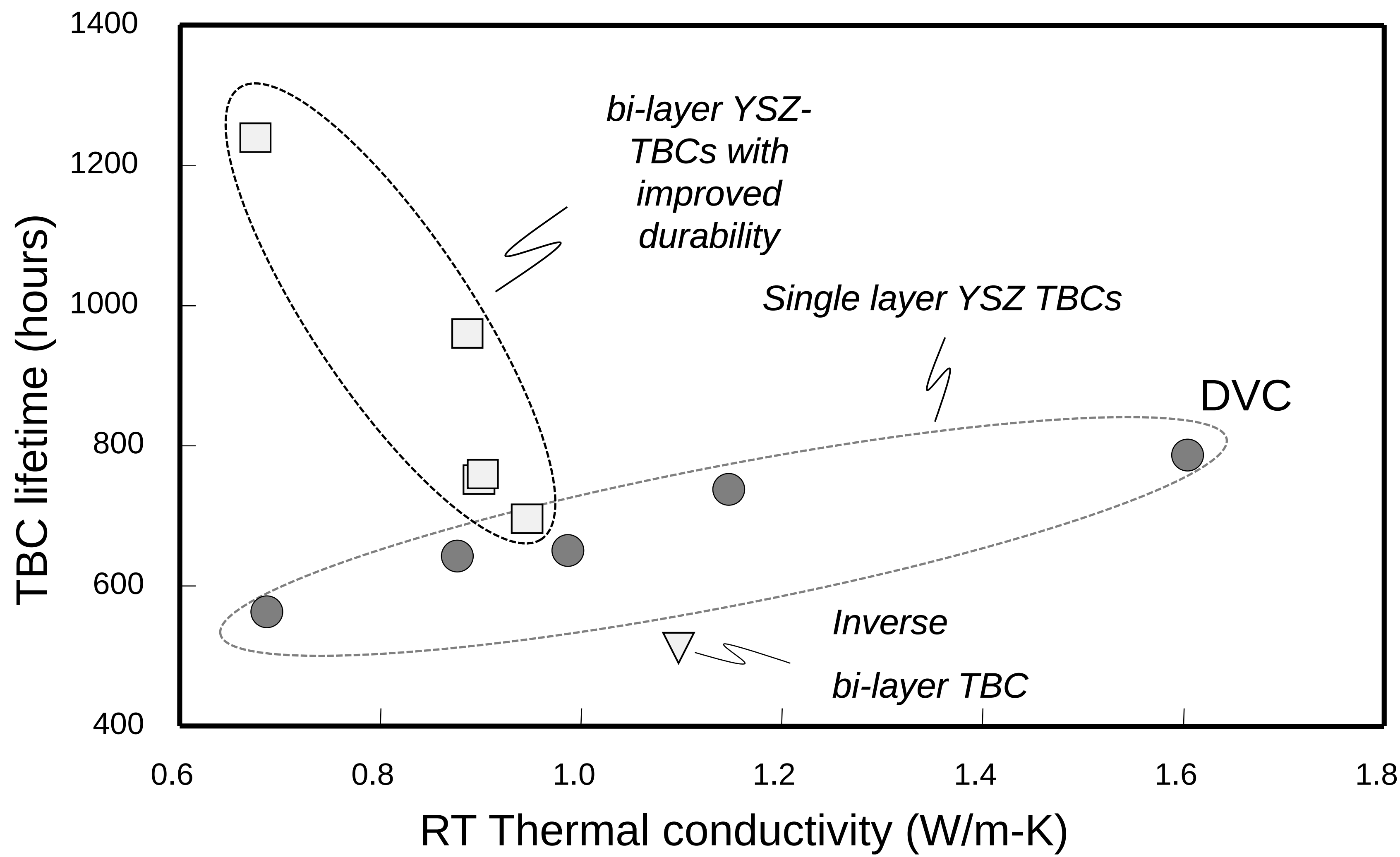
Critical microstructural parameters

- Intrinsic Material Toughness
- Manufactured Material Toughness

Toughness engineered multilayer TBCs



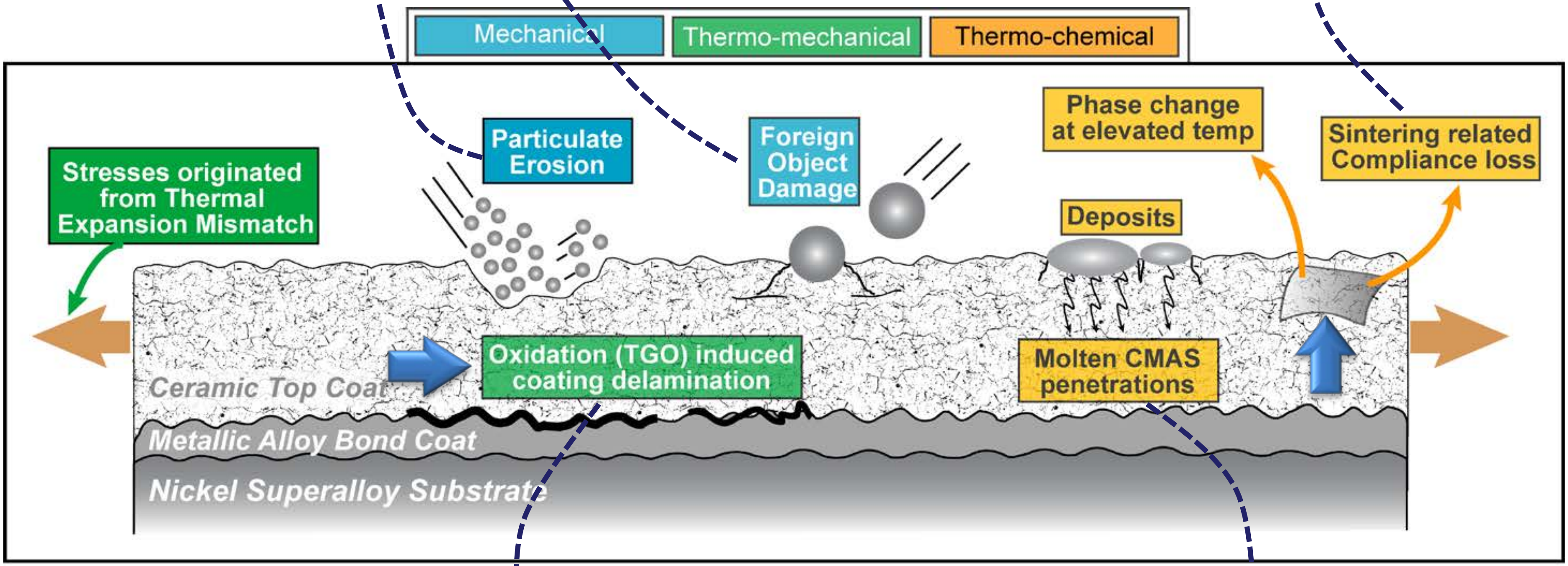
Simultaneous optimization of durability and functionality



Coatings experience multiple failure mechanisms

- Ceramic strength/toughness
- Coating density

- Ceramic coating compliance and ceramic chemistry
- Coating porosity/cracks



- Bond coat chemistry, Roughness
- Ceramic coating toughness
- Bond coat roughness
- Coating thickness

- Ceramic coating composition
- Pore architecture
- Coating thickness

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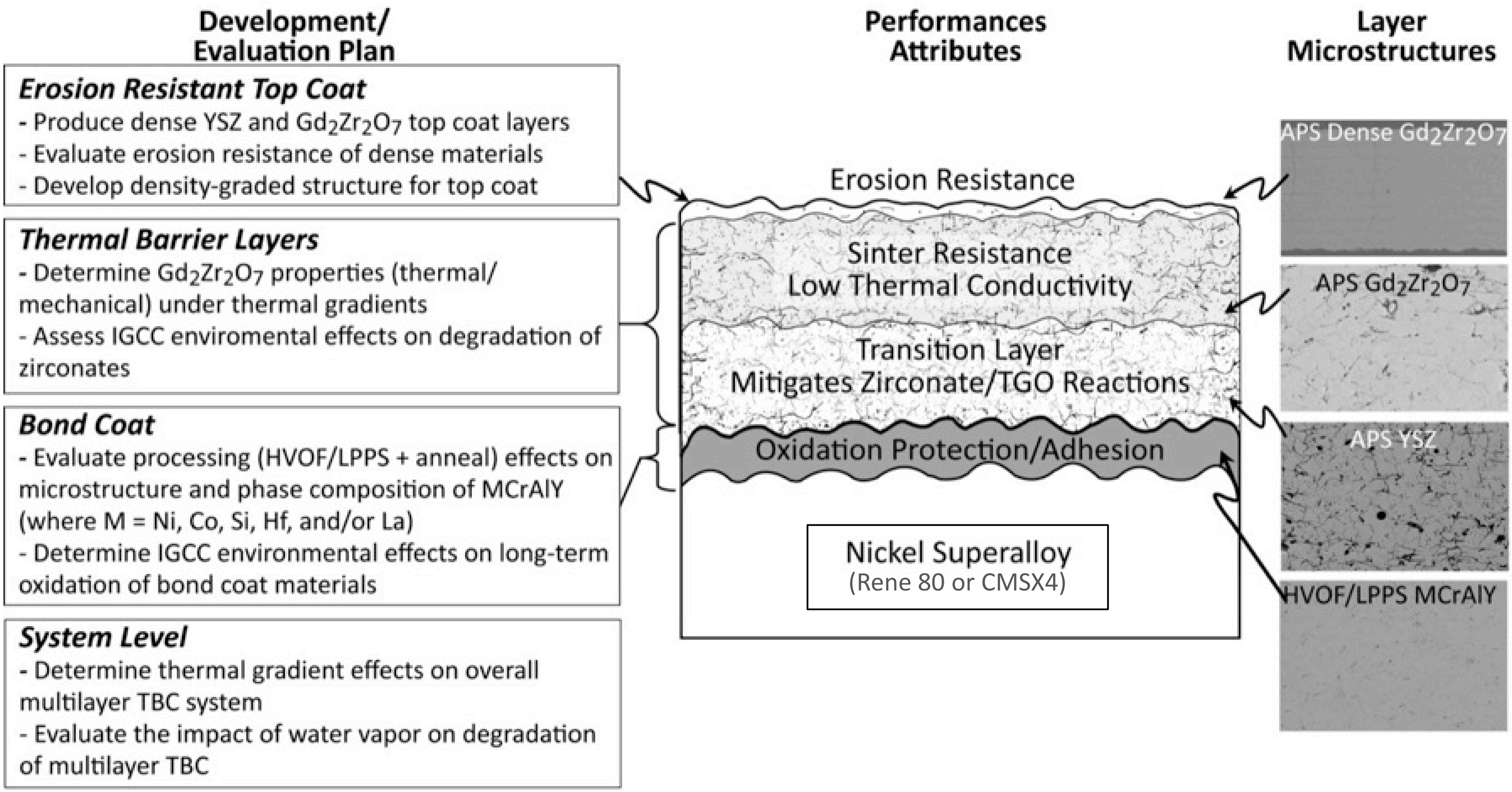
Multilayered architecture to combat multifunctional requirements



Plasma spray is naturally suited for such layered manufacturing

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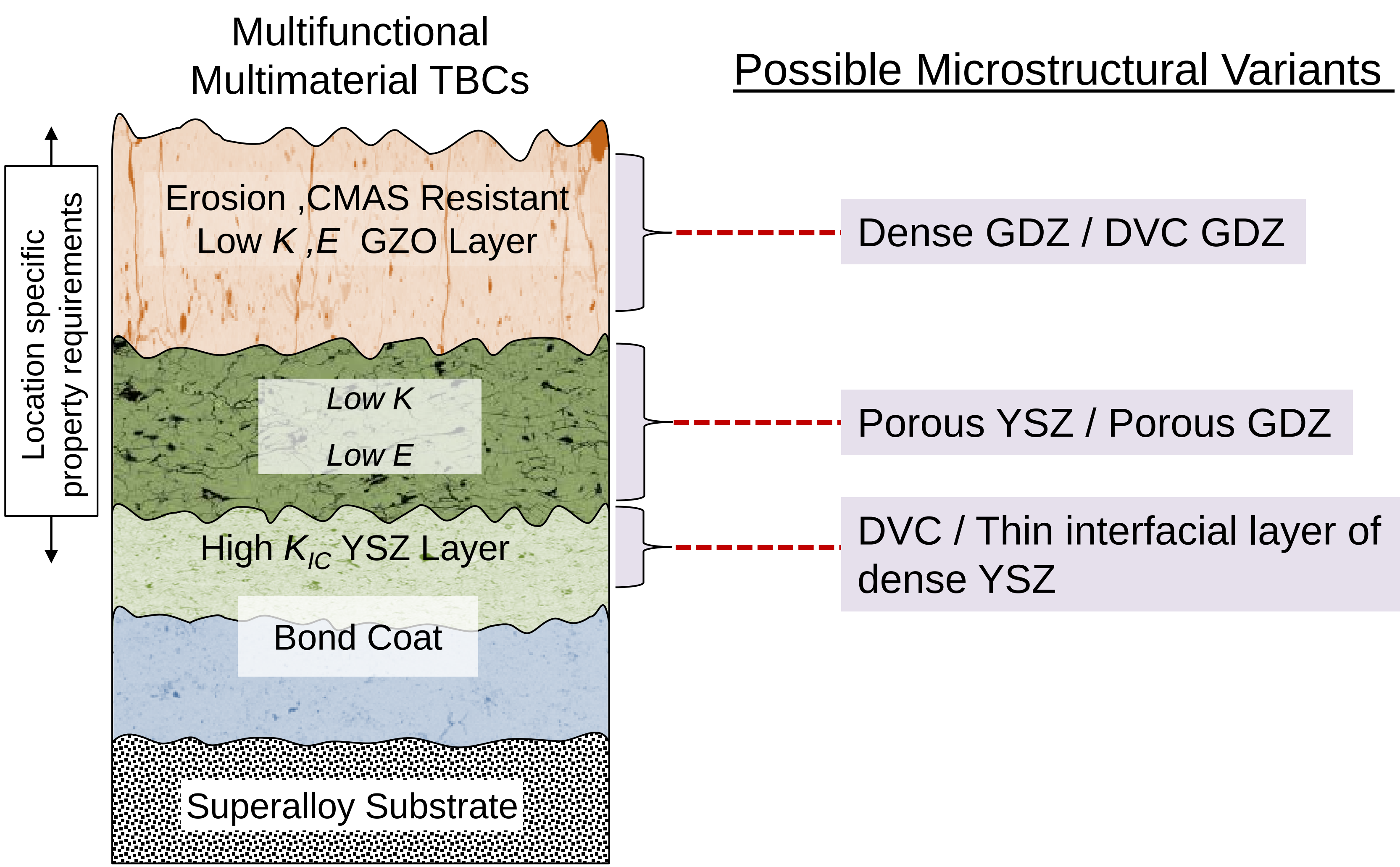
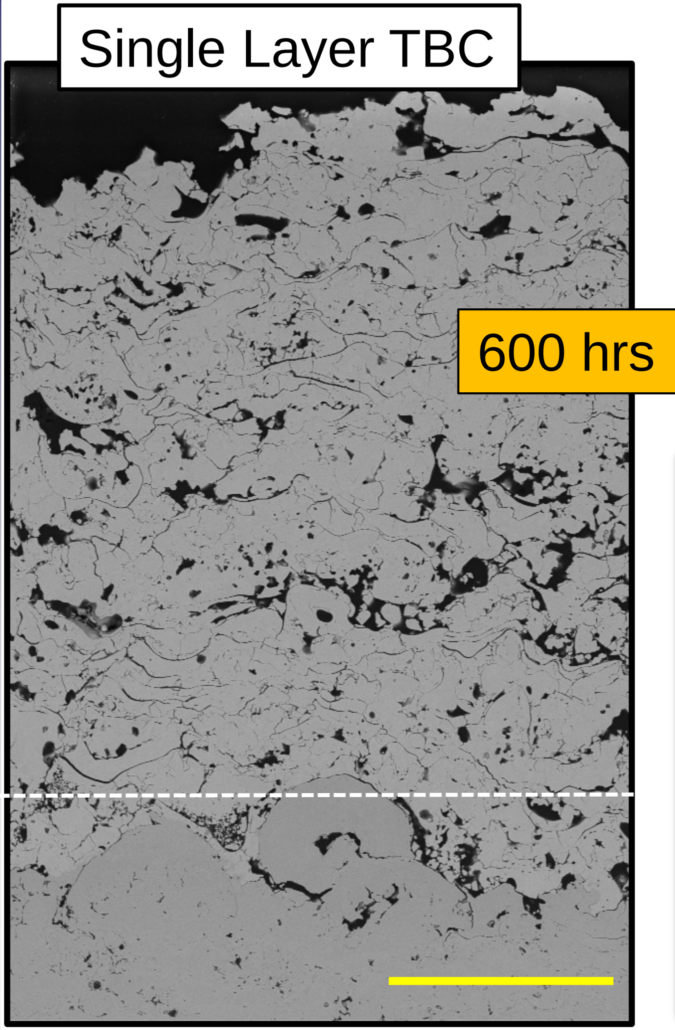
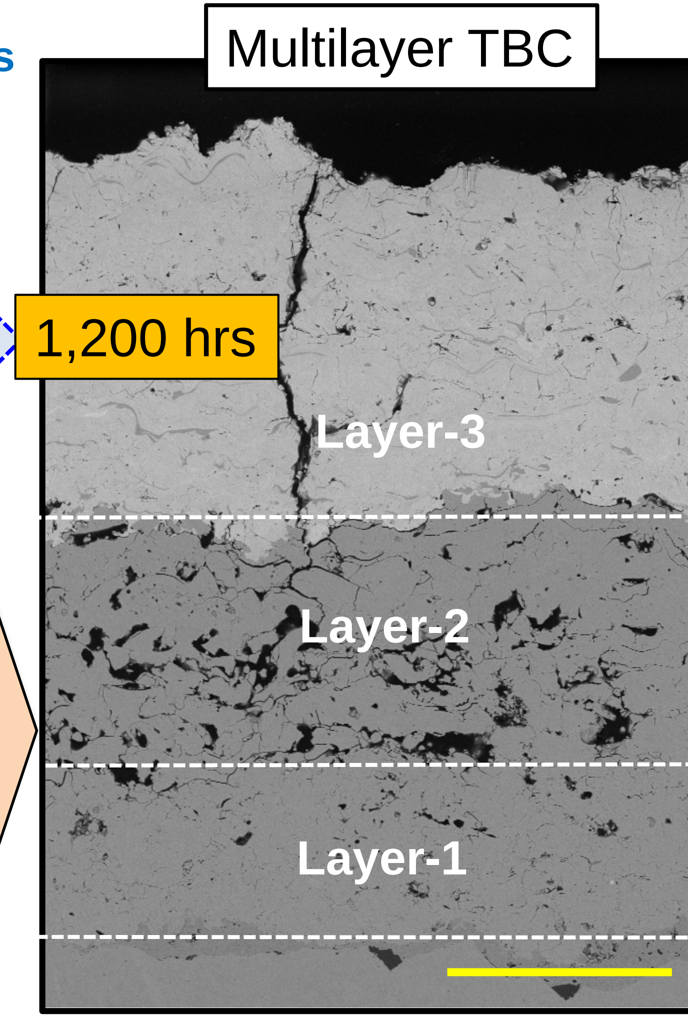
Design consideration for YSZ- GDZ multilayer architectures



The multilayer TBC architecture



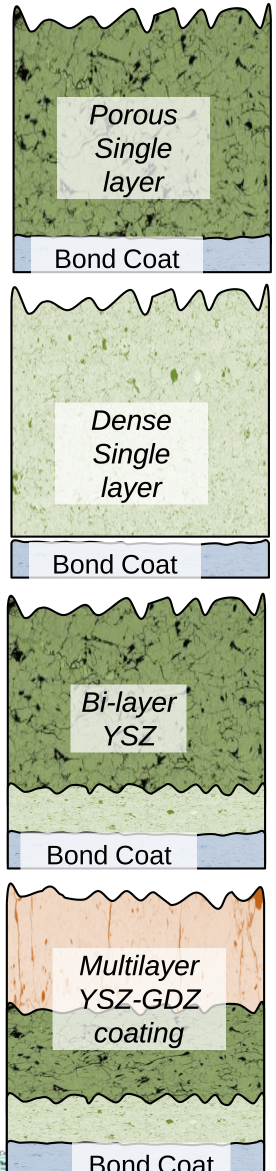
- 50 +coating conditions
- 40+ architectures
- 600+ FCT samples



- Adequate erosion resistance
- Significantly higher durability
- CMAS resistance
- Mechanisms and Methodology to incorporate andy new composition

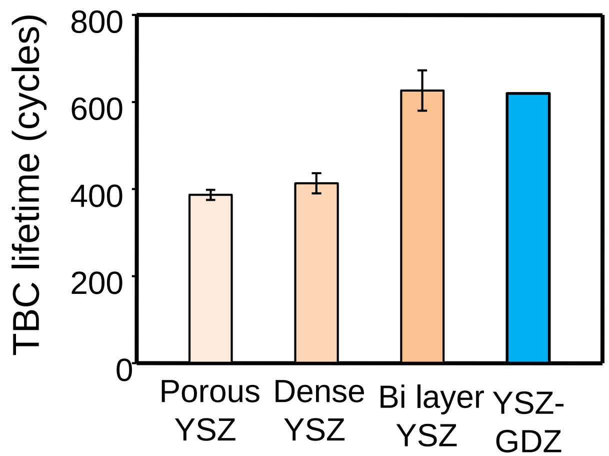
Validated through FCT testing both in house, ORNL and industry (Siemens, GE) during UTSR program

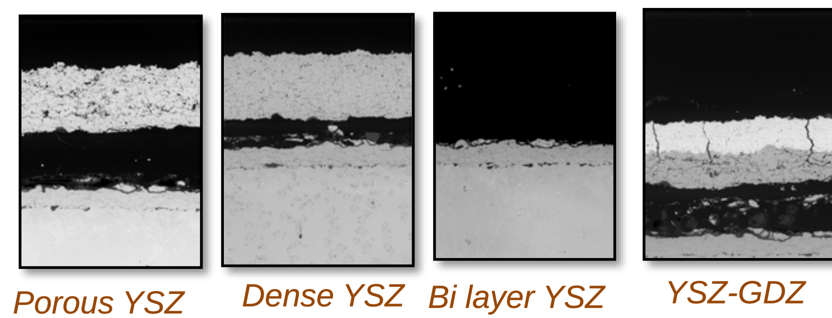
Successfully validated at industrial sites (GE, Siemens, Praxair)



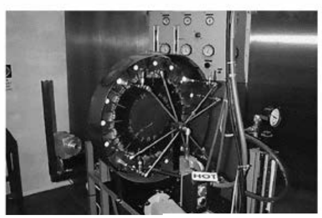
FCT: 2000F (1093°C), 45 mins cycling

Courtesy: Ben Nagaraj





All failed at BC/TC interface



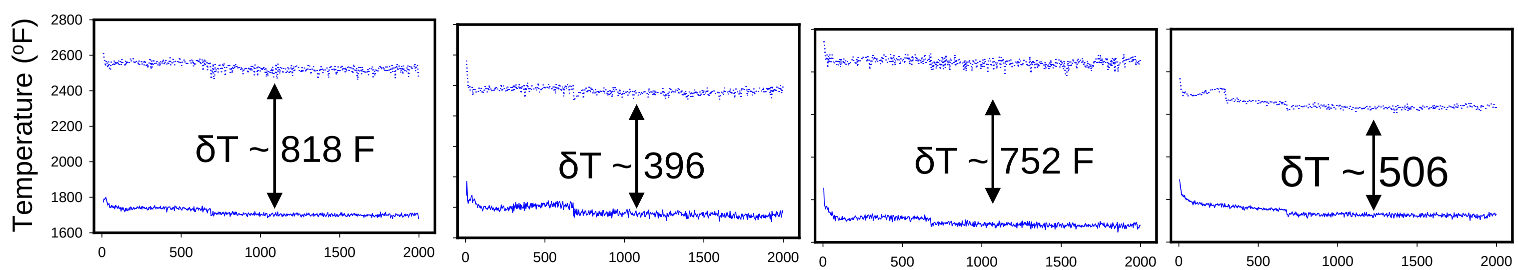
PRAXAIR SURFACE TECHNOLOGIES

JETS test

Courtesy: Dr. Li Li

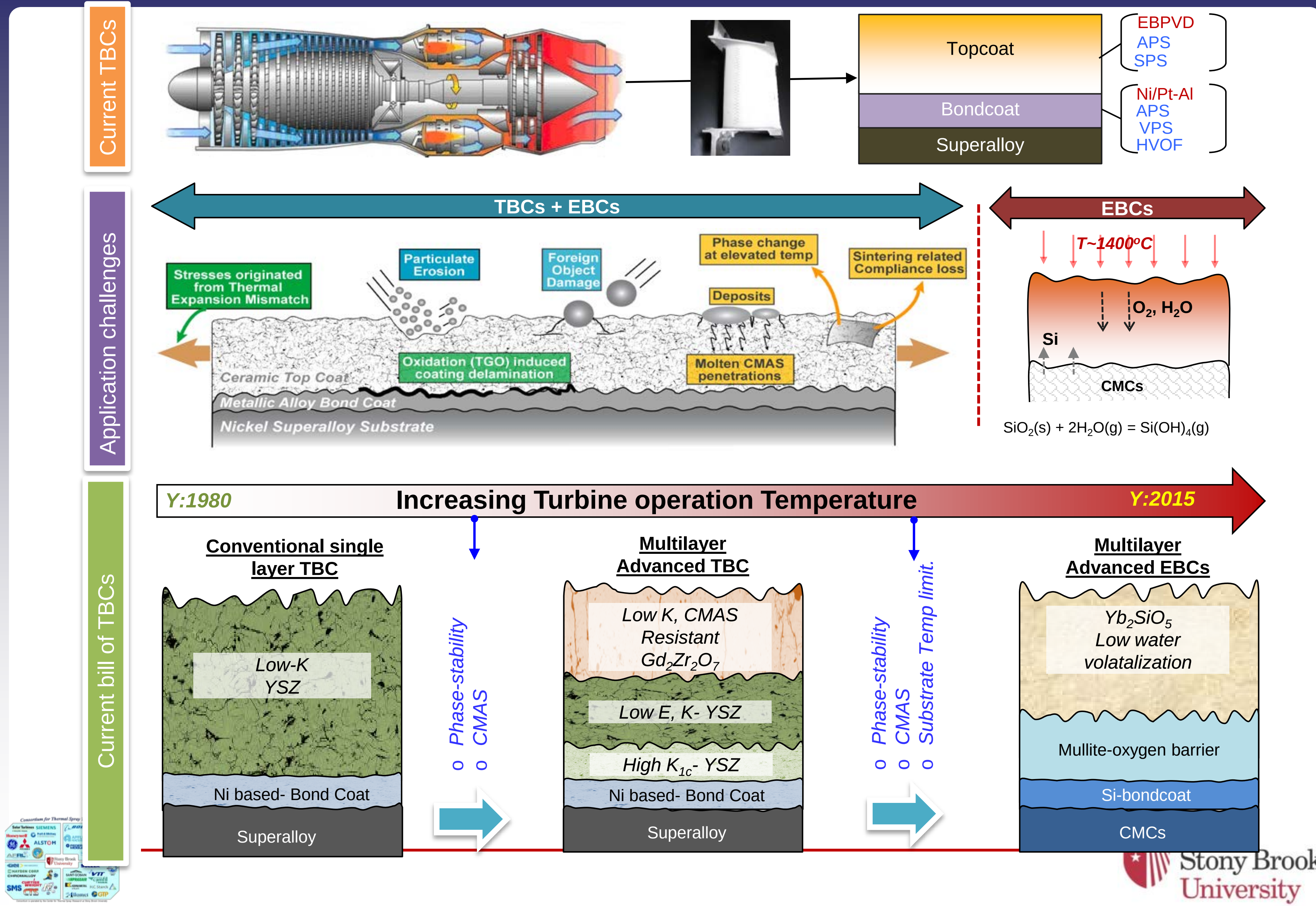
6 x 2000 cycles: No Failure yet

Ann Bolcavage J. Mater. Engg. Perf.



Stony Brook University

Applying similar ideas to emergent TBCs, EBCs, T/EBCs



MesoPlasma™ 3D-Printing Technology

- Provides **new process capabilities** not achieved with conventional plasma spray / cold spray

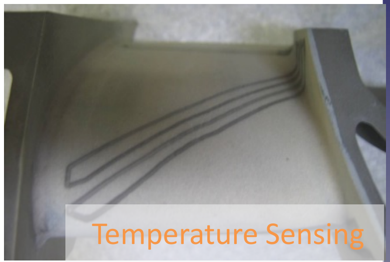
Direct Write Technology

✧ Precision, multi-layered metallic and ceramic dielectric <u>patterns</u>

✧ Printed thermocouples and high watt density heaters onto parts

✧ Stand-alone heat flux sensor and heater products

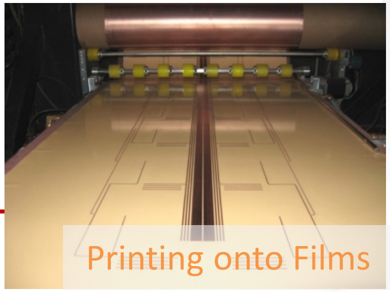
✧ Printed patterns onto temperature-sensitive polymer films



Temperature Sensing

Part Heating

Heat Flux Sensor Products



Printing onto Films