GAS TURBINE LOW CONDUCTIVITY THERMAL BARRIER COATING VALIDATION AND DEMONSTRATION

John Scheibel
Electric Power Research Institute
Palo Alto, CA, USA

Kirk Fick
Cincinnati Thermal Spray Inc.
Cincinnati OH, USA

Shane Elbel
Cincinnati Thermal Spray Inc.
Rocky Point, NC, USA

Jeffery Smith
Material Processing Technology, LLC
Norton Shores, MI, USA

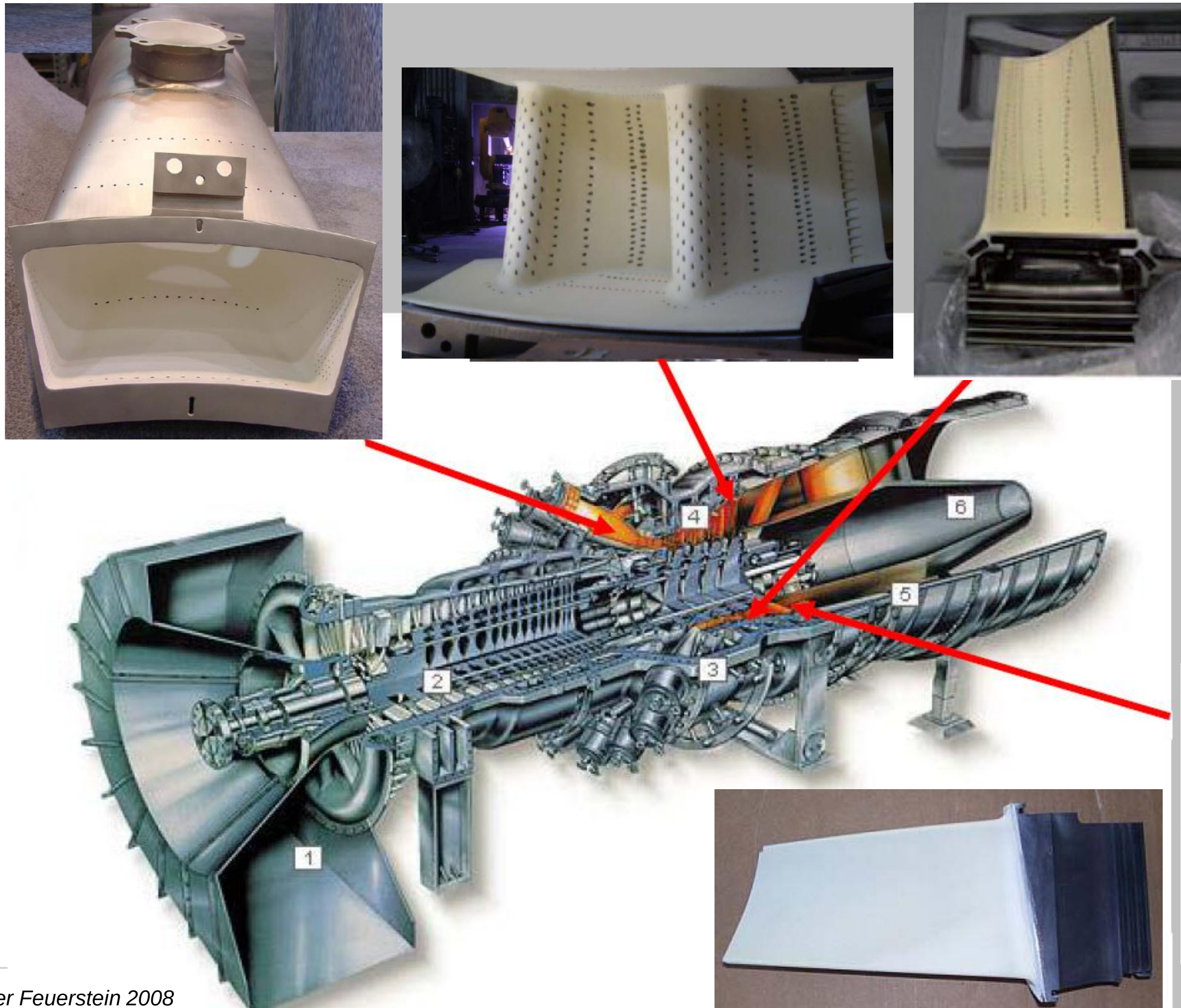
The Future of Gas Turbine Technology
8th International Gas Turbine Conference; 12-13 October 2016, Brussels, Belgium

Presentation Outline

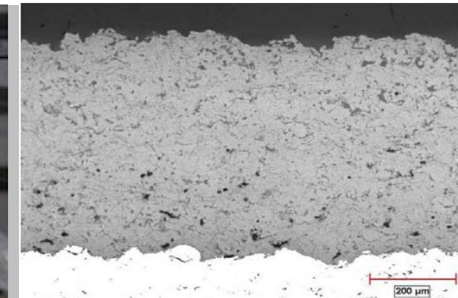
- Introduction / TBC overview and Background
- EPRI/CTS Low Conductivity TBC Combustion Hardware Program
  - Validation Testing Methods/Results
  - Qualification Results For CT1702 on Combustion Hardware
  - Inspection Results following Engine Testing for CT1702 TBC on GT Combustion Hardware
- EPRI / CTS Low K TBC Airfoil Program
- Summary/Conclusions
- Questions

IGT Thermal Barrier Coating Applications

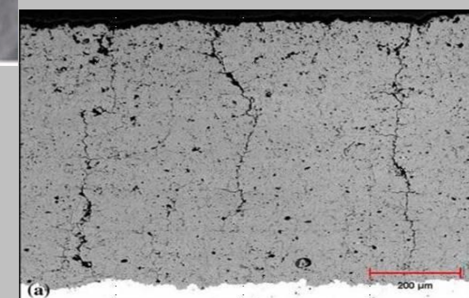
In Use Throughout the Hot Section



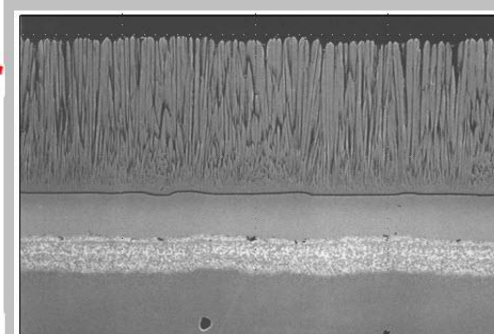
TBC Types in Use



APS Porous



APS Vertically Cracked

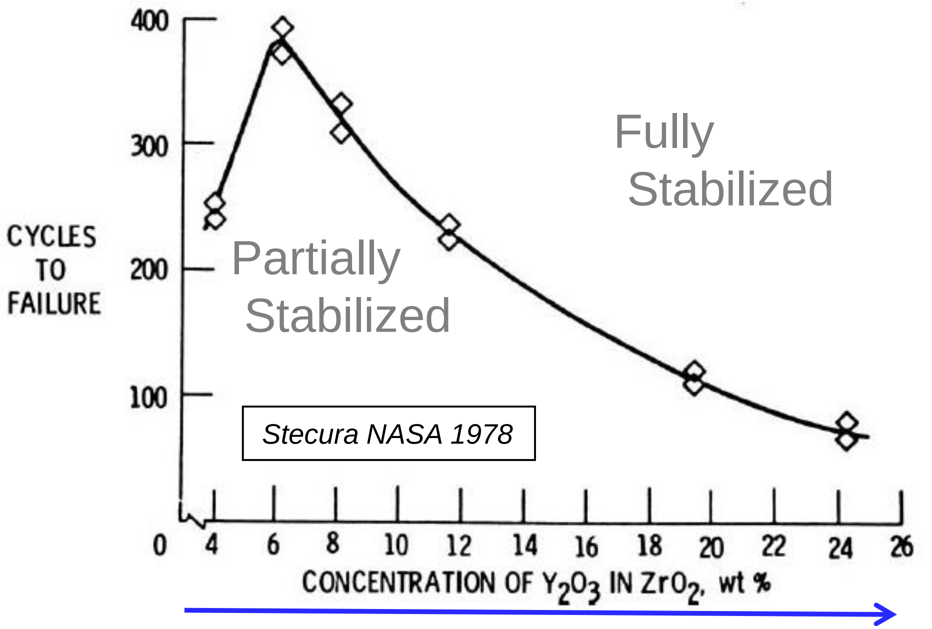


EB-PVD Columnar

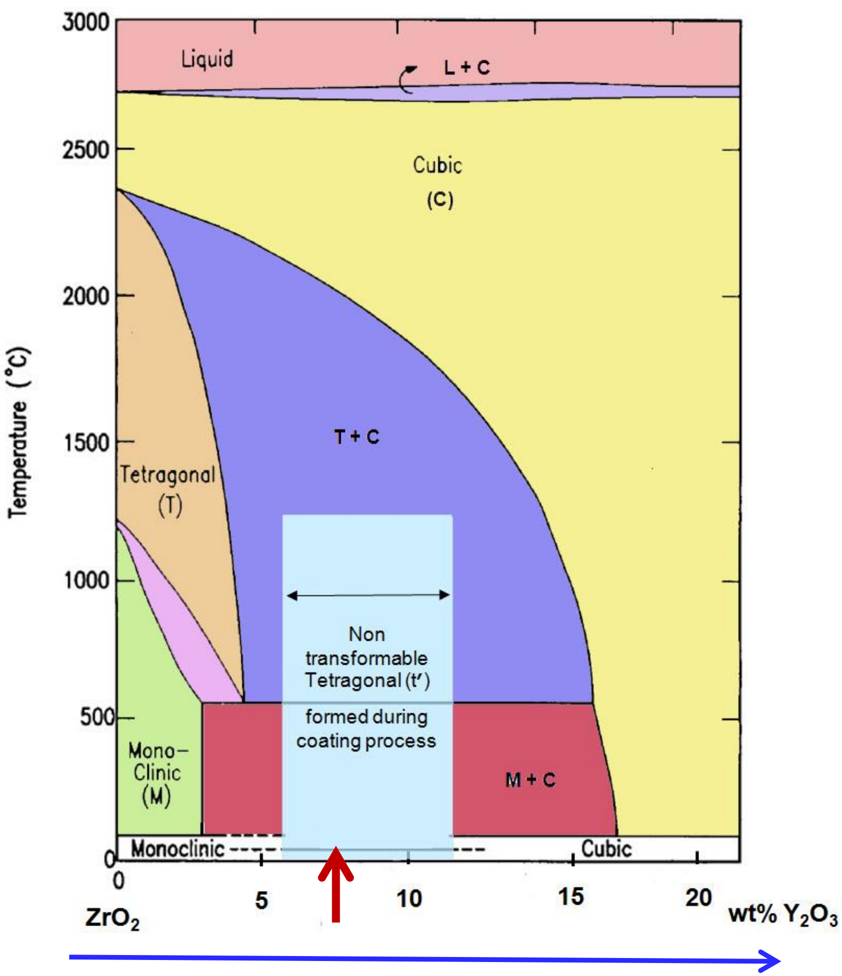
After Feuerstein 2008

Effect of Yttria Content on TBC Thermal Cycling Life

Thermal Cycle Life



Zirconia – Yttria Phase Diagram

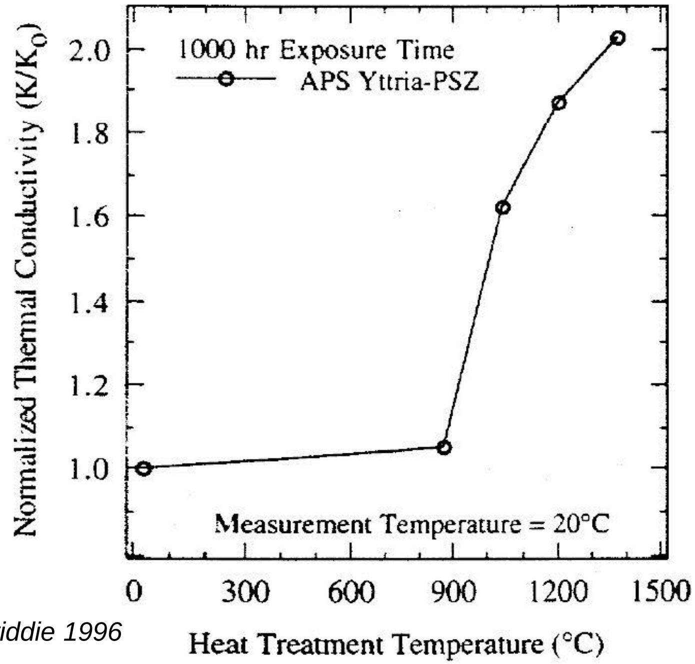


- 7-8 wt% Yttria Stabilized Zirconia Found to Have the Best Thermal Cycle Durability in 1978
- Is Still the Most Widely Used Composition Today
- Good Fracture Toughness and Erosion Resistance

ELECTRIC POWER RESEARCH INSTITUTE

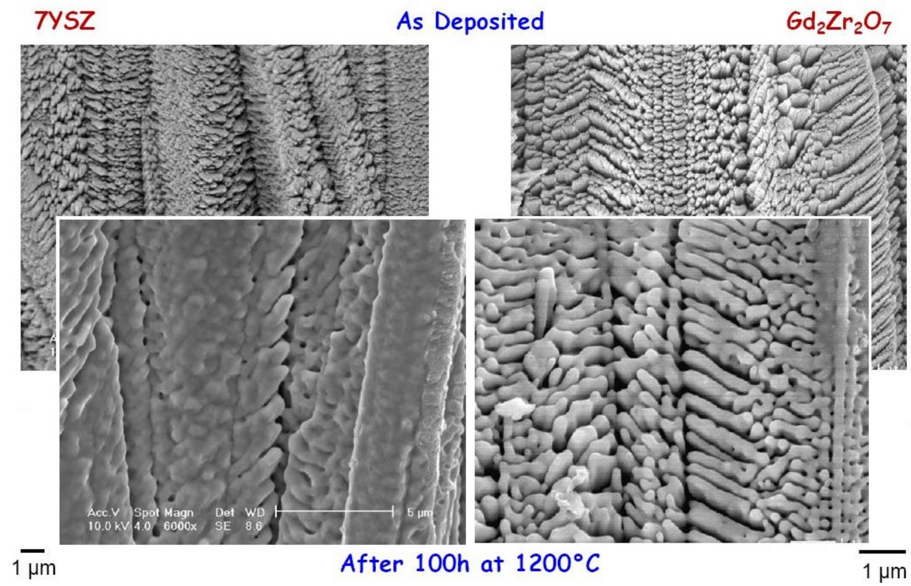
Sintering of TBCs

New compositions developed to be more sinter resistant



Dinwiddie 1996

Fig 8. The Effect of Heat Treatment Temperature on the Room Temperature Thermal Conductivity of APS Yttria-PSZ.

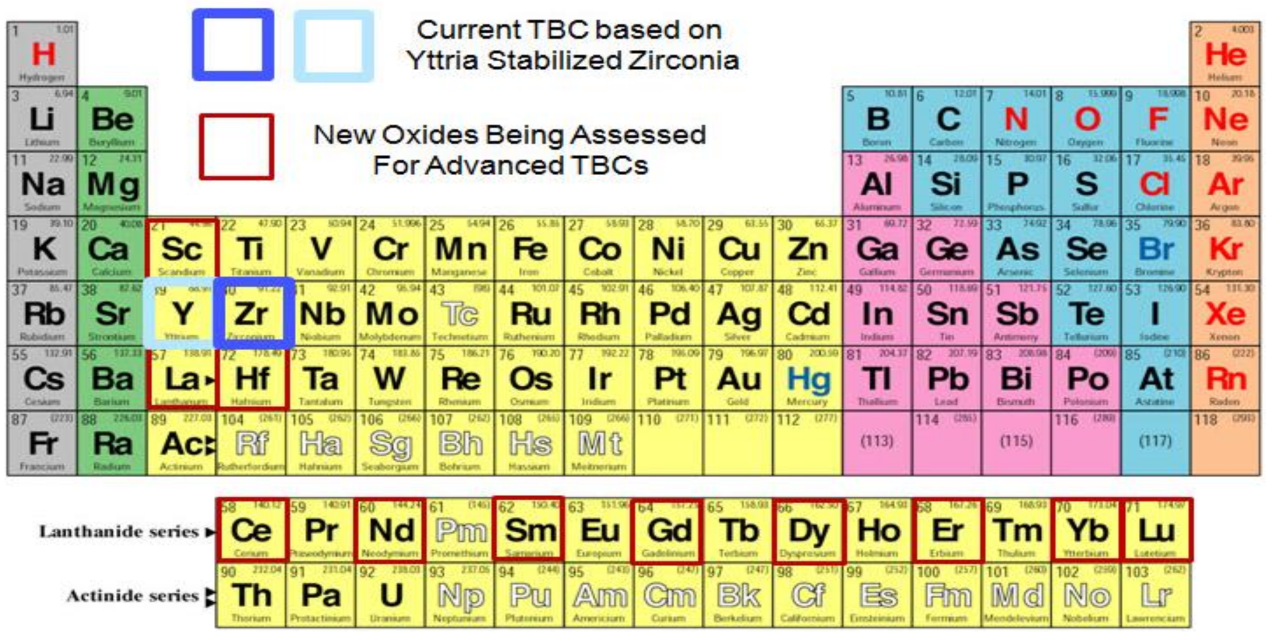


Levi 2005

- **Sintering (Densification) of 7YSZ Occurs above 900 C Over Time**
- **Sintering Effects are more Pronounced with More Porous Coatings and Reduce Compliance, Limiting Coating Life**

New TBC Compositions

Various TBC Crystal Structures and Compositions under Evaluation – Need to be Low k, Phase Stable, Sinter Resistant and have Good Thermal Cycling Life / Fracture Toughness



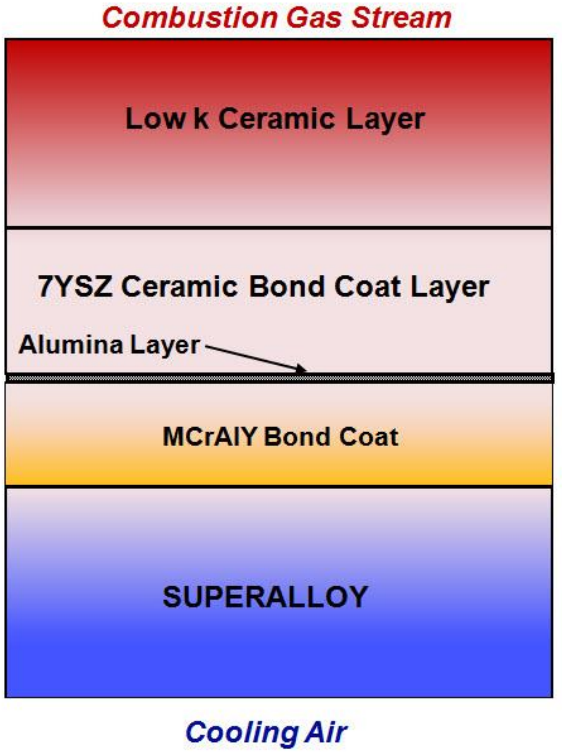
Tetragonal-t' (*6-8 wt% YSZ; 12 wt% YbSZ;* YbGd-YSZ; YbGdTiTa-YSZ; *YbSm Stb Zirconia; ZrO_2-HfO_2-$YbO_{1.5}$-TiO_2-$TaO_{2.5}$; $YTaO_4$- ZrO_2*)
Cubic (*Er-YSZ;* YbGd-YSZ; Nd-ZrO_2; Ln_3NbO_7, Ln_3TaO_7)
Pyrochlores (*e.g. $La_2Zr_2O_7$,* **$Gd_2Zr_2O_7$**, *$Nd_2Zr_2O_7$, $Sm_2Zr_2O_7$, $Gd_2Hf_2O_7$*
Perovskite structure (*e.g. $SrZrO_3$, $CaZrO_3$, $LaAlO_3$; BNT{ $BaNd_2Ti_3O_{10}$ }; $BaCeO_3$ or $SrCeO_3$)*
Rhombohedral (*e.g $Yb_3Zr_2O_{12}$, $Lu_3Zr_2O_{12}$ or $Er_3Zr_2O_{12}$, $Yb_3Hf_2O_{12}$;* **$Yb_4Zr_3O_{12}$**; *$Yb_4Hf_3O_{12}$)*
Hexagonal (*$Sc_4Zr_3O_{12}$)*
Spinels (BaY_2O_4 or SrY_2O_4)
YAG ($Y_3Al_{5-x}Fe_xO_{12}$)
Magnetoplumbite Structure (*$LaMgAl_{11}O_{19}$)*
Tungsten Bronze Structure (*e.g. BaO—RE_2O_3-xTiO_2 {$BaNd_2Ti_4O_{12}$}; Ba($Nd_{1.2}Sm_{0.4}Gd_{0.4}$) Ti_4O_{12}*
Monazite (*$LaPO_4$)*
Note (Ln or RE = Rare Earth Lanthanide)

Smith 2014 IP Study
580 Patent Families

EPRI ELECTRIC POWER RESEARCH INSTITUTE

NASA Low k TBC
10 Mol. % Yb, Gd, Y Stabilized Zirconia (Cubic)

Low k TBC System Architecture



1 - Low k , Sinter Resistant and Phase Stable Top Coat

2 - Standard Yttria Stabilized Zirconia

3 - MCrAlY Bond Coat

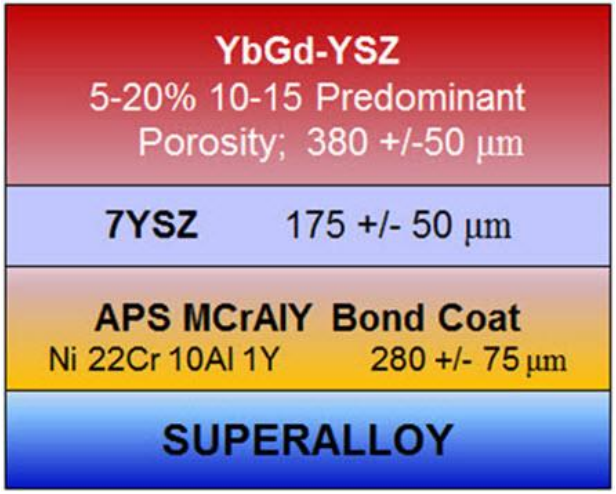
NASA Low Conductivity 10 Mol% YbGd-YSZ TBC

- **Co-Doping of Zirconia with multiple rare earth oxides – using "Defect Clustering" approach for improved phase stability, lower conductivity and sintering resistance** *(Zhu & Miller papers and patents)*
- **Low conductivity (*1/2 of the baseline YSZ TBC*) retained at 1315 C (2400°F)**
- **Substantially increases component durability beyond current TBC coatings (>2x)**
- **For same coating thickness *low k coating reduces metal temperature,* increasing component life**
- ***Improved sintering resistance and phase stability* (up to 1650 C / 3000°F)**
- **Excellent durability and mechanical properties**
- ***Performance benefits demonstrated on multiple advanced Aero engine applications***

EPRI Advanced TBC for Combustion Hardware

Commercialization of NASA "Cubic" YbGd-YSZ TBC for IGT combustion hardware sponsored by EPRI in conjunction with Cincinnati Thermal Spray

Two Layer TBC System

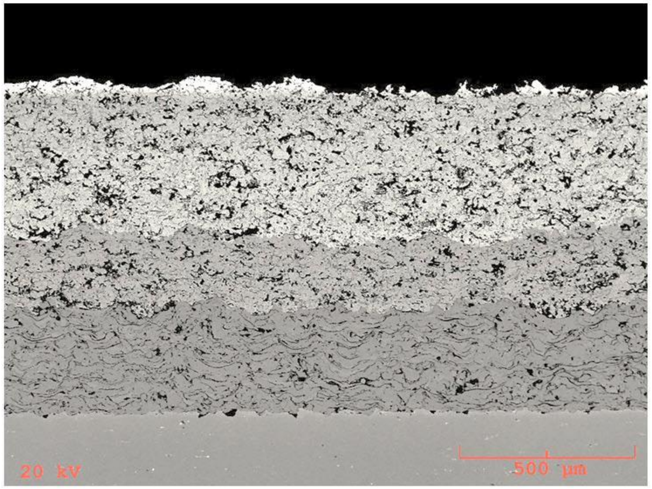


"Cubic" YbGd-YSZ Layer

7YSZ Layer

MCrAlY Layer

Superalloy



Objective: Develop Specification for Advanced TBC System for Land Based Gas Turbine Combustion Hardware and Support Engine Test Demonstrations

Task 1: EPRI Validation Testing of Low k Coating System

- Microstructure, Thermal Cycle Performance (FCT), Bond Strength, Sinter Resistance, Erosion Resistance and Thermal Conductivity *compared to Baseline Production Combustion Hardware TBCs*

Task 2: Develop Advanced TBC Specification

Task 3: Qualify YbGd-YSZ TBC Coating on Selected Hardware

- Adv. TBC Qualified on EPRI Utility MHI 501F Transition Pieces & Liners

Task 4: Monitor YbGd-YSZ TBC IGT Engine Testing

- Inspect EPRI Utility MHI 501F Transition Pieces & Liners following Engine Test
- Visual & Eddy Current Testing Conducted 4th Qtr 2015

Validation Test Types and Test Conditions

Validation Tests

Metallographic Coating Structure

Optical and SEM

Tensile Bond Strength

Bond Coat to Substrate and Ceramic Top Coat to Bond Coat

Erosion Test

Ceramic Layer Erosion Resistance

Sintering Resistance

1400 C (2550 F) for 100 hrs

Thermal Conductivity

Before and after Sintering cycle

Furnace Cycle Testing

1.25 hr cycles from room Temperature to 1093 C (2000 F) with standard 1 inch diameter buttons

Results used to Establish Coating Specifications

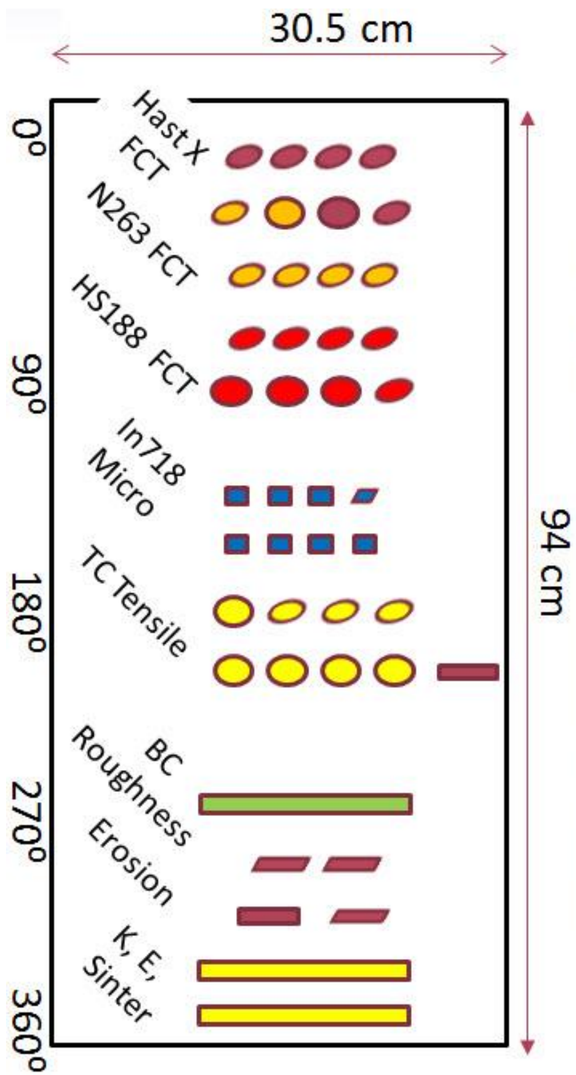
F Class GT Transition Piece being Plasma Sprayed with a TBC and a TBC Coated Combustion Liner

Transition Piece

Combustion Liner

(Courtesy of CTS)

All Coating Runs made on 30.5 cm Diameter Cylinder Simulating IGT Liner or Transition Piece

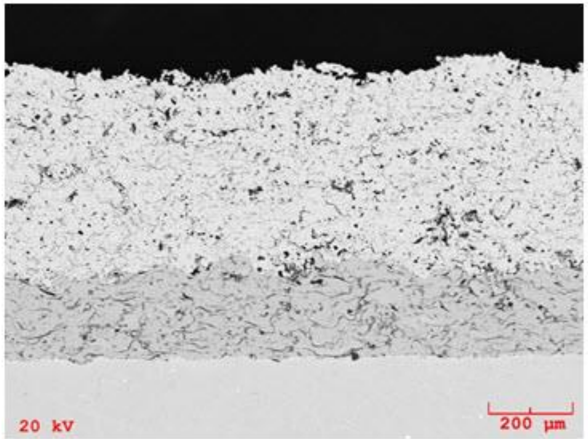


Test Specimen Configuration for TBC Property Validation Testing

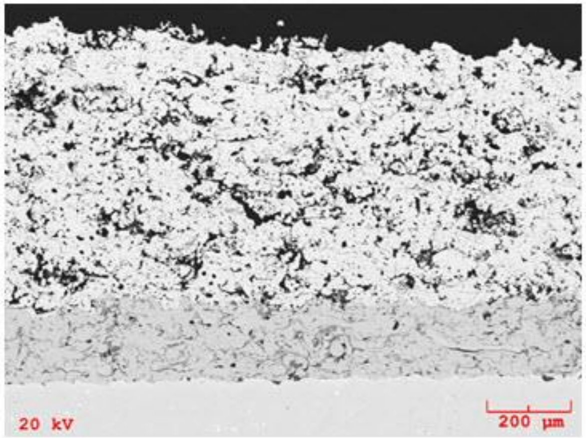
Low k TBC Coating on Property Validation Test Specimens

Baseline Combustor TBCs used in Validation Testing

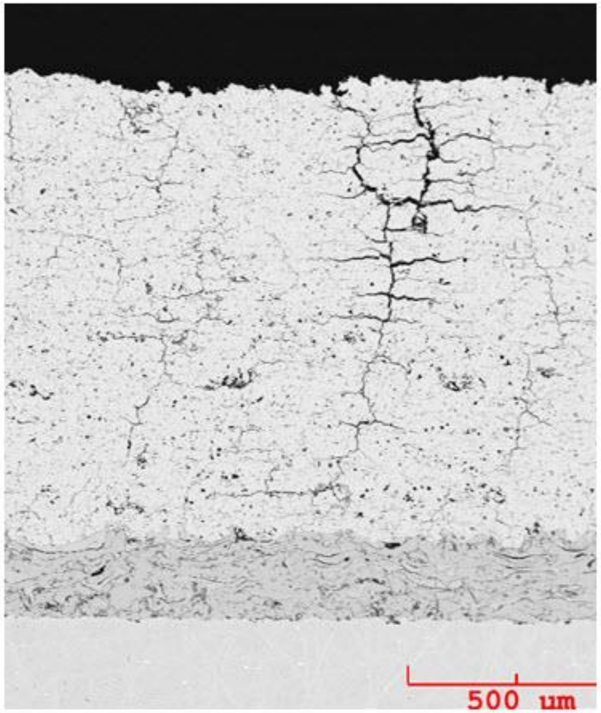
Coating Series "B"
EPRI Type 2
7YSZ Baseline



Coating Series "A"
EPRI Type 1
7YSZ Baseline



Coating Series "C"
EPRI Type 4
7YSZ Baseline



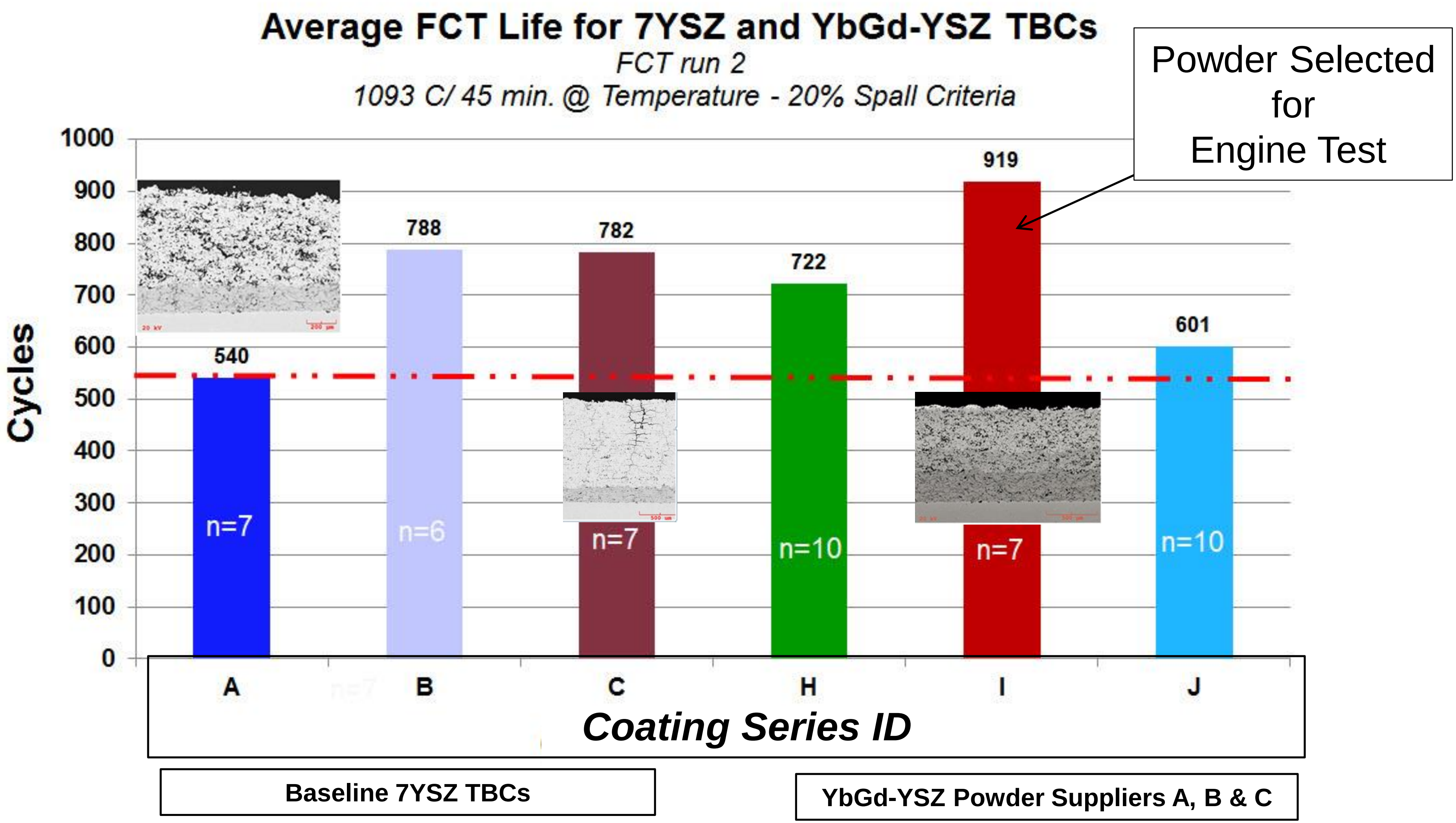
CTS Furnace Cycle Test for Assessing TBC Performance

CTS Furnace Cycle Test

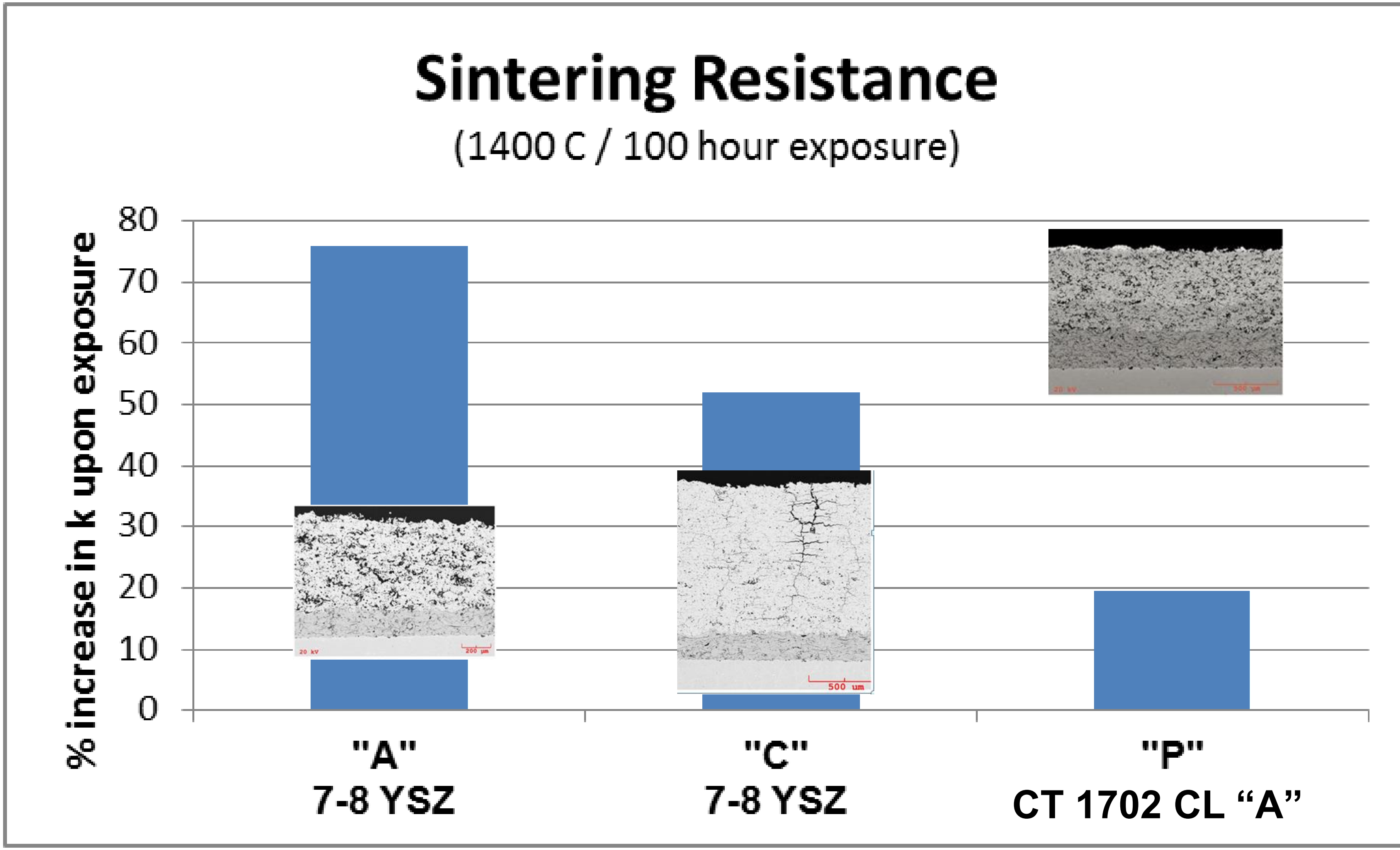
60 FCT Buttons Tested in Per Run

Furnace Cycle Test Results

Low k TBCs Demonstrate FCT Life Equivalent or Better Than the Baseline EPRI Type 1 7YSZ Coating –Coating series "A"



Sintering Resistance of TBCs
7YSZ Baseline and CT 1702 CL "A"



EPRI | ELECTRIC POWER RESEARCH INSTITUTE

CT 1702 Class "A" Optimized Coating

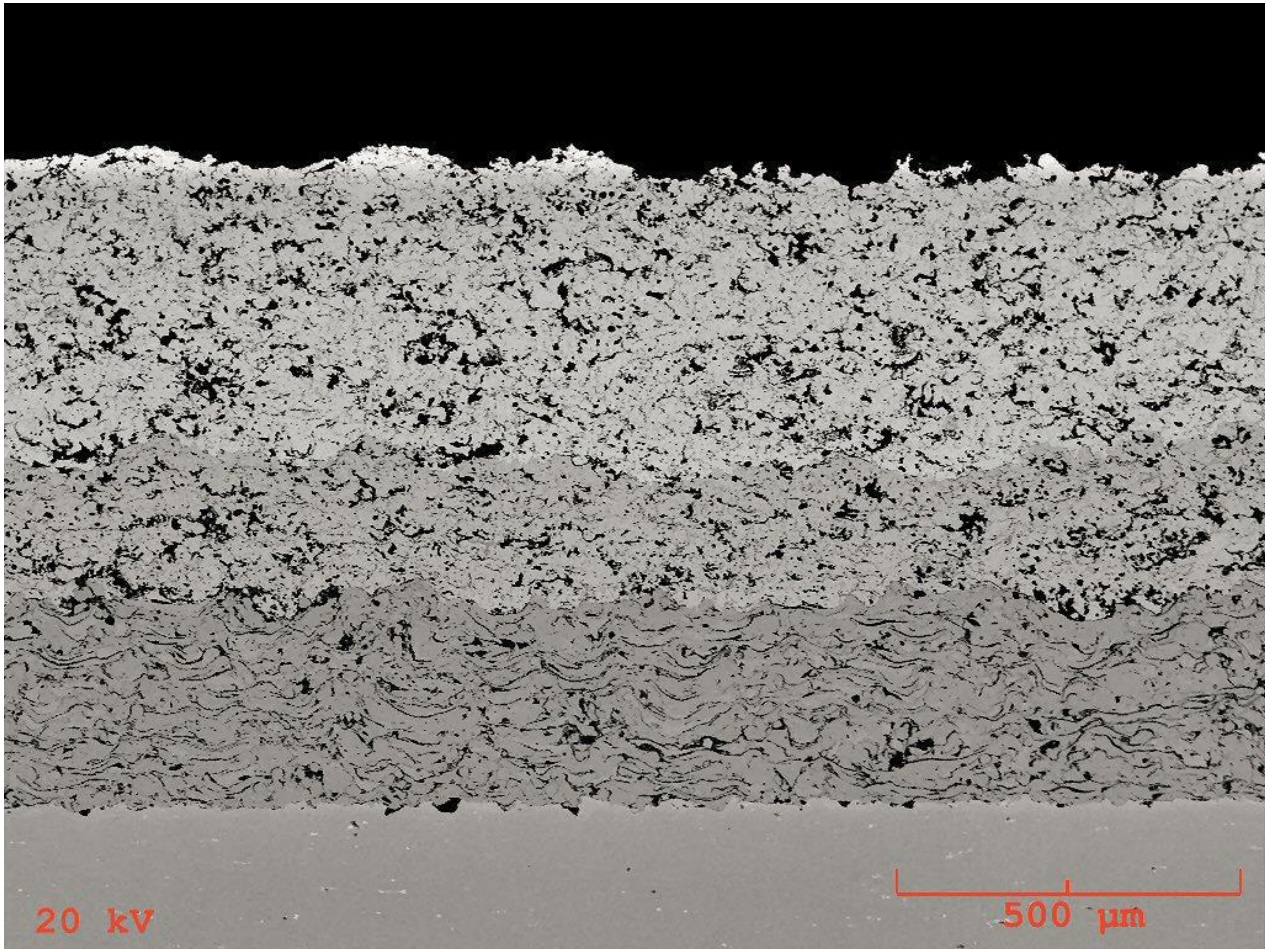
Validation Testing Successful and Coating Specifications Issued

"Cubic" YbGd-YSZ Layer

7YSZ Layer

MCrAlY Layer

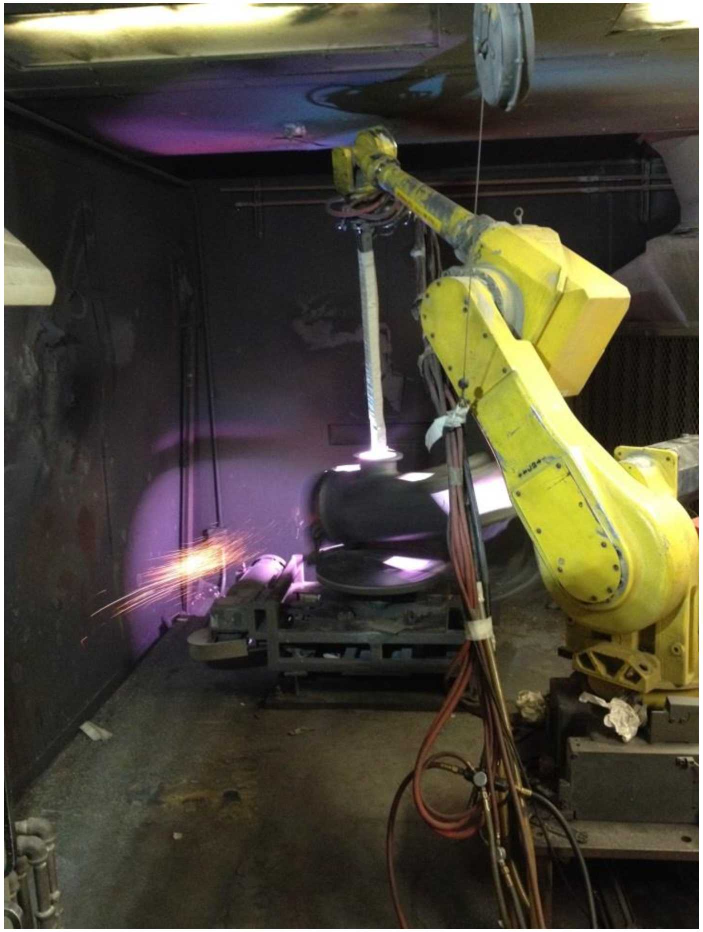
Superalloy

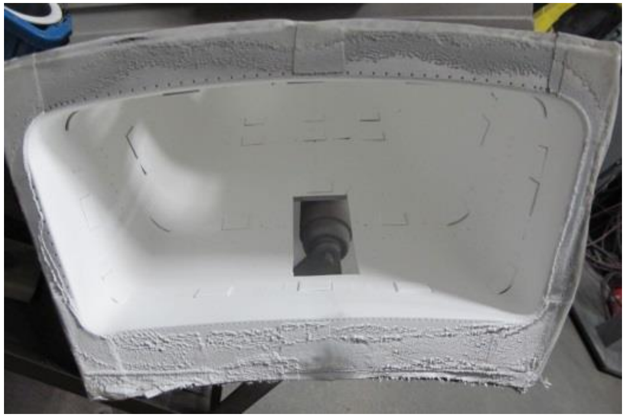


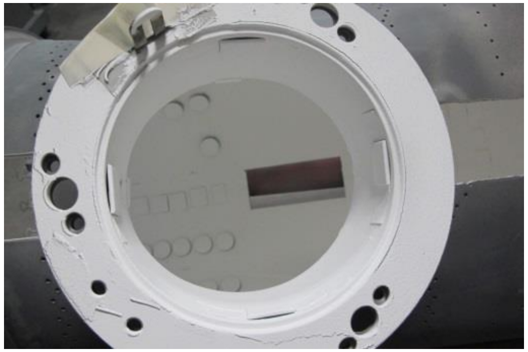
EPRI ELECTRIC POWER RESEARCH INSTITUTE

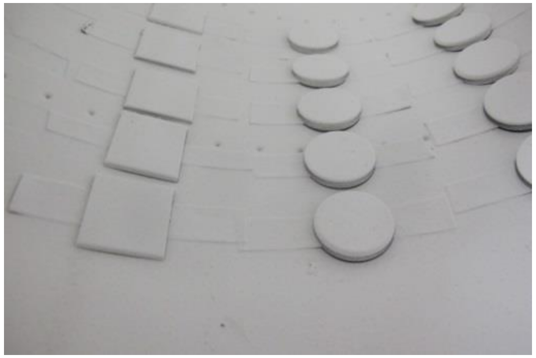
Task 3 - F Class Transition Piece and Combustion Liners

Process Qualification with Metallography, Eddy Current and FCT Testing







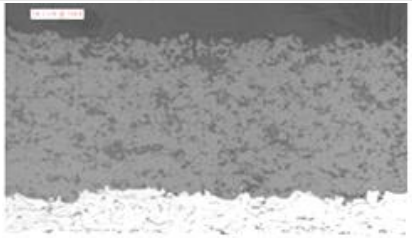


Task 3 QC results for MHI 501F Combustion Baskets – As Coated– S/N 209, 210 & 211

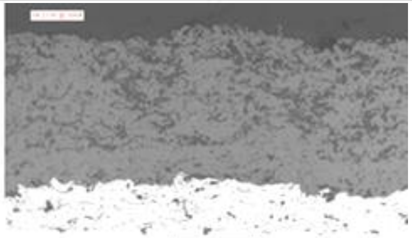
Task 3 QC results for MHI 501F Transition Pieces As Coated – S/N 177, 178 & 179

Task 3 QC As Coated Results for MHI 501F Engine Test Transition Pieces – S/N 177, 178 & 179

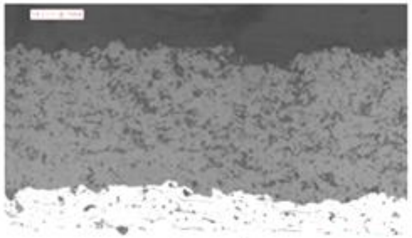
Panel #	Bond Coat (mils)	Intermediate Coat (mils)	Top Coat (mils)	Total TBC Ceramic (mils)	Eddy Current results - Duct (mils)
Production #1 S/N 179	5.0	5.5	16.0	21.5	20.8 +/- 6.0
Production #2 S/N 178	5.0	5.5	15.5	21.0	21.9 +/- 3.0
Production #3 S/N 0177	5.0	5.5	15.5	21.0	19.0 +/- 4.1



S/N 179



S/N 178

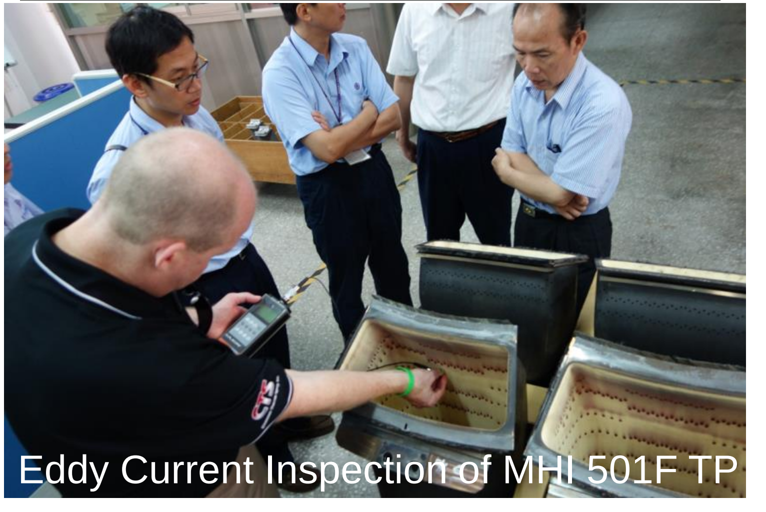


S/N 177

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Tasks 3&4 EPRI Advanced TBC for Combustion Hardware

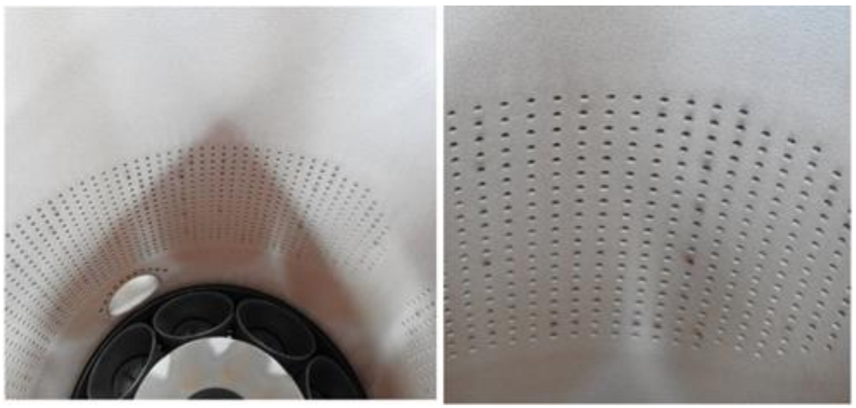
Engine Test At Utility Power Plant in MHI 501F GT



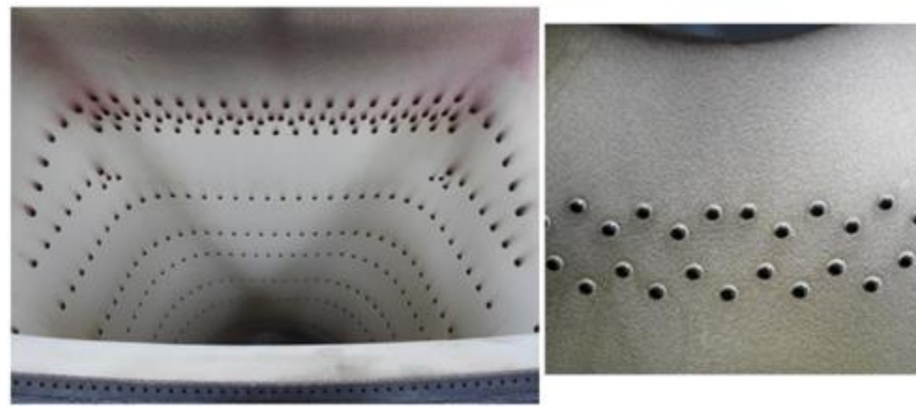
CTS Inspected Parts (Visual & Eddy Current) Dec 2015 after ~ 8,000 hrs service

Task 4 Inspection Results following Engine Testing for CT1702 TBC on GT Combustion Hardware – *Visual Inspection*

Basket Visual Appearance of TBC after engine test



Transition Piece Visual Appearance of TBC after engine test



- Visual inspection was performed on all baskets and TPs
- The TBCs were characterized as being in “pristine” condition and no evidence of coating distress was observed
- Close inspection of the coatings around the cooling holes appeared identical to the as shipped condition with no evidence of erosion

Inspection Results following Engine Testing for CT1702 TBC on GT Combustion Hardware – *Eddy Current*

Baskets

	CTS Coated S/N			OEM Coated S/N	
	209	**210**	**211**	**214**	**212**
As Coated					
Average Thickness	**21.9**	**25.1**	**29.0**	*na*	*na*
max	24.5	28.7	32.5	*na*	*na*
min	17.5	18.6	24	*na*	*na*
Plus/Minus	3.5	4.85	3.7	*na*	*na*
After Engine Operation					
Average Thickness	**23.2**	**27.8**	**28.1**	**17.3**	**17.4**
Max	18.5	21.3	21.3	12.4	12.0
Max	29.1	33.8	33.7	19.5	20.0
Plus/Minus	5.3	6.3	6.2	3.6	4.0

Comparison of Eddy Current Readings Taken As Coated and Following Engine Service for Baskets. *Thickness readings in Mils*.

Inspection Results following Engine Testing for CT1702 TBC on GT Combustion Hardware – *Eddy Current*

Transition Pieces

	CTS Coated S/N			OEM Coated S/N	
	177	178	179	TP7	TP12
As Coated					
Average	**19.0**	**21.9**	**20.8**		
Max	24.4	25.0	27.0		
Min	16.2	19.1	15.1		
Plus/Minus	4.1	3.0	6.0		
After Engine Operation					
Average	**21.0**	**23.8**	**22.8**	**18.8**	**15.5**
Max	24.2	29.3	25.4	30.0	40.9
Min	17.3	16.1	19.7	9.2	2.6
Plus/Minus	3.5	6.6	2.8	10.4	19.2

Comparison of Eddy Current Readings Taken As Coated and Following Engine Service for Transition Pieces. *Thickness readings in Mils.*

Inspection Results following Engine Testing for CT1702 TBC on GT Combustion Hardware – Summary

- All tasks in the EPRI advanced TBC program have been successfully completed.
- Three F-class transition pieces and three combustion baskets coated with CT 1702 YbGd-YSZ TBCs were successfully engine tested at an EPRI member utility's site.
- The components completed 7,846 EOH.
- Visual inspection and eddy current testing of the TBC indicated that they could be returned to service for another 8000 hr interval.
- The plan is to install them 4^{th} Qtr 2016 and run for an additional 8,000 hrs. The next inspection is planned for Nov. 2017

EPRI Airfoil TBC Program

EPRI/CTS Advanced TBC Program Phase 2– Airfoil Applications

Objective: : Demonstrate TBC coating Conformance to Specification Requirements on Scrap 7FA Buckets with Baseline YSZ and Multilayer YbGd-YSZ TBCs

Demonstrate conformance to the EPRI coating specification on actual component(s) at CTS for:

1) **class B YSZ TBC**

2) ***Vertically Segmented YSZ TBC***

3) **Multilayer YbGd-YSZ;**

a) Characterize coating microstructure, thickness distribution, bond strength, erosion resistance and FCT on coupons coated during ***flat plate airfoil analogue trials with 10 TBC Systems*** *(1 – Baseline Class B, 6 – VCC Variants and 3 – Multilayer low K TBCs)*

b) Characterize coating microstructure, thickness distribution, and other CTQ's on ***scrap 7FA buckets using same processing parameters in task 1a***.

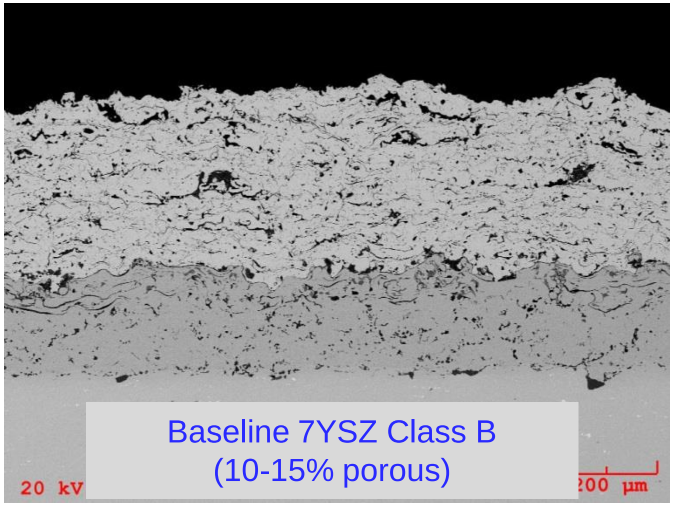
c) Demonstrate readiness to coat engine test hardware in 2017

Advanced Airfoil TBCs – Three basic Classes;

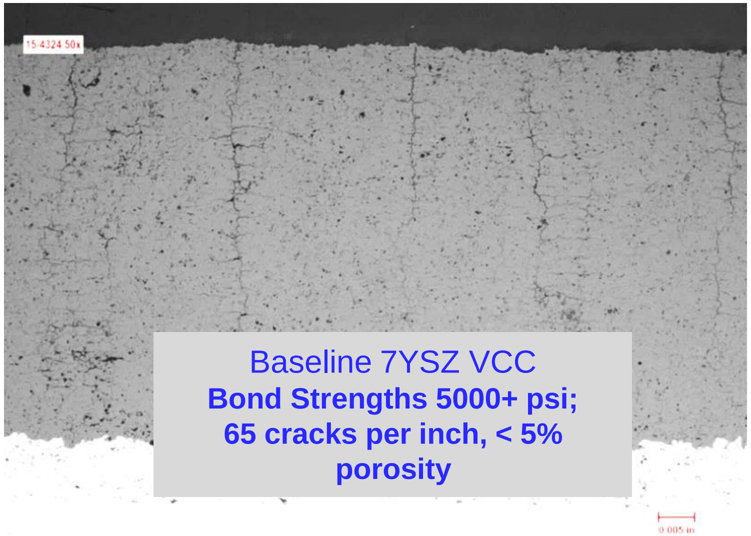
Main focus is VCC variations in structure/Tensile Bond Strength/ processing

Phase 2 Coatings for Component Qualification – Target 27.5 mil TBC thickness; Test different VCCs

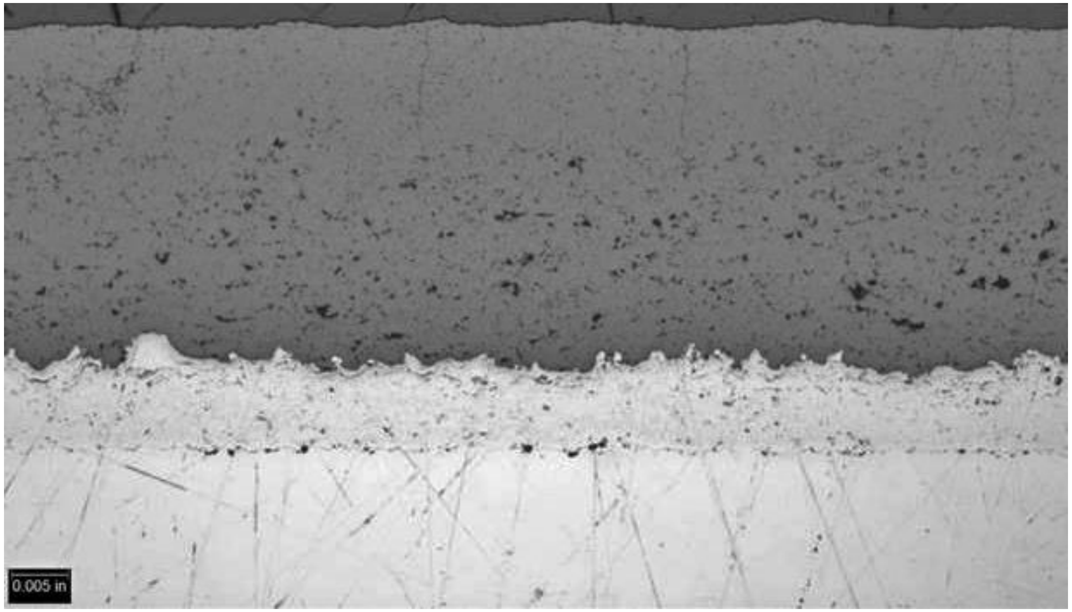
1)



2)

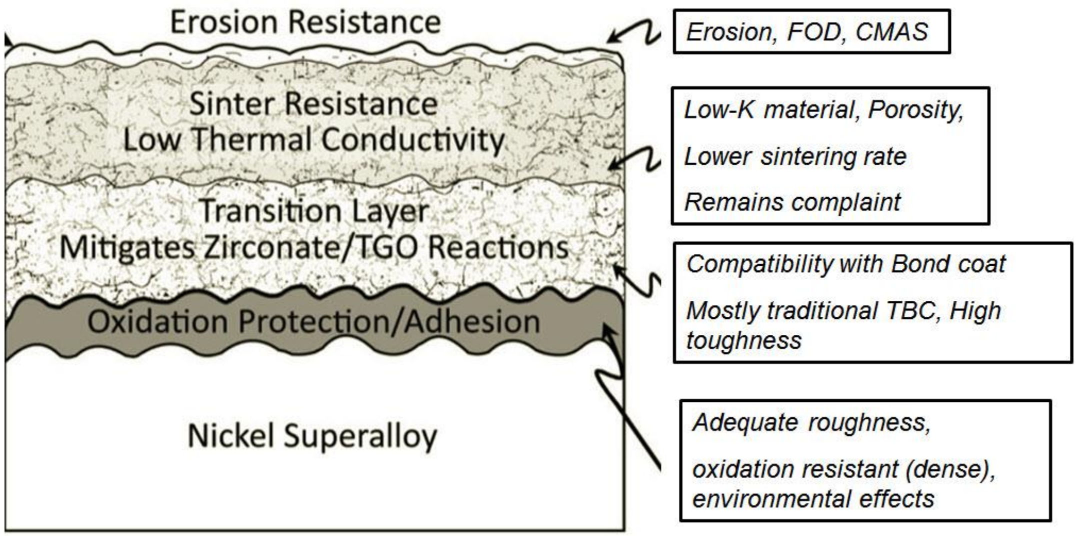


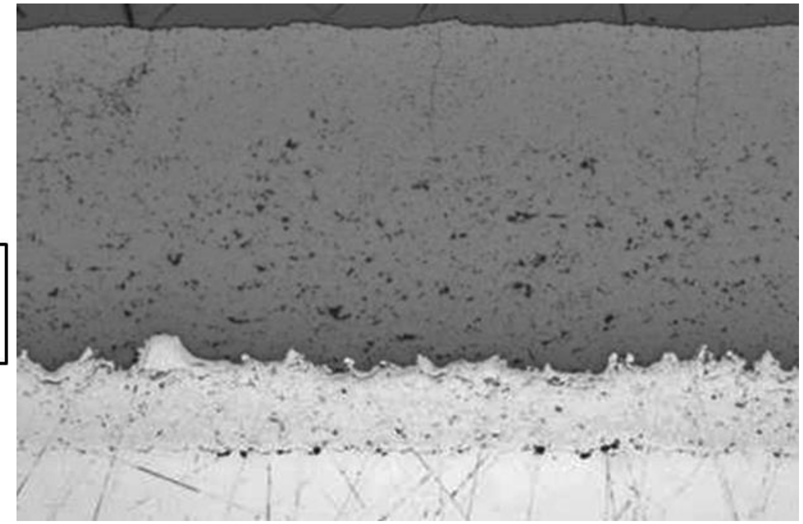
3)



Advanced TBC Systems are Becoming More Complex

New Low k, Sinter Resistant Compositions have Lower Erosion Resistance and Fracture Toughness than 7YSZ – Driving multilayer systems





Sampath / Stony Brook Univ. Center for Thermal Spray Research

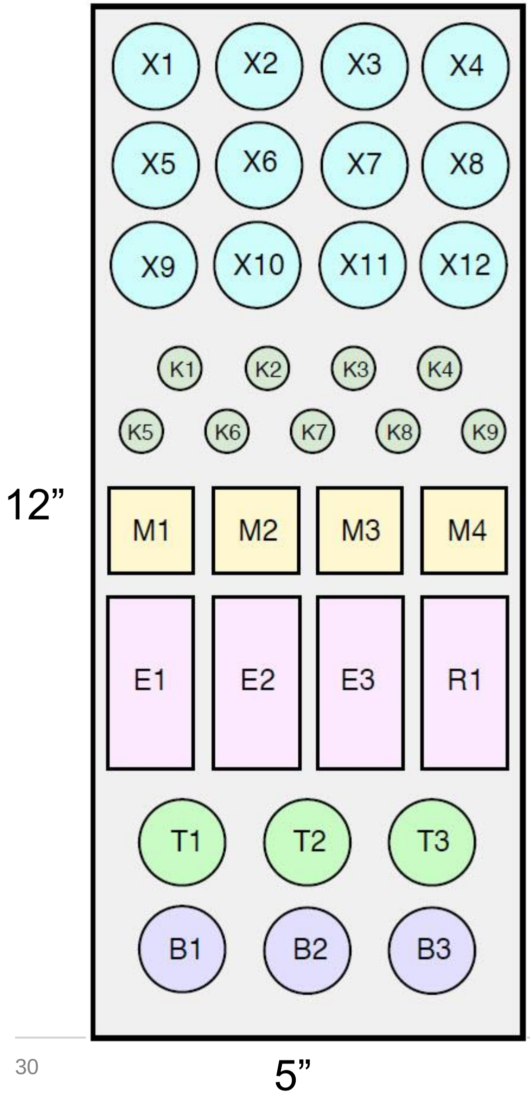
EPRI Phase 2 Advanced Airfoil TBC Concept

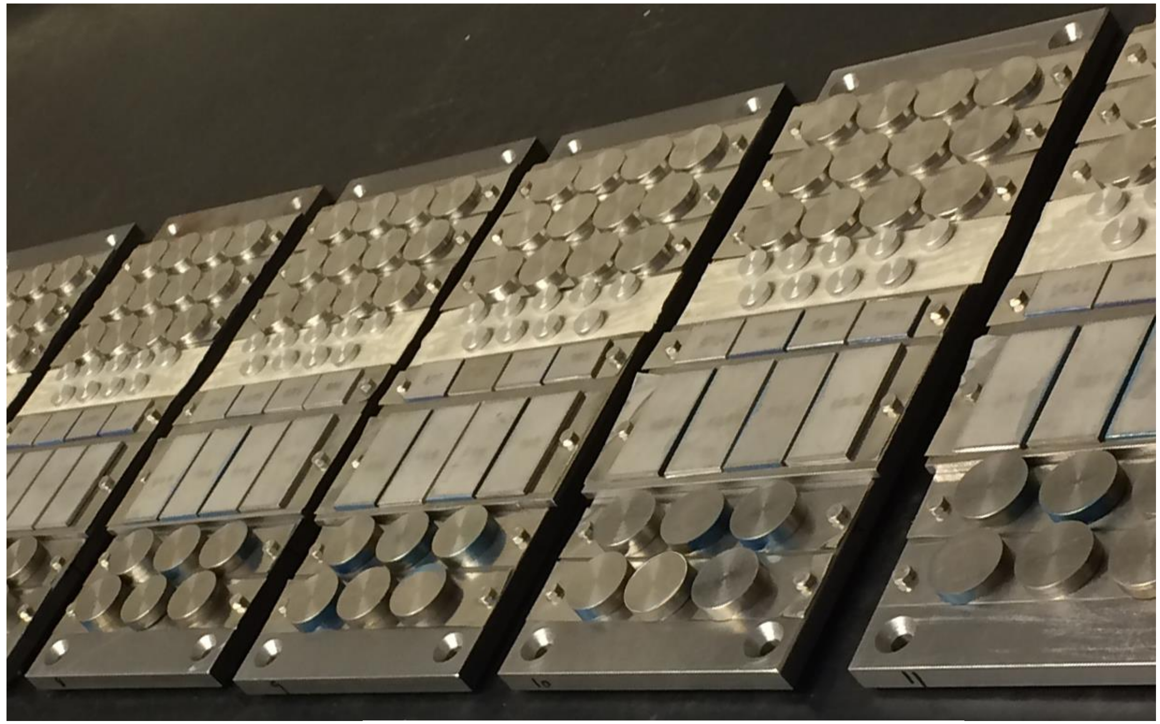
1) dense Vertically Cracked cubic YbGd-YSZ outer layer for best erosion resistance
2) porous cubic YbGd-YSZ middle layer for lowest conductivity and sinter resistance
3) dense 7YSZ inner layer for best TBC thermal cycling performance

Benchmark against 7YSZ 1) Class B (10-15% porous) and 2) VCC 7YSZ (<5% Porosity with Vertical Cracks for Compliance); 5000+ psi, 65 cracks per inch, < 5% porosity;

Airfoil Demo Program Thermal Spray Specimen Layout

Test Specimen Panel Emulates Plasma Spraying of F Class Airfoils

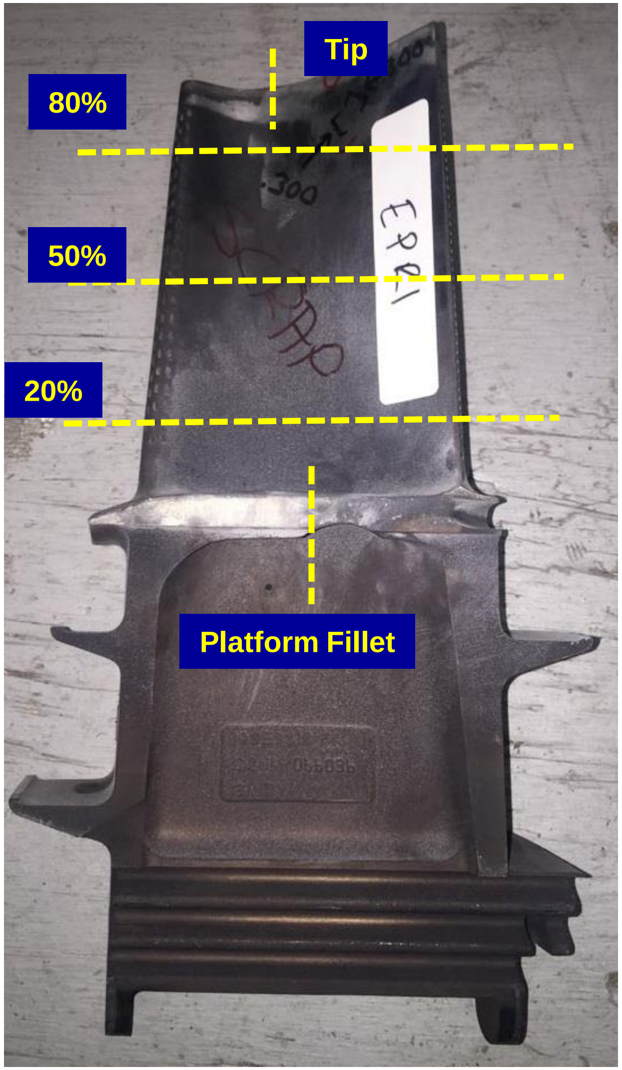


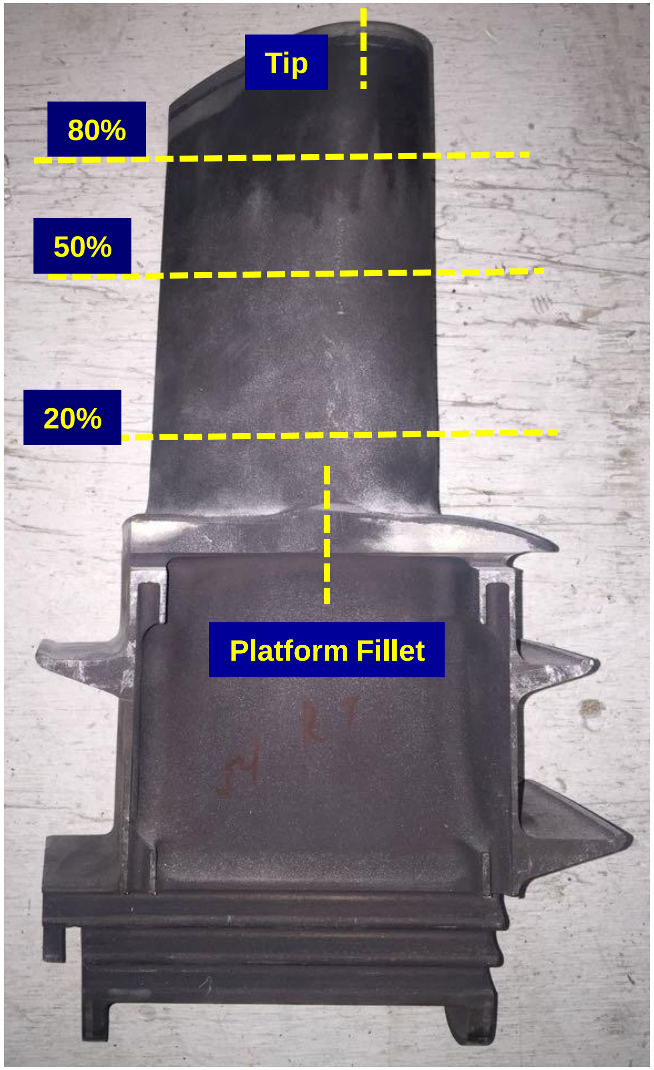


ID each sample with a unique 3 place code - XYZ

- X is the plasma spray run number
  - 1 thru however many runs are made
- Y is the test ID
  - X for FCT
  - M for Micro
  - E for Erosion
  - T for Topcoat Tensile
  - B for Bond coat Tensile
  - R for BC roughness
- Z is the individual couple ID
  - 1 thru however many of that test type

Scrap 7FA 1st Stg Buckets

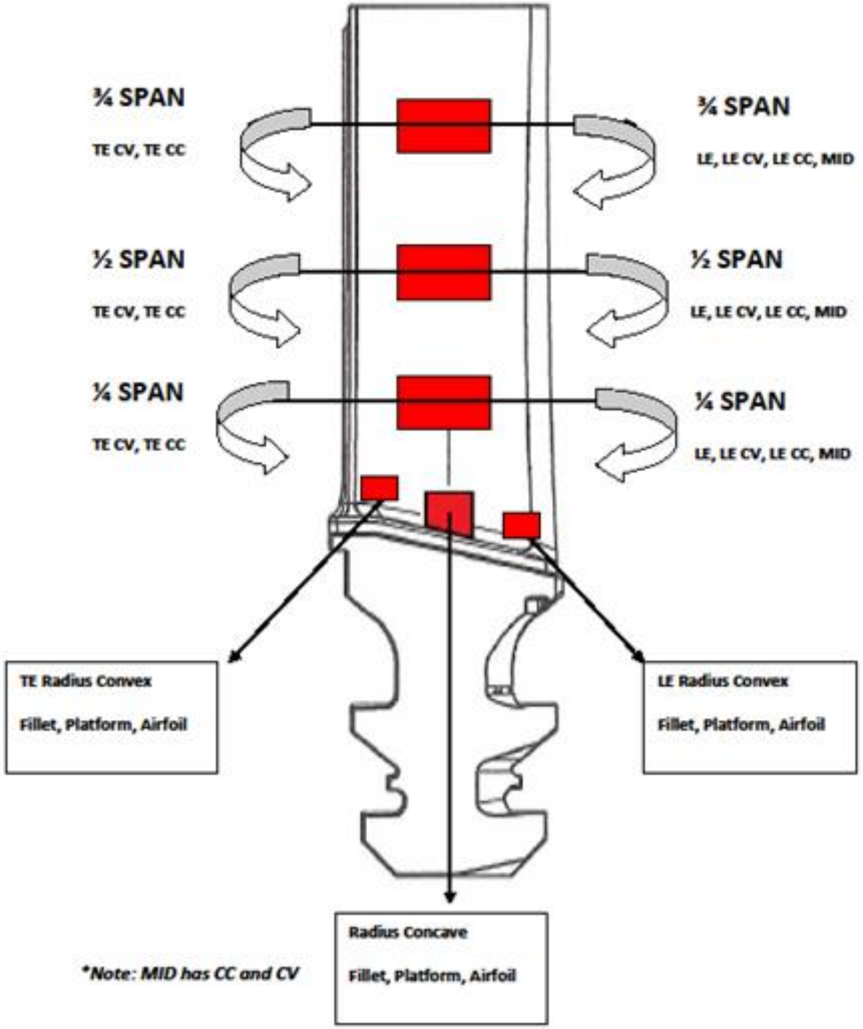




Demonstrate Bond Coat and TBC Thickness and Structure meet Coating Spec Requirements establish in Validation Test Task 1a.

Airfoil TBC Summary

- Low-K Multi-layer processing optimization in progress
- Scale to production spraying of F-Class components
- Ready for limited engine demonstration in 2017
  - Host site selection
- Incorporate into EPRI Repair Guidelines for next generation hot section (G/H/J-class)



Together…Shaping the Future of Electricity