Advanced Thermal Barrier Coatings for Next Generation Gas-Turbine Engines Fueled by Coal-Derived Syngas

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BROWN

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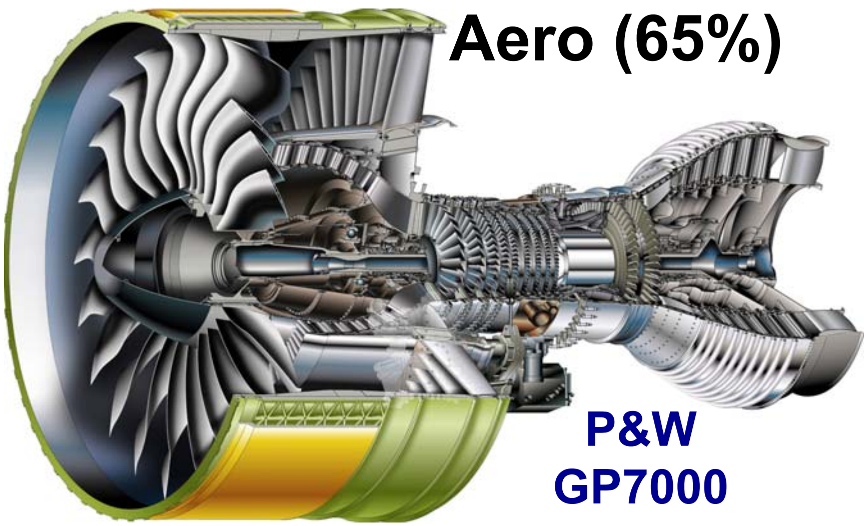
Support
DoE NETL University Coal Research Program

DoE Project Officer
Dr. Jason Hissam

Grant No.
DE-FE0008933

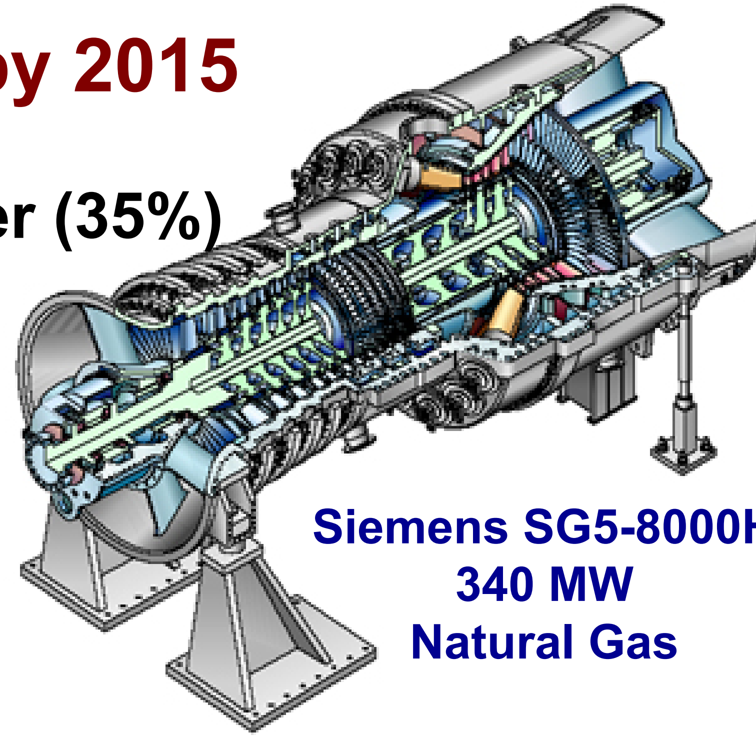
Gas-Turbine Engines: $55B by 2015

Aero (65%)

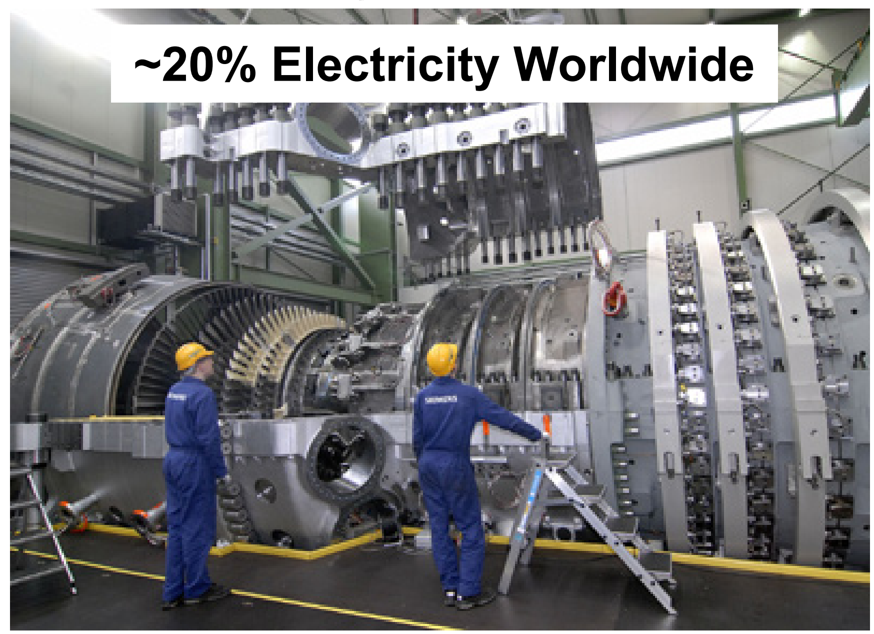


P&W GP7000

Power (35%)



Siemens SG5-8000H
340 MW
Natural Gas



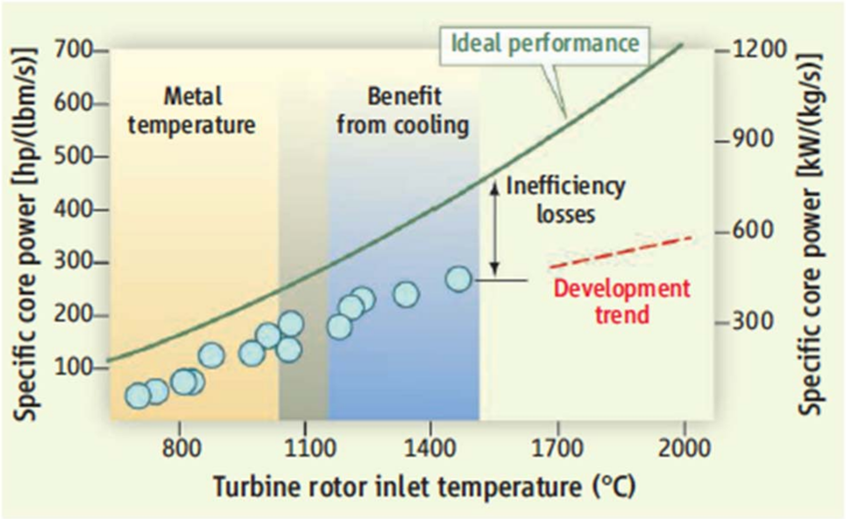
Langston, 2011

Motivation

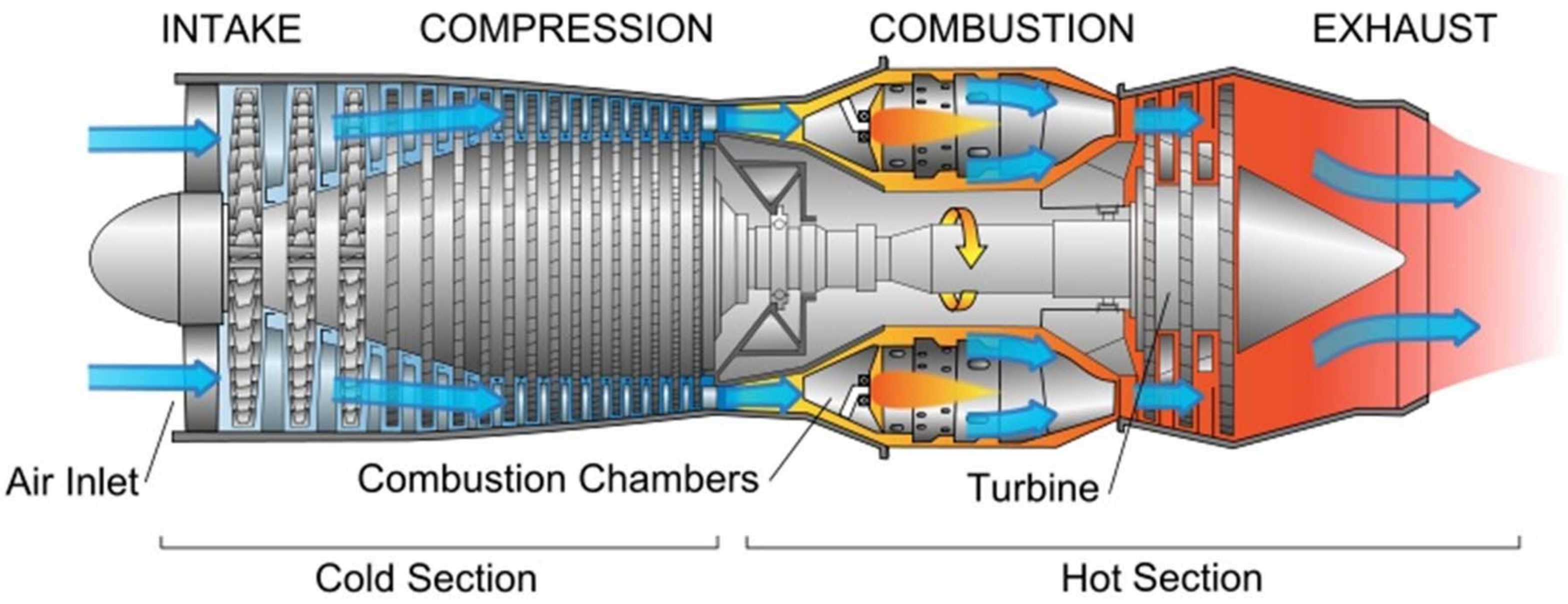
* Need for Higher Power and Efficiency
  - Aircraft Propulsion
  - Electricity Generation

* Need for Higher Hot-Section Temps.

* Materials "Bottleneck":
  - Improved Structural Alloys
  - Ceramic Matrix Composites
  - Ceramic Thermal Barrier Coatings (TBCs)



Perepezko, 2009



Ceramic Thermal Barrier Coatings (TBCs)

* Engines
  - Aero
  - Power

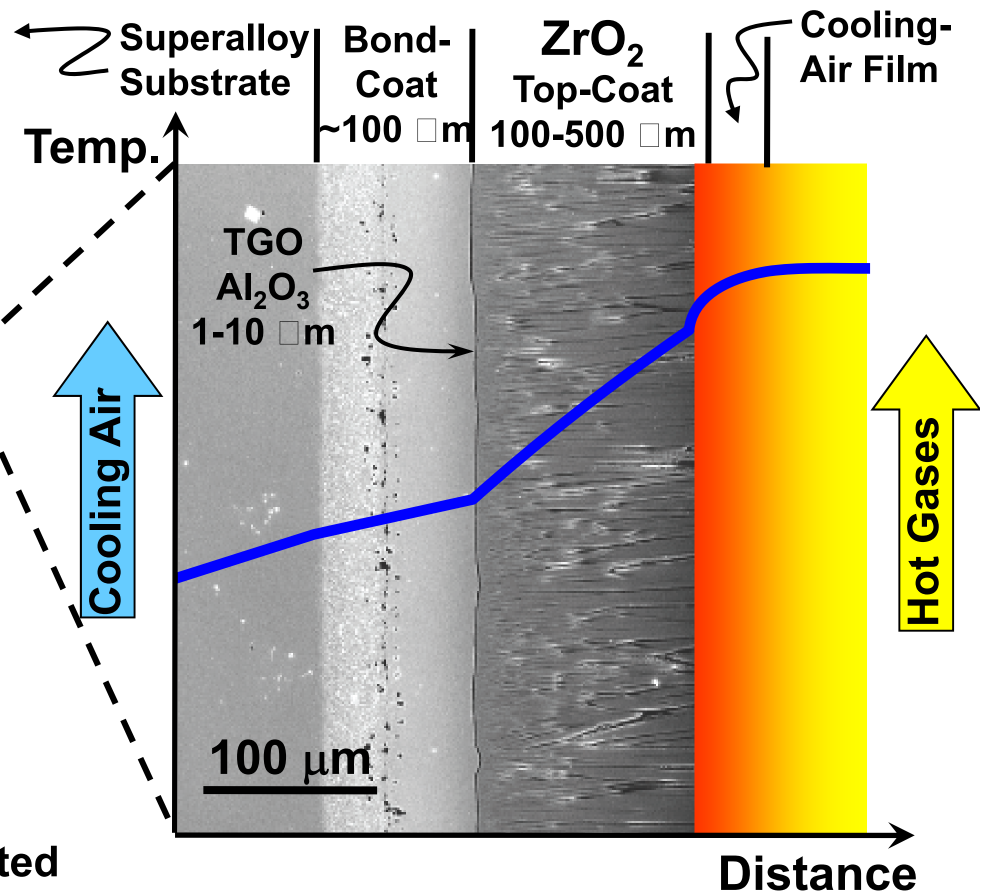
* Blades/Vanes, Combustors, Shrouds

* Strain-Tolerant, Low Th. Cond.

* Up to 300 ˚C Temp. Reduction

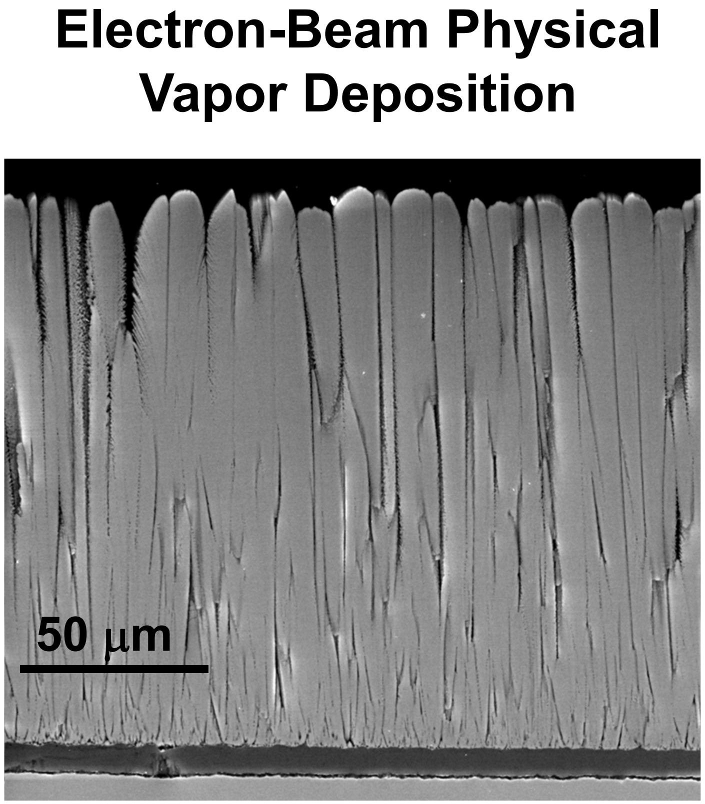
* Improved
  - Performance
  - Efficiency
  - Durability

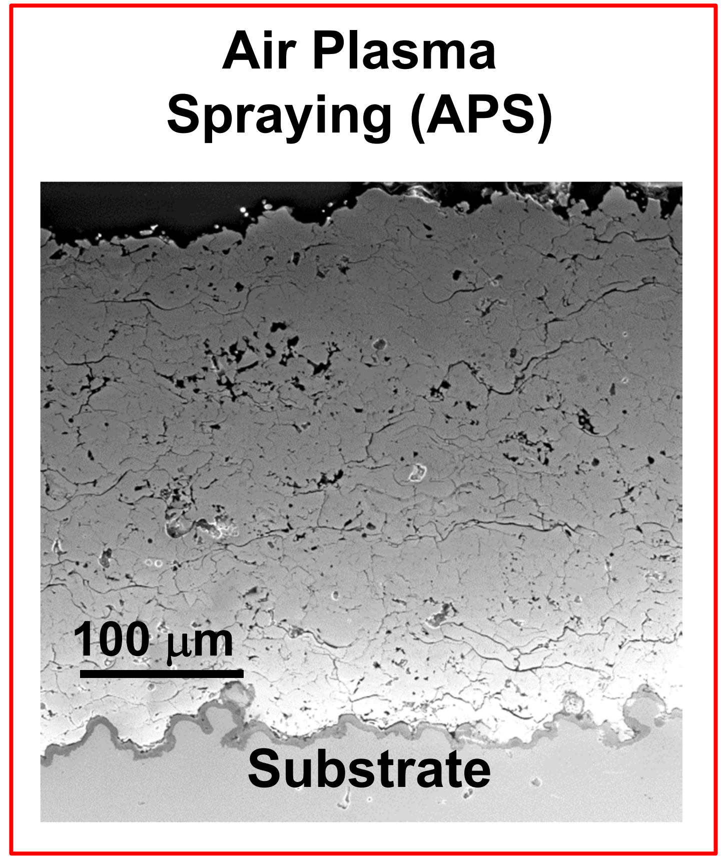
Thermal-Barrier-Coated Turbine Blade



Science, 2002; *MRS Bull.*, 2012

Ceramic TBCs



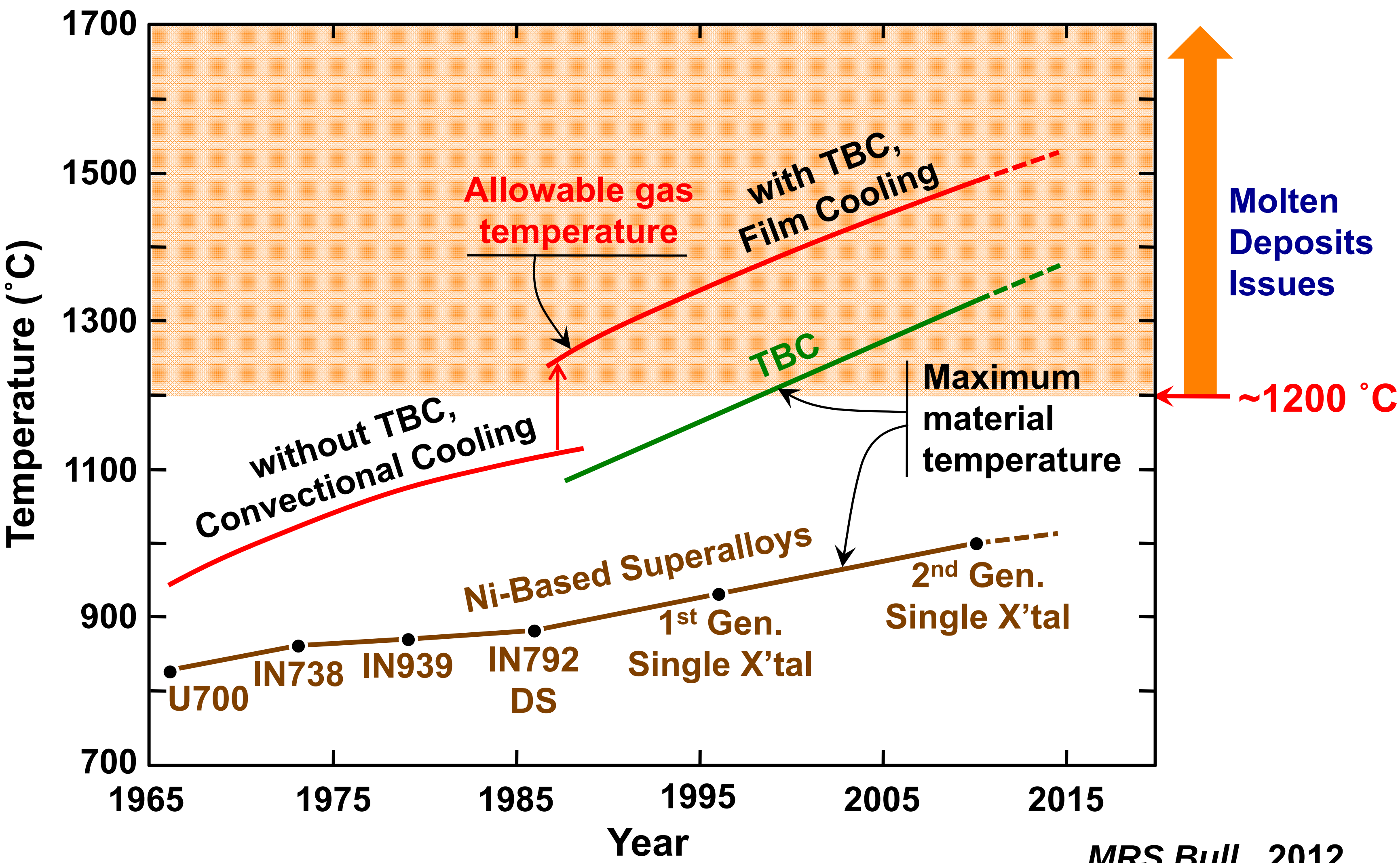


* Low Thermal Conductivity (ZrO_2 + 7 wt% Y_2O_3 Solid Soln.: 7YSZ)

* High Porosity (15 - 20%); Thickness 100 to 500 μm

* "Strain Tolerant" to Accomodate Th. Exp. Mismatch with Metal

Thermal Barrier Coatings (TBCs)



MRS Bull., 2012

Push for Higher Temperatures => New Materials Issues

Sources of Silicate Deposits in Aero Engines

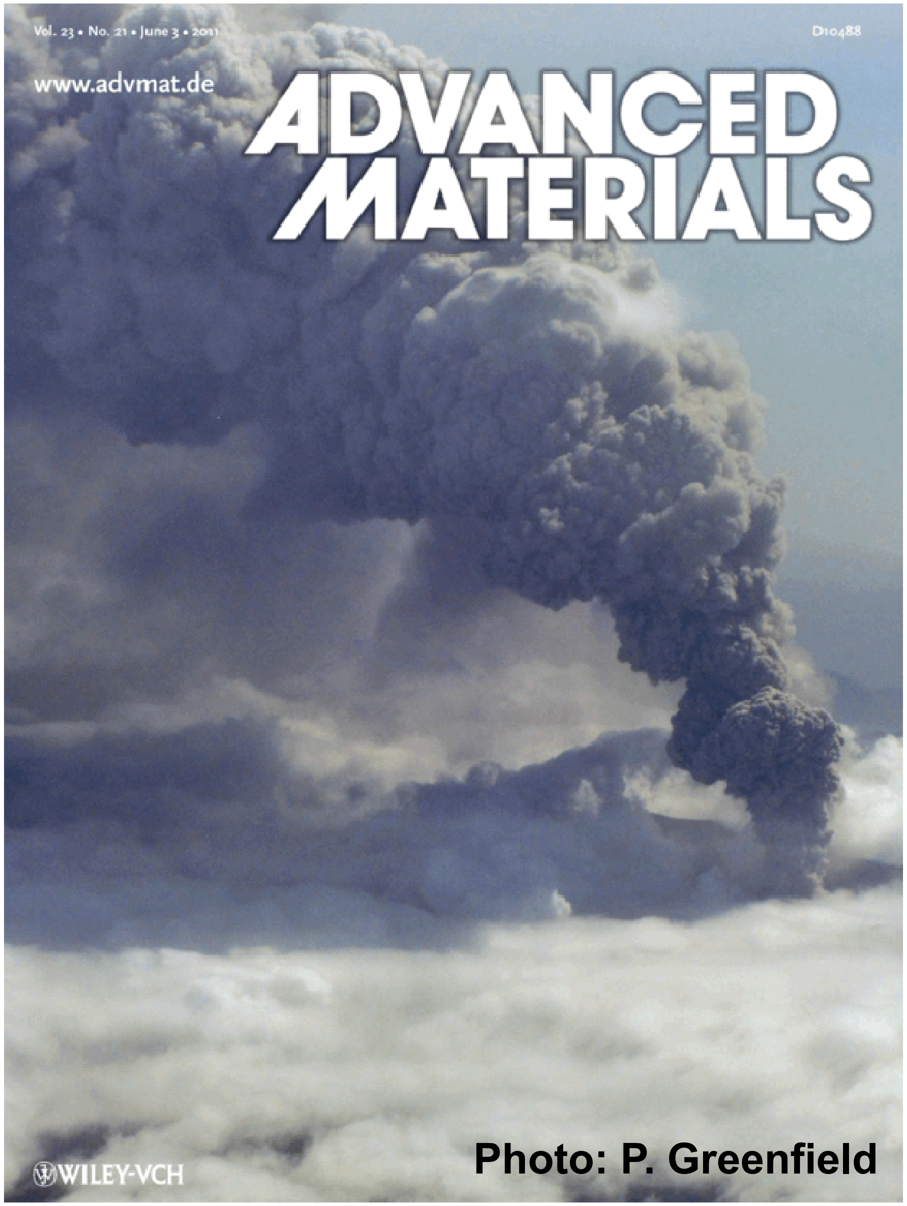
Calcium-Magnesium-Alumino-Silicate (CMAS) Sand

- * **Sandstorms: ~0.1 mg/m^3**
  (Ansmann, *et al*. 2003)
- * **Ambient: ~0.01 mg/m^3**
- * **Runways: >1.0 mg/m^3 (?)**
- * **Sand Ingested by Engines: 1 to 100 g/h (Depends on Engine, Bypass Ratio...)**

Damage to TBCs and Engines

Sources of Silicate Deposits in Aero Engines

Volcanic Ash CMAS



* Eyjafjallajökull Eruption in Iceland in 2010

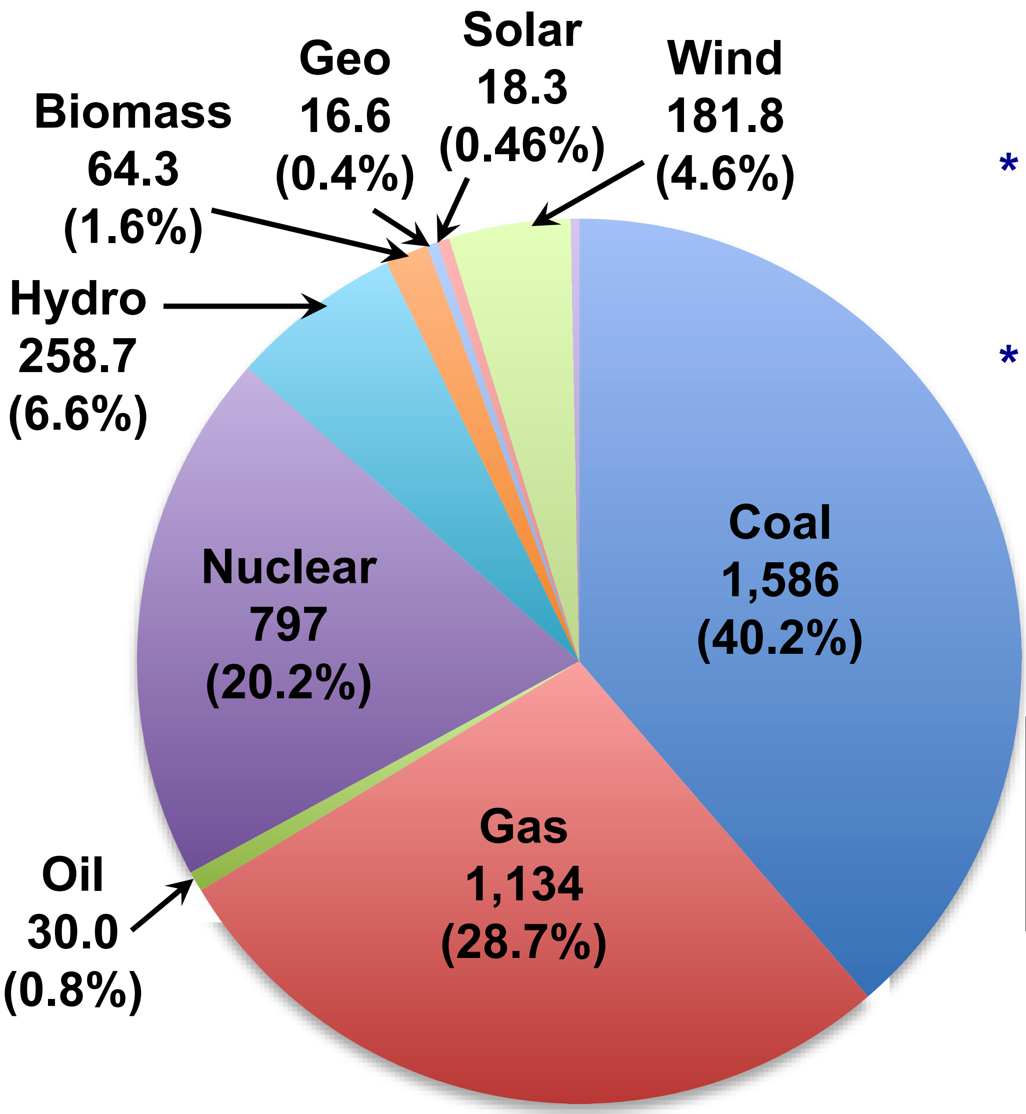
* Shut Down of Vast European Air Space for Several Days

* Economic Loss Approaching $2B

* Conc.: No-Fly Zone: >4.0 mg/m^3
Limited-Fly: 2.0-4.0 mg/m^3
Unrestricted: <2.0 mg/m^3
(Sultana, 2010)

Damage to TBCS and Engines

Sources of Silicate Deposits in Power Engines



* USA Electricity Generation
  by Source in 2014

* USA Total ~4,100 Billion KWh
  (World ~20,000 Billion KWh)

Need for Environmentally Responsible, Efficient Way of Using Available Coal

US Energy Info. Admin.
http://www.eia.doe.gov/fuelelectric.html

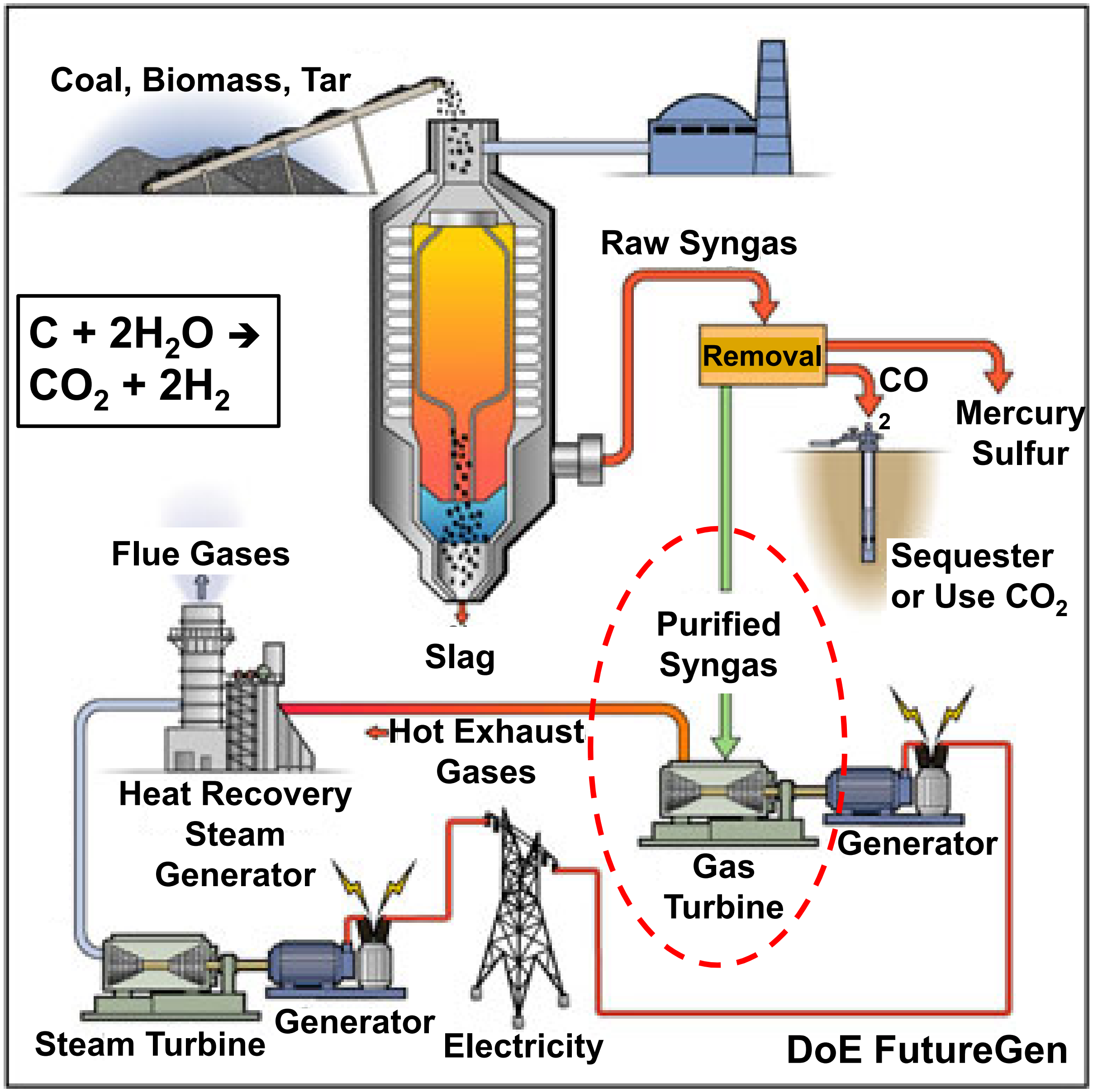
Sources of Silicate Deposits in Power Engines

Fly Ash CMAS

* Syngas Produced from Abundant Coal + H_2O
* CO_2 Capture/Sequester
* IGCC Plants Highly Efficient (~55%)
* H_2-Rich Syngas-Fired: Higher Temps., Water
  * F-Class: 1370 ˚C
  * H-Class: 1430 ˚C
  * J-Class: 1480 ˚C
  * X-Class: 1700 ˚C
* Syngas has Fly Ash ($0.4\ mg/m^3$) (R. Wenglarz)
* Amb. Dust (0.01-$0.1\ mg/m^3$)
* Kgs/day

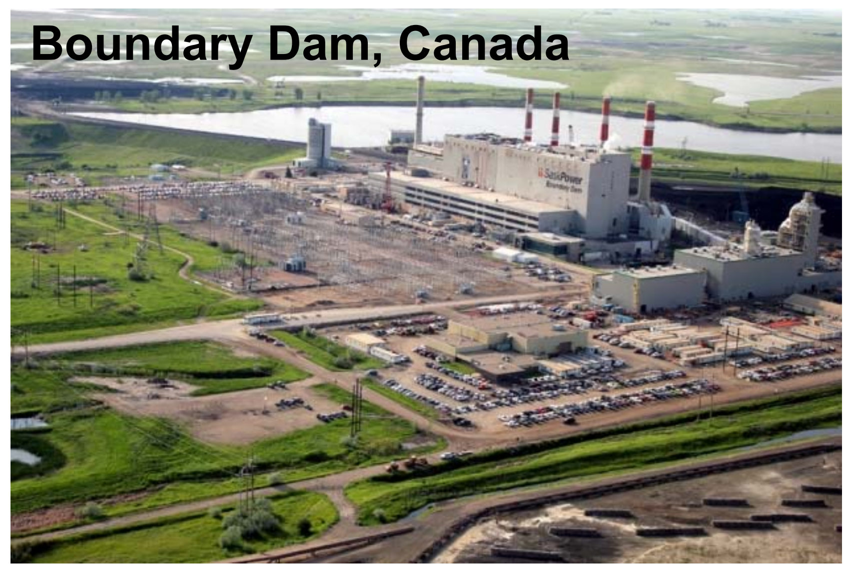
Damage to TBCs and Engines

Integrated Gasification Combined Cycle (IGCC)



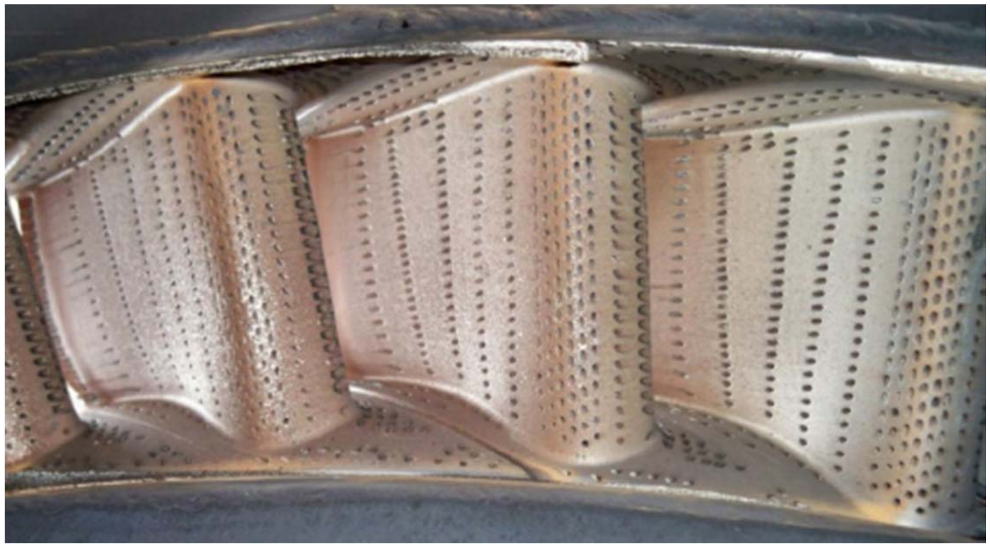
IGCC Power Plants

DoE

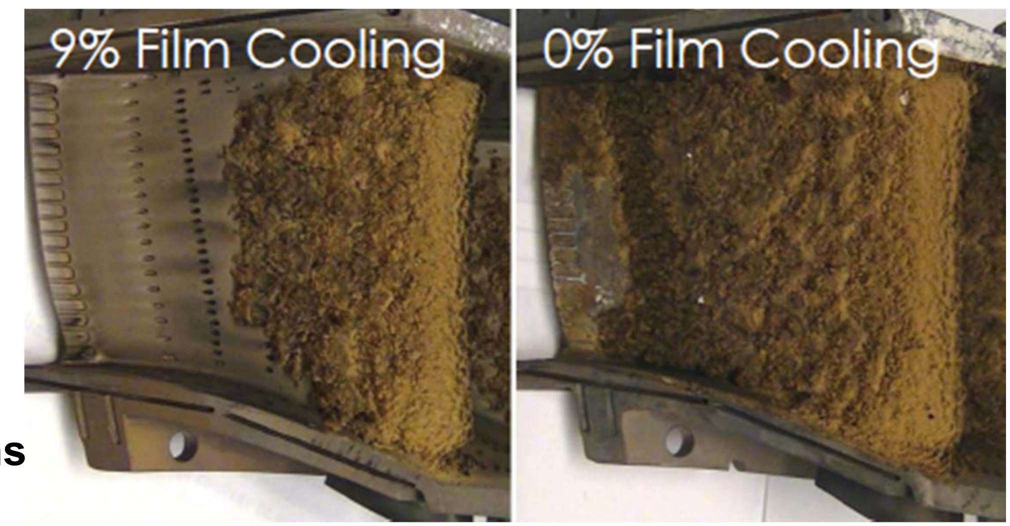


Sources of Silicate Deposits in Power Engines

Fly Ash (Lignite) Injection Tests on Hot Vanes (without TBC)



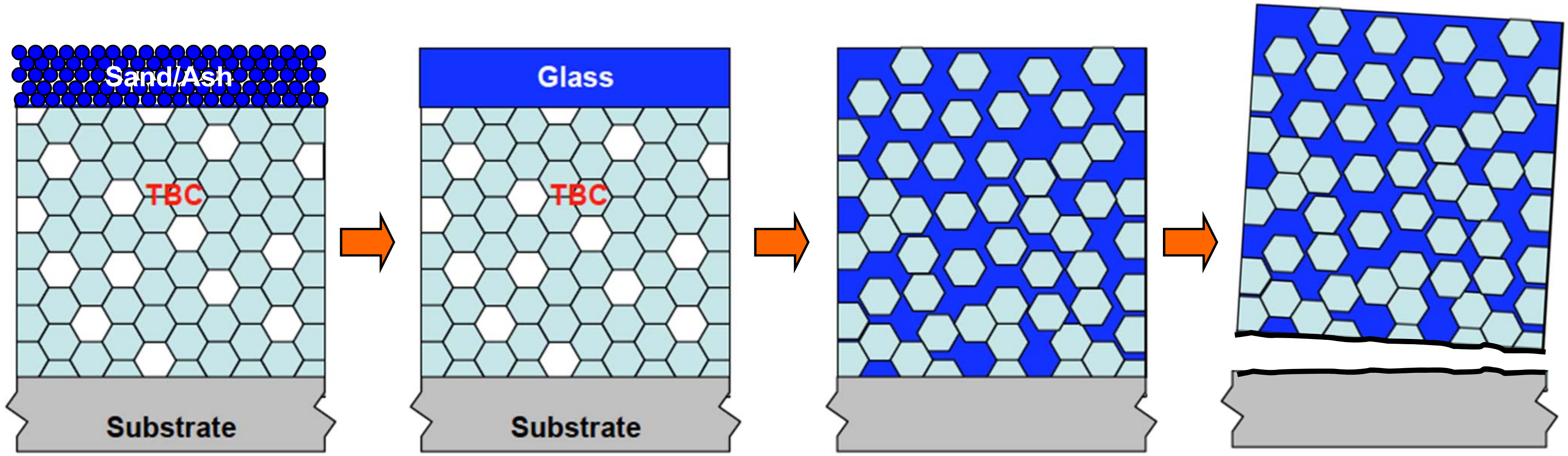
1010 ˚C
1 h Fly Ash Injection



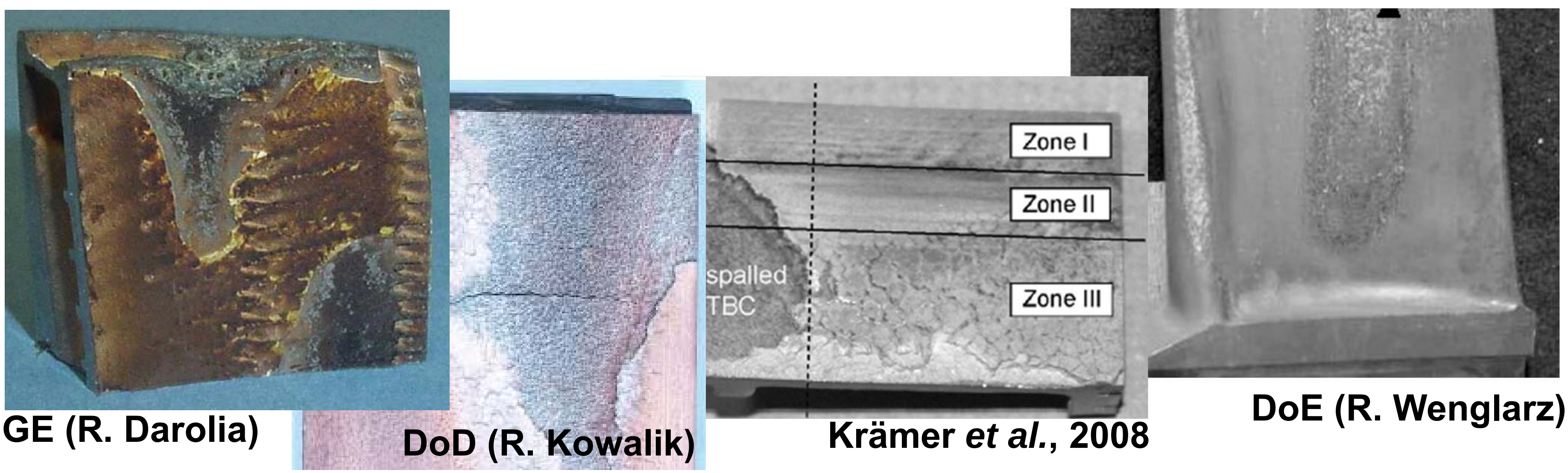
1066 ˚C
0.5 h Fly Ash Injection

J. Bons

Thermo-Chemo-Mechanical Damage of TBCs



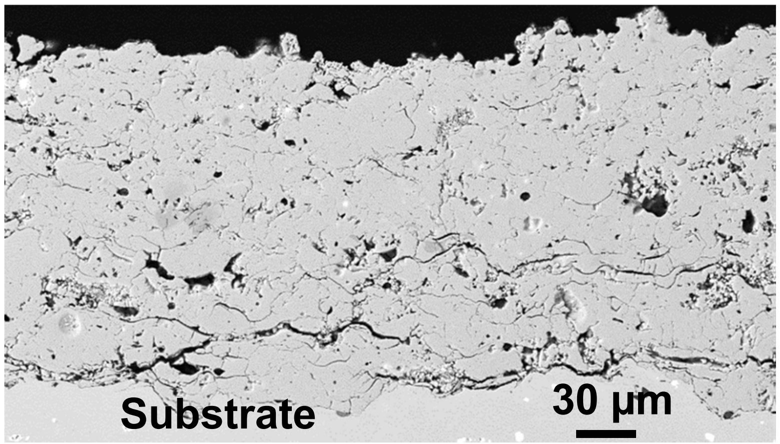
Accumulation → **Melting** → **Penetration, Exfoliation** → **Loss of Strain Tolerance**

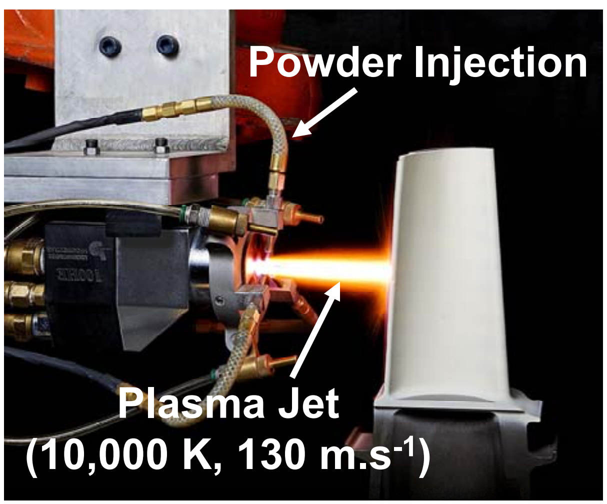


GE (R. Darolia) DoD (R. Kowalik) Krämer *et al.*, 2008 DoE (R. Wenglarz)

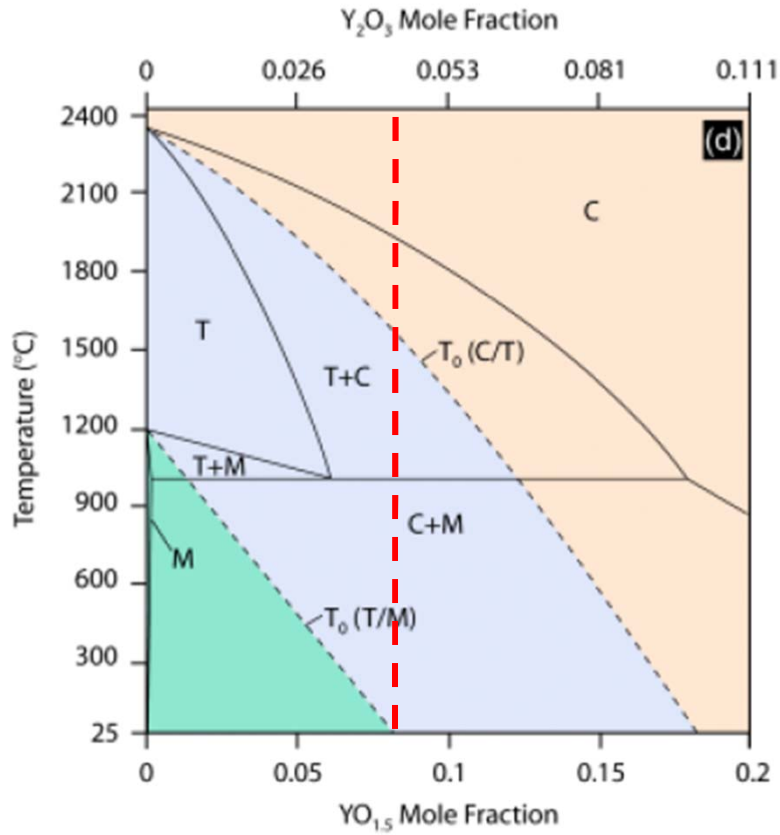
Molten Silicates Damage to APS 7YSZ TBCs

Air Plasma Spray (APS)
7 wt% Y_2O_3 Stabilized ZrO_2 (7YSZ) TBC



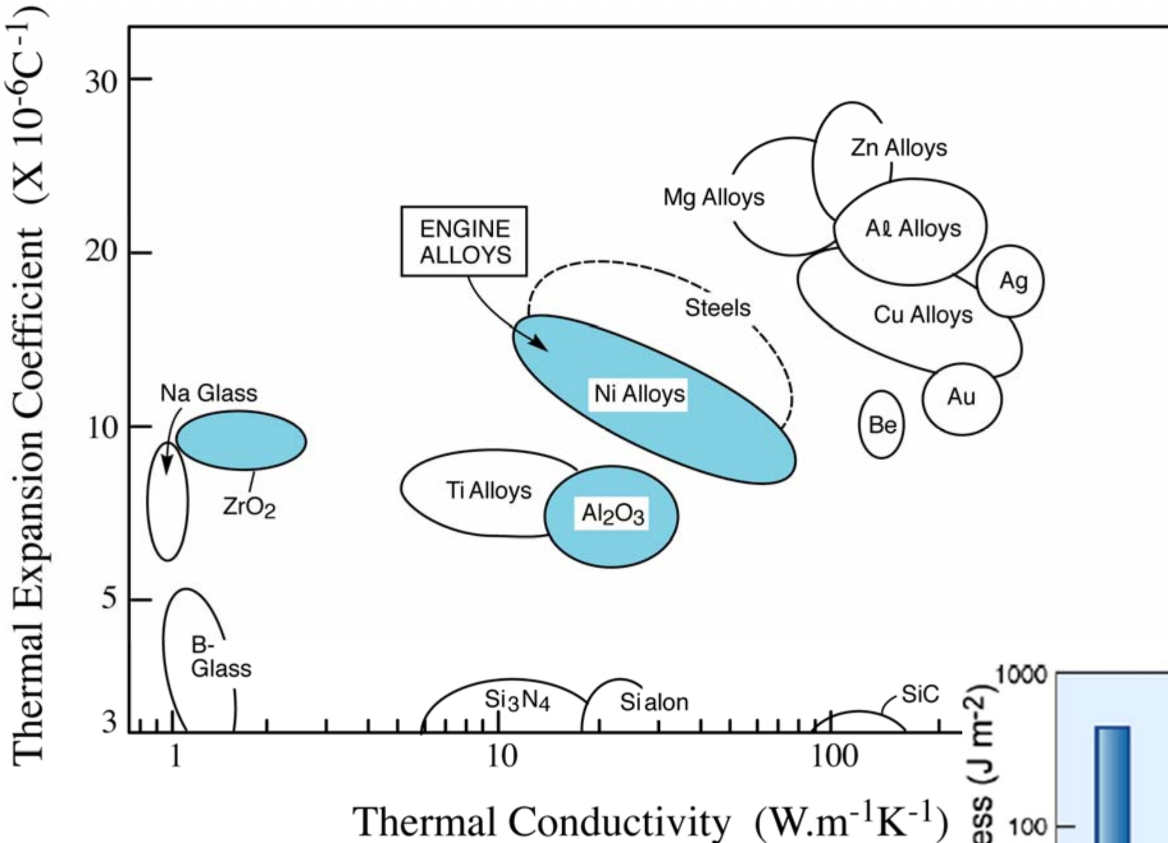


In Collaboration with Prof. S. Sampath



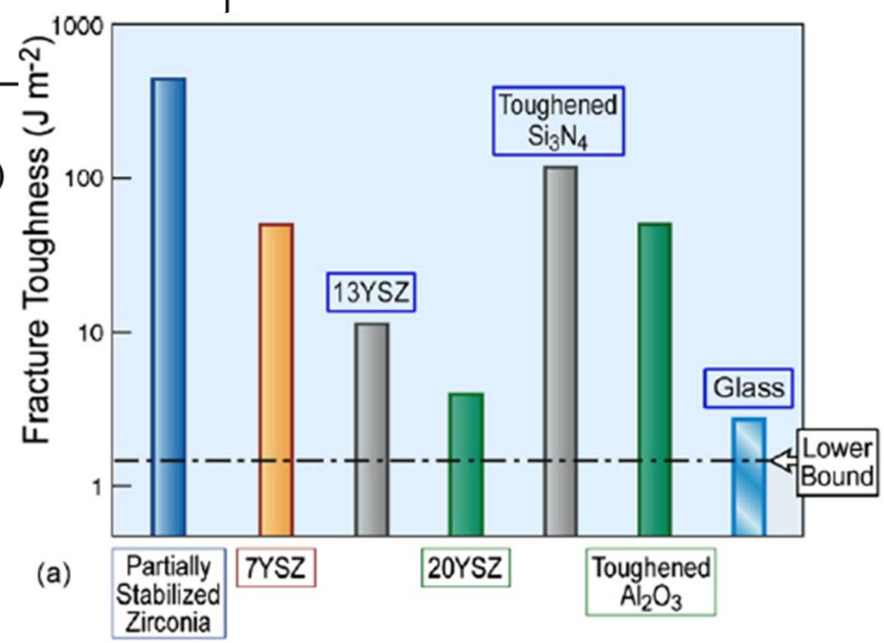
Chevalier *et al.* 2009

7YSZ TBCs

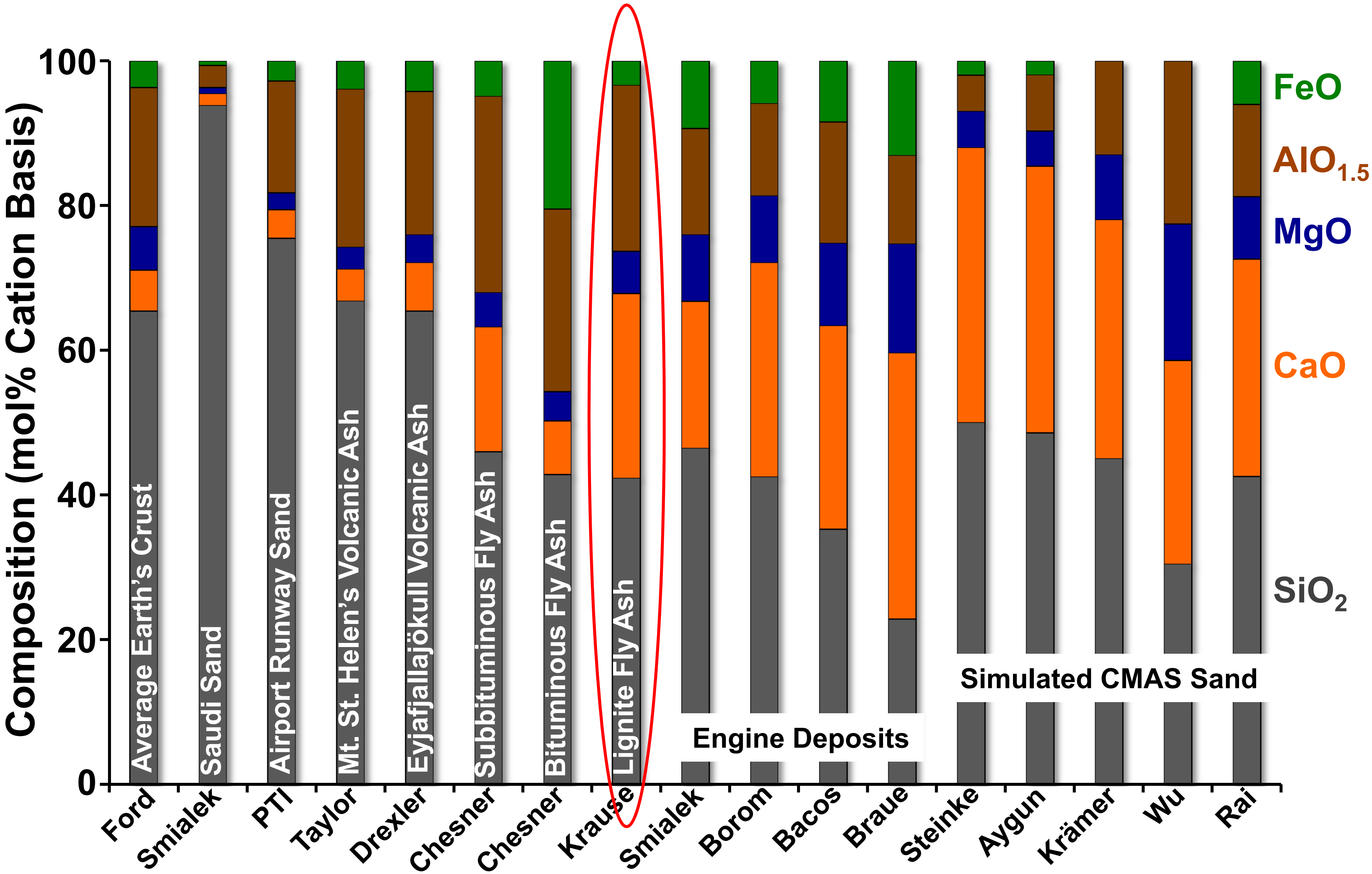


Evans *et al.*, 2008

- **Low Th. Cond.**
- **High Th. Expn. Coeff.**
- **High Toughness (Reversible Ferroelastic)**



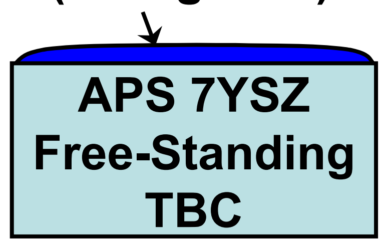
Major CMAS Compositions



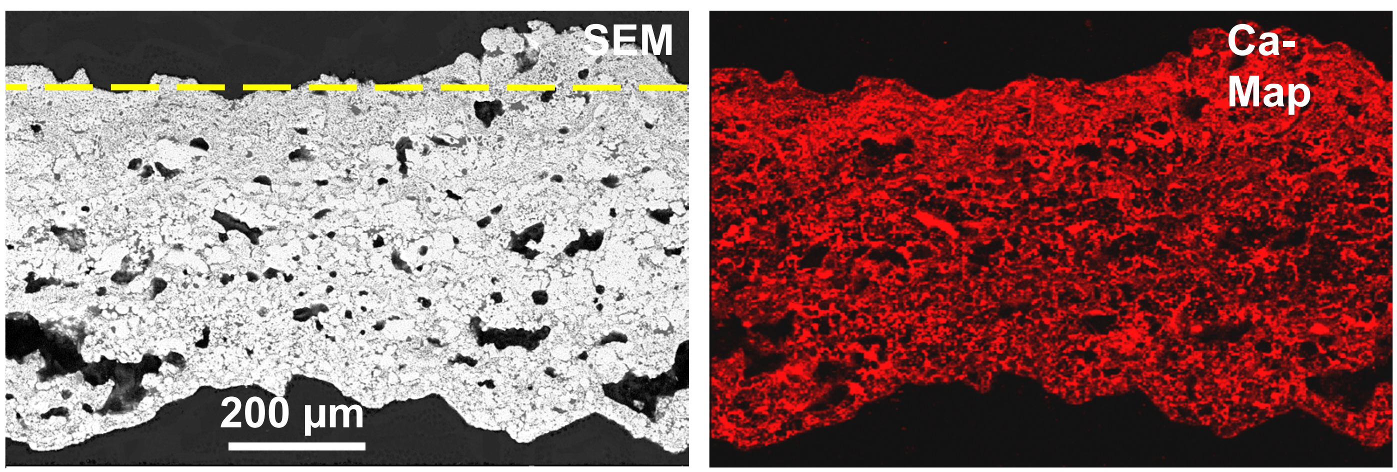
After Levi *et al.*, 2012

APS 7YSZ TBCs Interactions with Fly Ash CMAS

CMAS Fly Ash
(30 mg.cm^{-2})



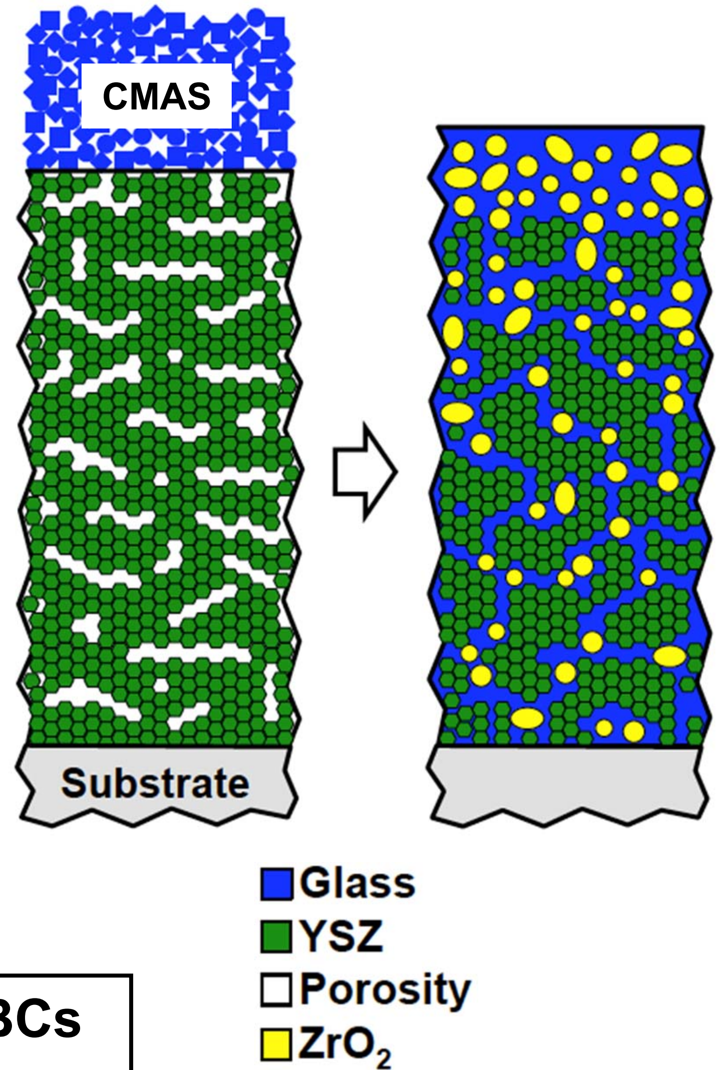
Heat-Treatment 1340 ˚C, 24 h



TBC Fully Penetrated

CMAS Damage Mechanisms in 7YSZ

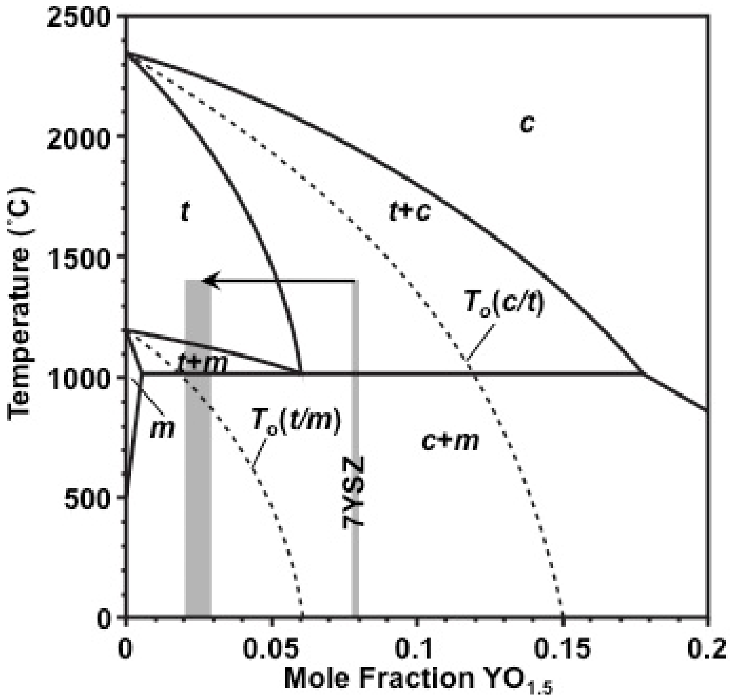
* CMAS Melts into a Glass
* Infiltrates Pores/Cracks
* Penetrates 7YSZ Grain Boundaries
* Dilatation and Exfoliation
* Reaction Between CMAS and 7YSZ: Dissolution of Some *t'*-7YSZ, Reprecipitation as Y-Depleted *m*-ZrO_2, Glass Y-Enriched
* *t'* -> *m* Transformation Stress
* Little Effect on Glass Composition with Small Amount of Solute (Y_2O_3) in TBC: Y:Zr :: 0.083:1



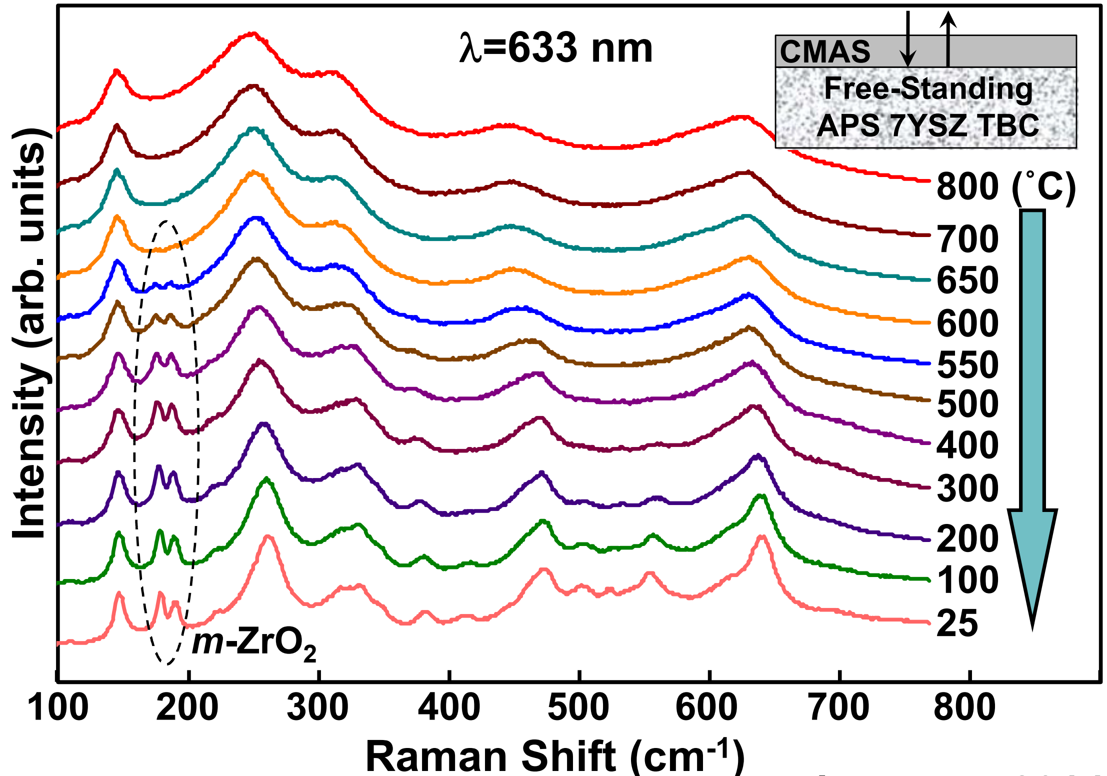
Optimized 7YSZ TBCs Not Suitable for Repelling CMAS Attack

7YSZ TBC/CMAS: *In Situ* Raman

* Equilibrated at 1400 ˚C, 6 h
* Spectra Collected from CMAS/TBC Interface During Cooling



Fabrichnaya *et al.*, 2005

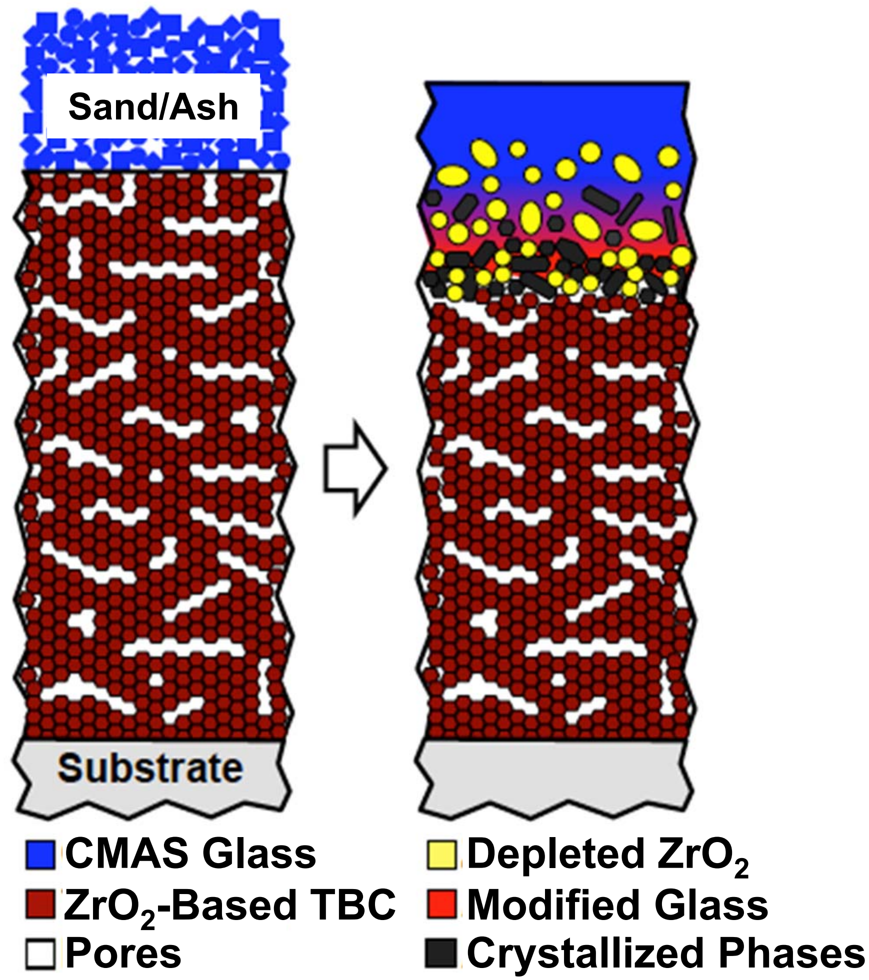


Scripta Mat., 2014

* Y-Depletion
* *t* -> *m* ZrO_2 Transformation Onset ~600˚C
* 3-5% Volume Expansion
* Sand CMAS Glass T_g~705 ˚C
* Consider Transformation Strain in Themomechanical Modeling

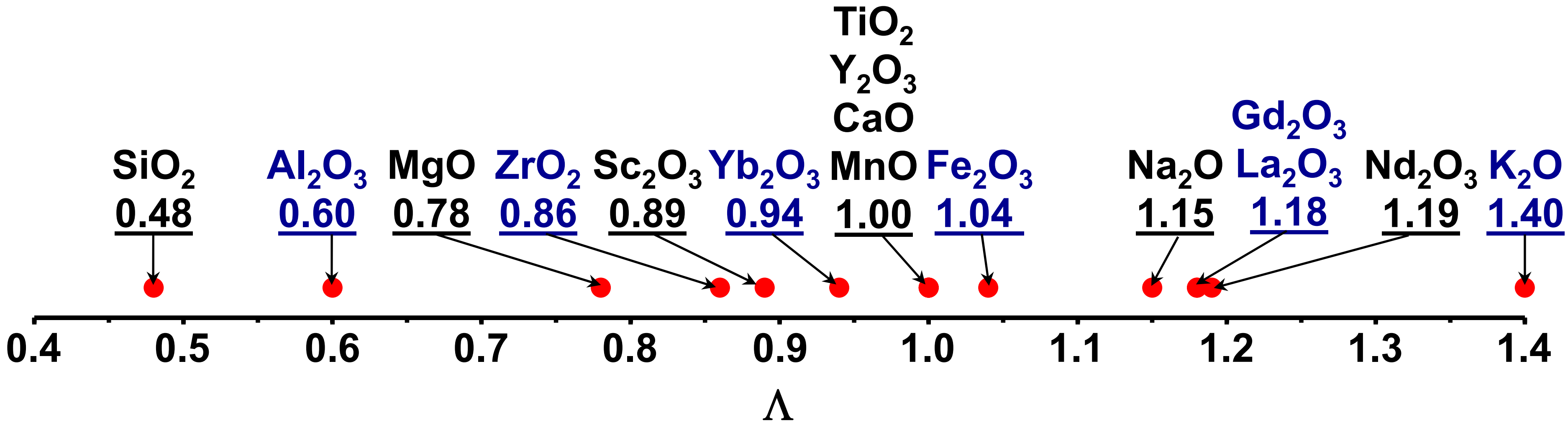
CMAS Damage Mitigation Approach

* Vigorous Reaction Between TBC and CMAS
* Large Amount of Solute in ZrO_2-Based TBC: Solute:Zr :: 1:1 (cf. Y:Zr :: 0.083:1 in 7YSZ)
* Rapid Accumulation of Solute in CMAS Glass Over Short Penetration Depth
* Crystallization of Modified CMAS
* Refractory Crystallized Phases Seal TBC
* Arrest of CMAS Front



TBC/CMAS Reactivity: Optical Basicity (Λ) Concept

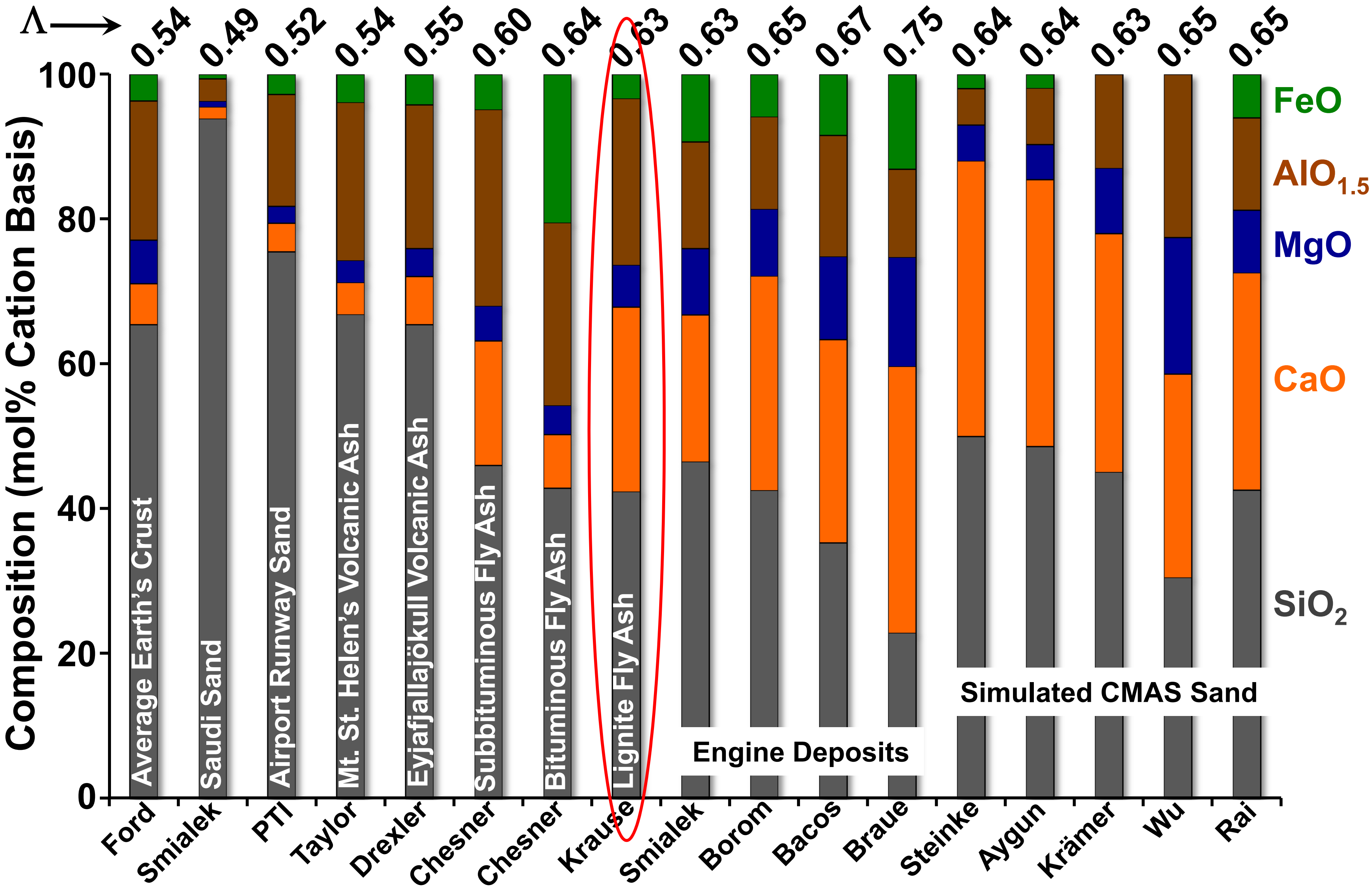
* Used in Glass Sci. to Quantify Chemical Reactivity of Oxide Glasses
* Based on Lewis Acid-Base Theory, Purely Chemical
* Ability of O^{2-} to Donate Electrons
* Depends on the Polarizability of the Cation(s)
* Measured Using UV-Spectroscopy, XPS, Refractivity, Electronegativity



* $\Lambda = X_A \times \Lambda_A + X_B \times \Lambda_B + X_C \times \Lambda_C + \ldots$ (Glasses, Mixed Oxides)
* Reactivity Proportional to $\Delta\Lambda$: Large $\Lambda_{TBC} - \Lambda_{CMAS}$

Duffy;
Dimitrov and Sakka

Major CMAS Compositions: Optical Basicities



After Levi *et al.*, 2012

*** CMAS Λs Within a Narrow Range: 0.52 to 0.67**

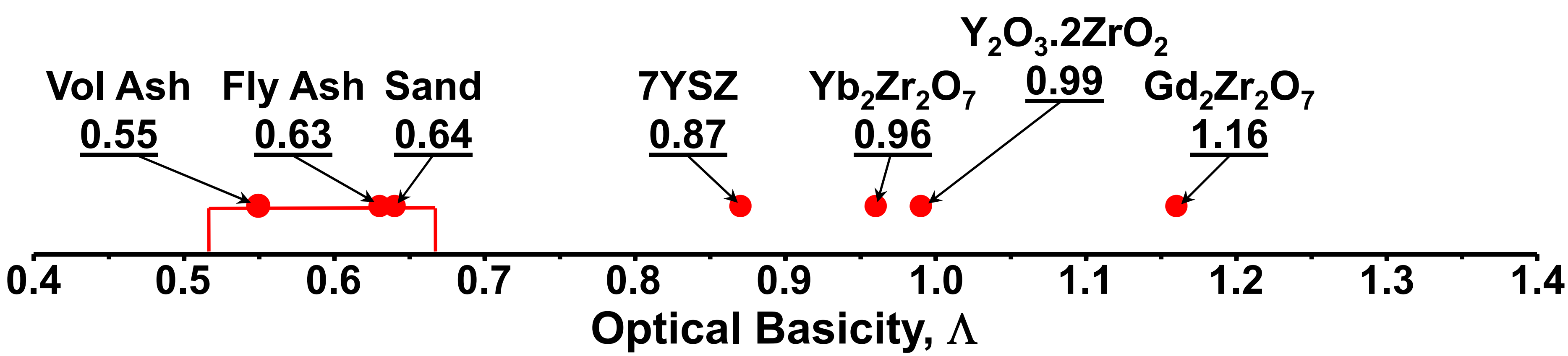
TBC/CMAS Reactivity and "Solute"

*** Effect of "Solute" Type and Concentration in ZrO_2-Based TBC Ceramics**

- Ionic Radius: $Gd^{3+} > Y^{3+} > Yb^{3+}$

TBC Composition	Solute:Zr Ratio	Λ	$\Delta\Lambda$ (Sand Λ 0.64)	$\Delta\Lambda$ (Fly Ash Λ 0.63)	$\Delta\Lambda$ (Vol Ash Λ 0.55)
7YSZ	0.08:1	0.87	0.23	0.24	0.32
$Yb_2Zr_2O_7$	1:1	0.96	0.32	0.33	0.41
$Y_2O_3.2ZrO_2$	1:1	0.99	0.35	0.36	0.44
$Gd_2Zr_2O_7$	1:1	1.16	0.52	0.53	0.61

*** High Reactivity Between TBCs and CMASs Expected**

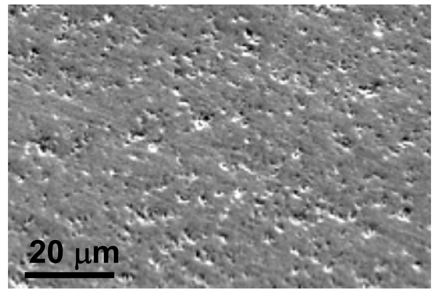


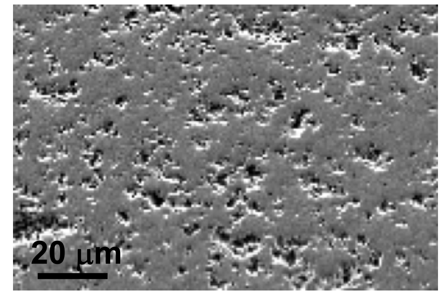
TBC Ceramics/Sand CMAS: "Model" Experiments

* Partially Sintered Ceramic Pellets (~15% Porosity)

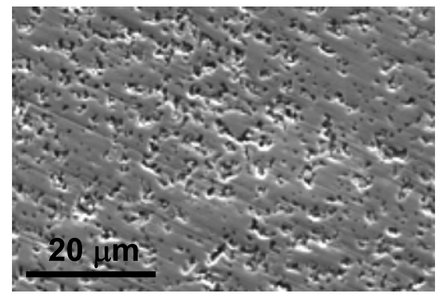
* Sand CMAS Glass Plates: Λ = 0.64

7YSZ
3.9 m% Y_2O_3
Y:Zr::0.08:1

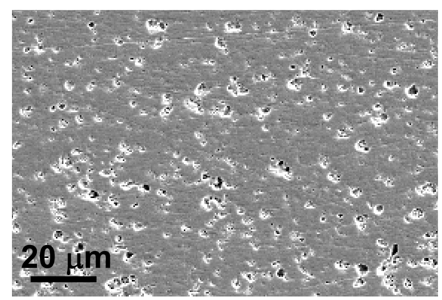




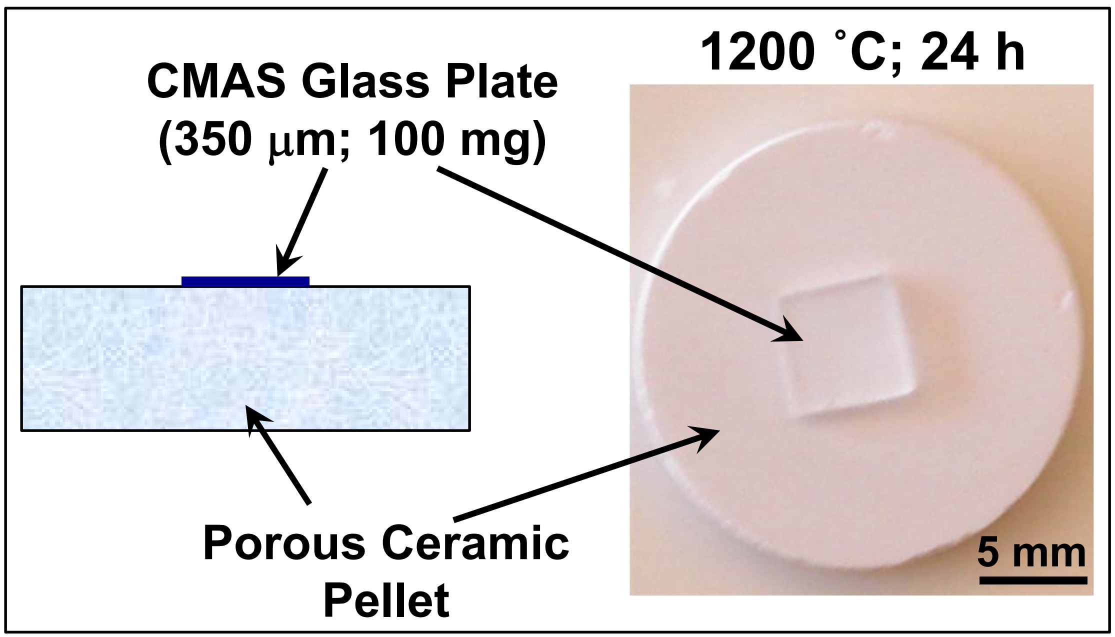
$Y_2O_3.2ZrO_2$
33.3 m% Y_2O_3
Y:Zr::1:1



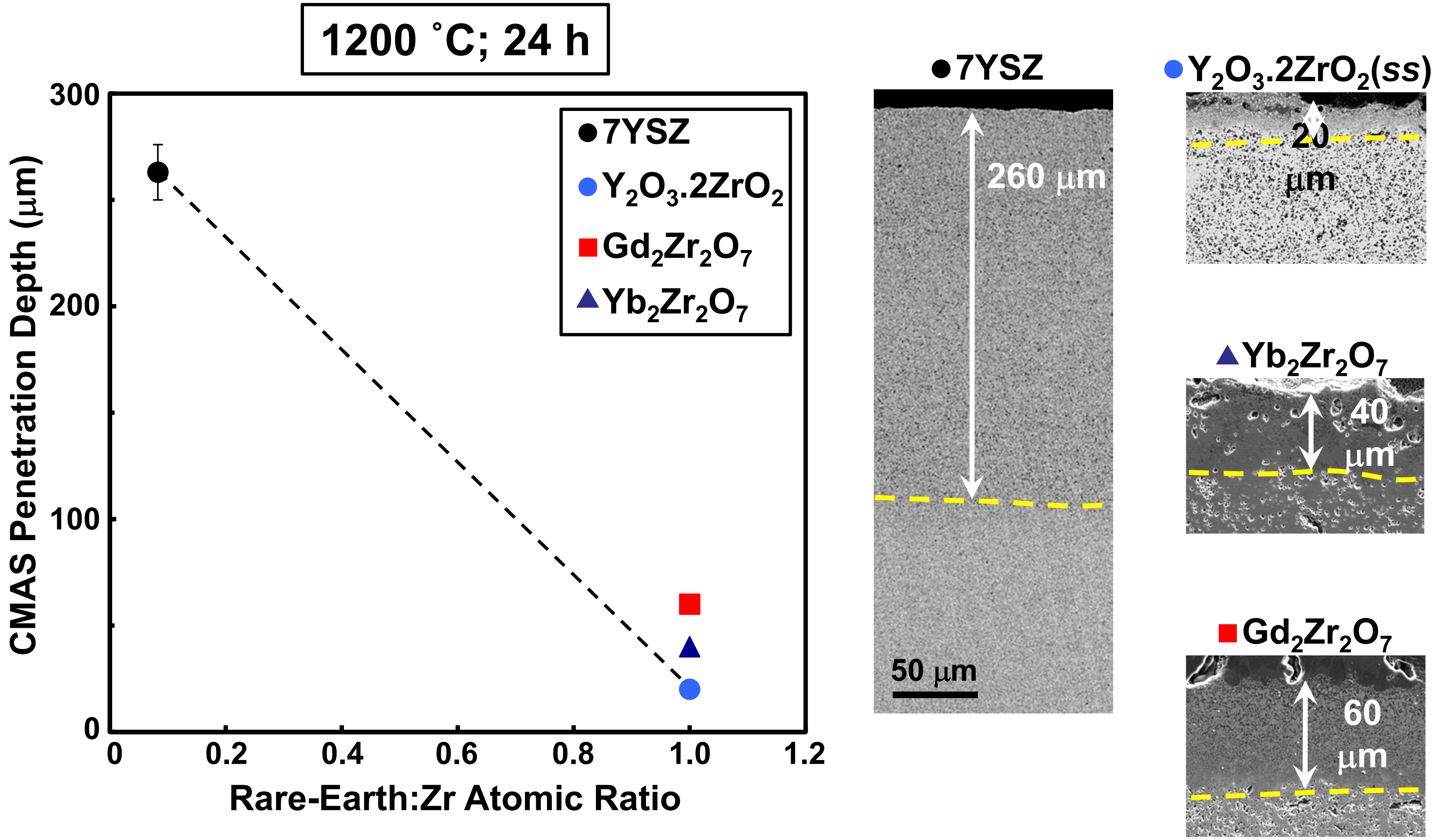
$Gd_2Zr_2O_7$
33.3 m% Gd_2O_3
Gd:Zr::1:1



$Yb_2Zr_2O_7$
33.3 m% Yb_2O_3
Yb:Zr::1:1



TBC Ceramics/Sand CMAS: "Model" Experiments



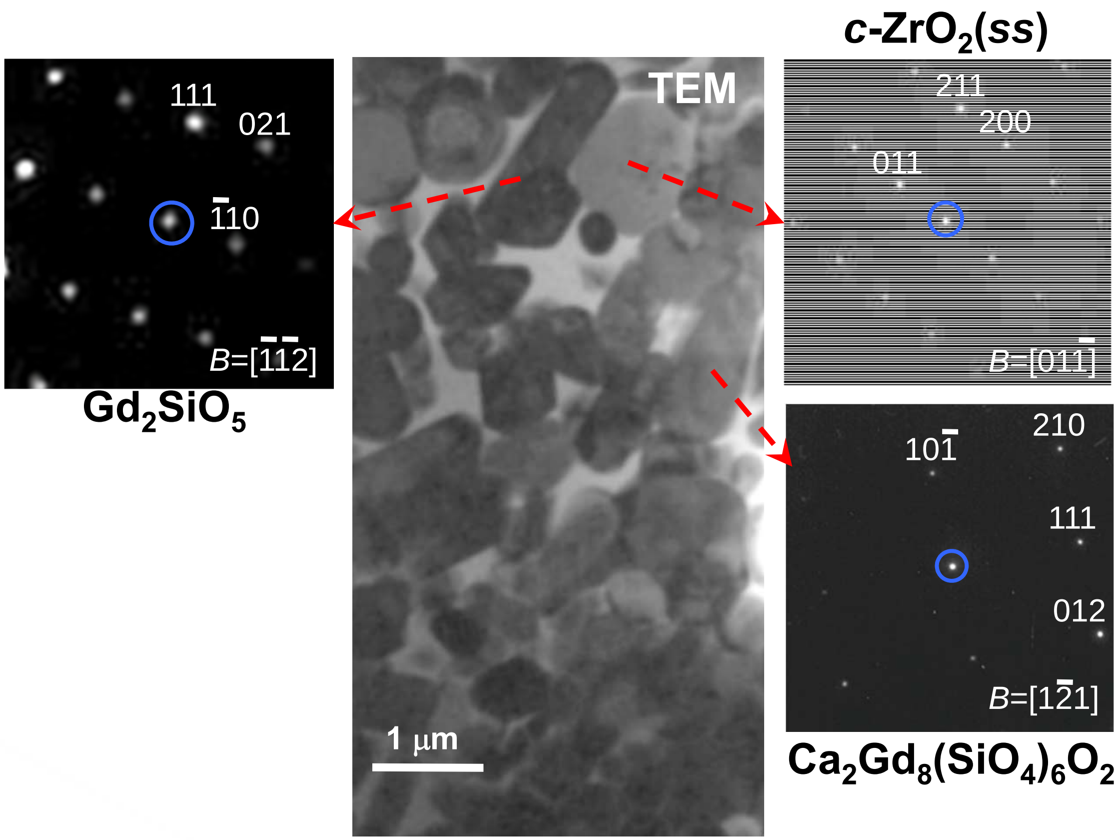
* Solute Concentration Most Effective

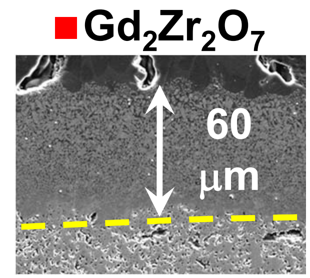
* At High Conc.: Gd < Yb < Y in Effectiveness

* Almost Complete Suppression in $Y_2O_3.2ZrO_2$(*ss*)

Acta Mat. 2012

$Gd_2Zr_2O_7$

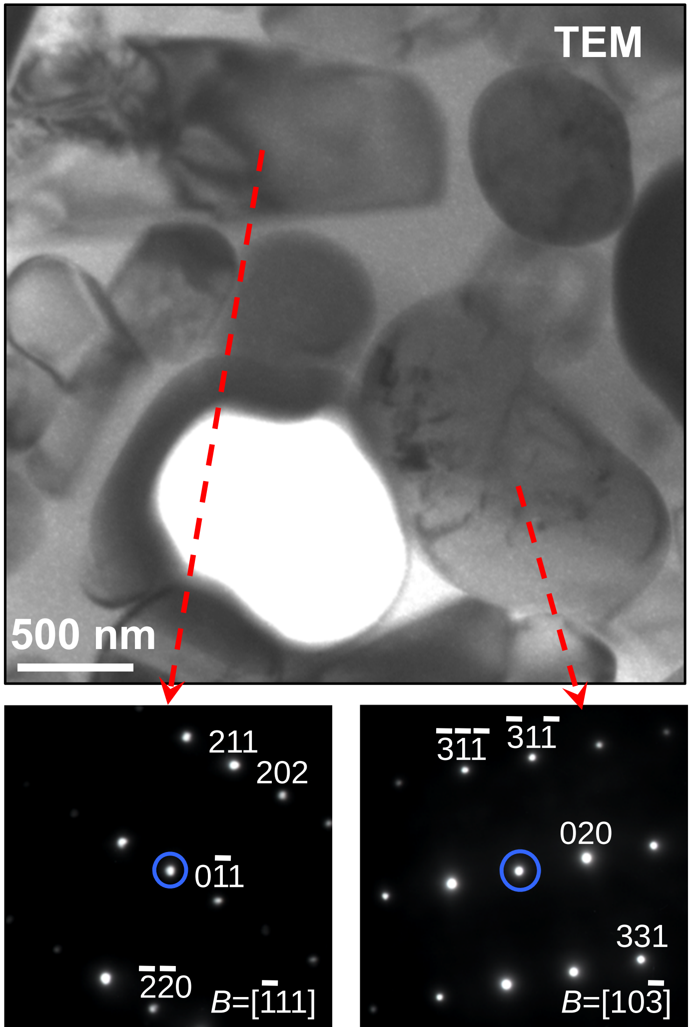




*** Primary Crystallized Phase in Arrest Region:**
Apatite $Ca_2Gd_8(SiO_4)_6O_2$
Gd-Depleted c-$ZrO_2(ss)$

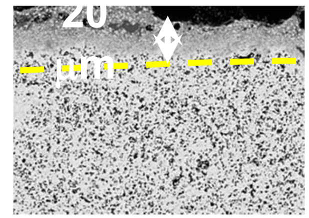
Consistent with results of Levi *et al.* (2009)

$Y_2O_3.2ZrO_2(ss)$



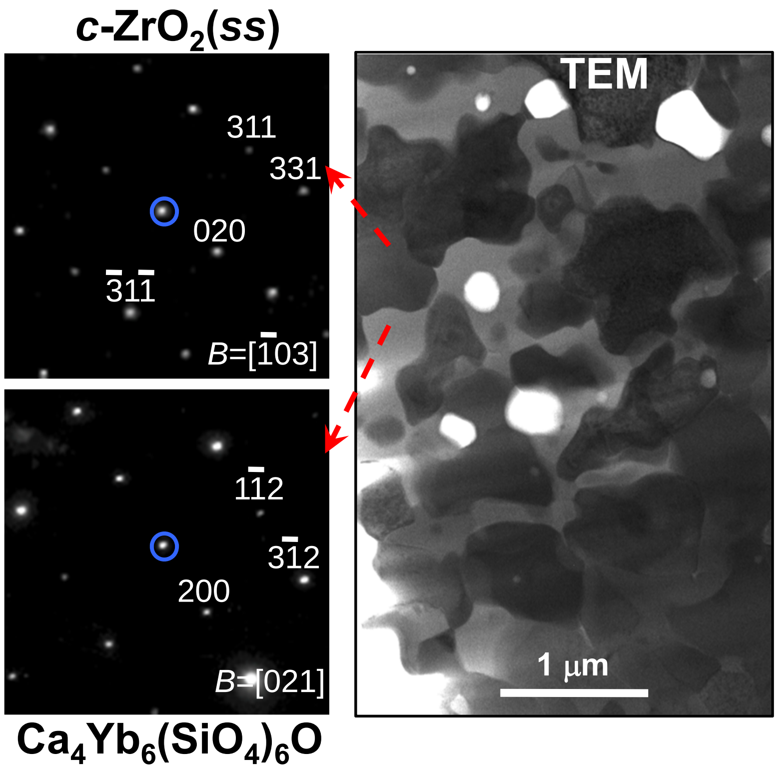
$Ca_4Y_6(SiO_4)_6O$ $c\text{-}ZrO_2(ss)$

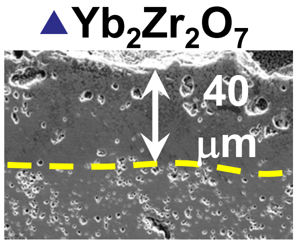
● $Y_2O_3.2ZrO_2(ss)$



*** Primary Crystallized Phase in Arrest Region:**
Apatite $Ca_4Y_6(SiO_4)_6O$
Y-Depleted $c\text{-}ZrO_2(ss)$

$Yb_2Zr_2O_7$





*** Primary Crystallized Phase in Arrest Region:**
Apatite $Ca_4Yb_6(SiO_4)_6O$
Yb-Depleted *c*-ZrO_2(*ss*)

Silicate Apatites

* $Gd_2Zr_2O_7$
  - Forms $Ca_2Gd_8(SiO_4)_6O_2$
  - A^I: All (2) Ca^{2+} + 2 Gd^{3+}
  - A^{II}: 6 Gd^{3+}
  - $(Ca_2Gd_2)Gd_6(SiO_4)_6O_2$
  - Need 8 Gd Atoms
* $Y_2O_3.2ZrO_2$(*ss*)
  - Forms $Ca_4Y_6(SiO_4)_6O$
  - A^I: All (4) Ca^{2+}
  - A^{II}: All (6) Y^{3+}
  - Need 6 Y Atoms
* $Yb_2Zr_2O_7$
  - Forms $Ca_4Yb_6(SiO_4)_6O$
  - A^I: All (4) Ca^{2+}
  - A^{II}: All (6) Yb^{3+}
  - Need 6 Yb Atoms, But Apatite Crystallization Propensity Decreases with RE Size

(Quintas *et al.*, 2008)

Acta Mat. 2012

CN=9 (A^I) CN=7 (A^{II})

$$A^I_4A^{II}_6(SiO_4)_6O_x$$

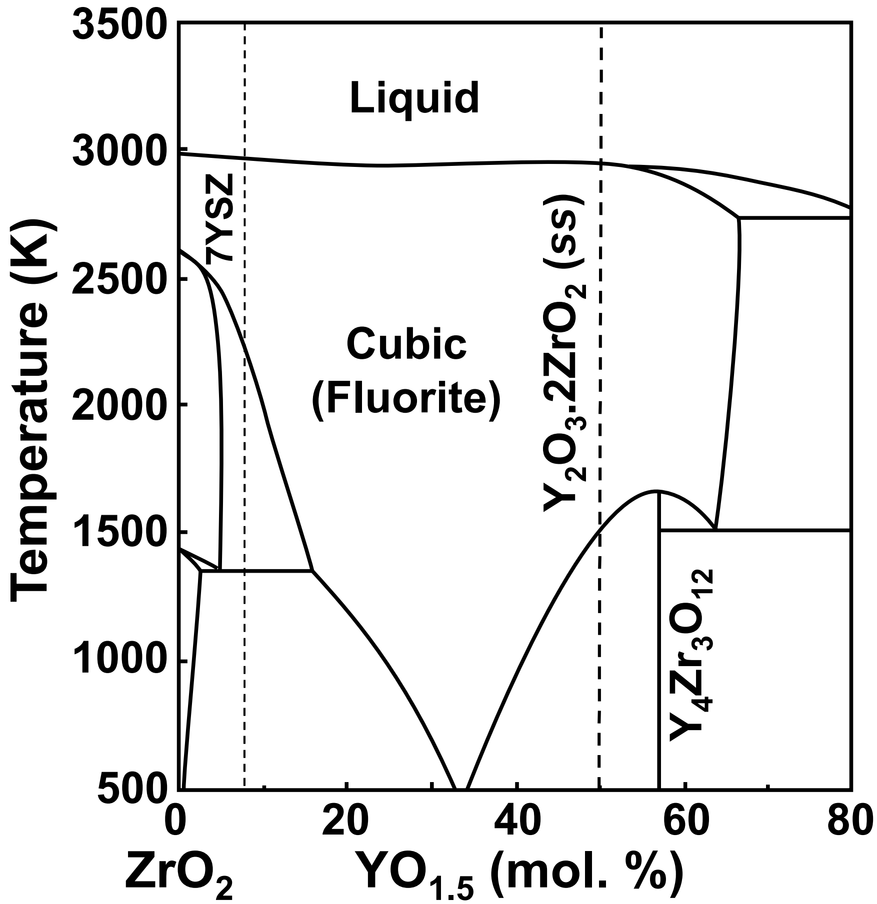
Cation "A"	A^I Site (pm)	A^{II} Site (pm)
Lu^{3+}	103	-
Yb^{3+}	104	93
Er^{3+}	106	95
Y^{3+}	108	96
Gd^{3+}	111	100
Sm^{3+}	113	102
Nd^{3+}	116	-
Ca^{2+}	118	106
Ce^{3+}	120	107
La^{3+}	122	110

↑ Harder to Crystallize Apatite

↓ Need More RE^{3+} to Form Apatite

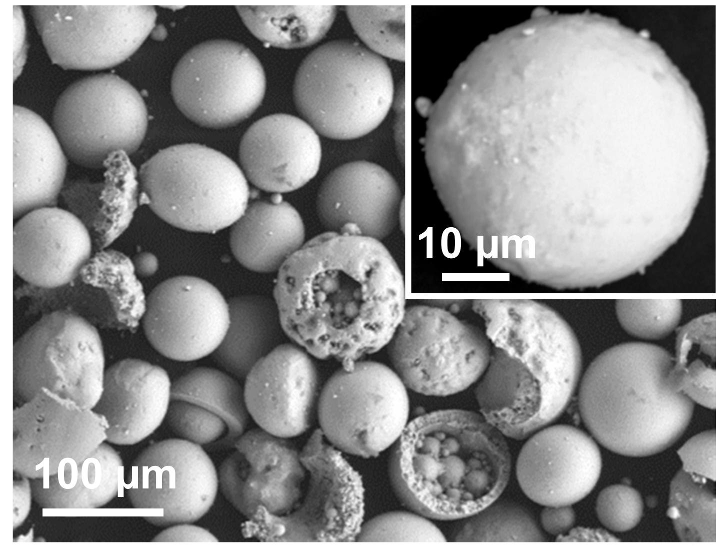
1976

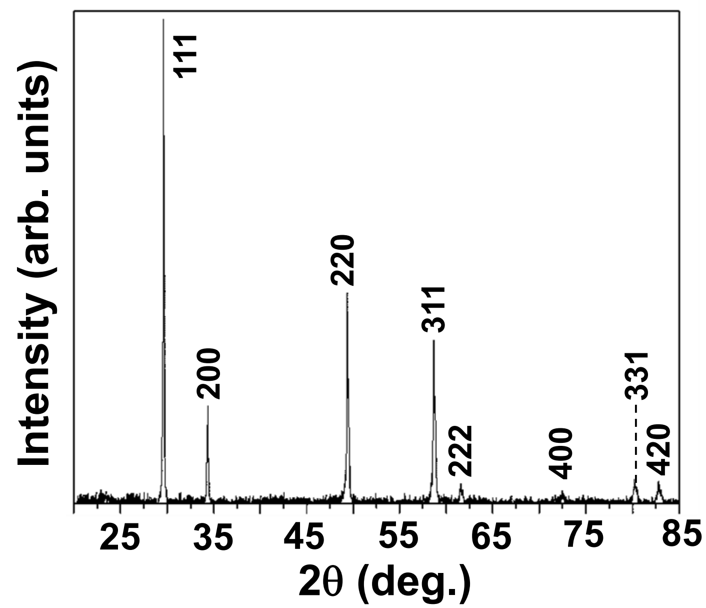
$Y_2O_3.2ZrO_2$(*ss*) APS TBCs



Jacobson *et al.*, 2004

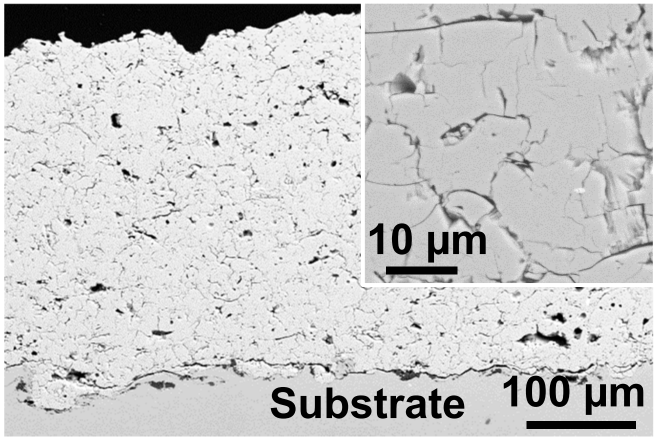
APS Custom Powders
(in collaboration with Sulzer)





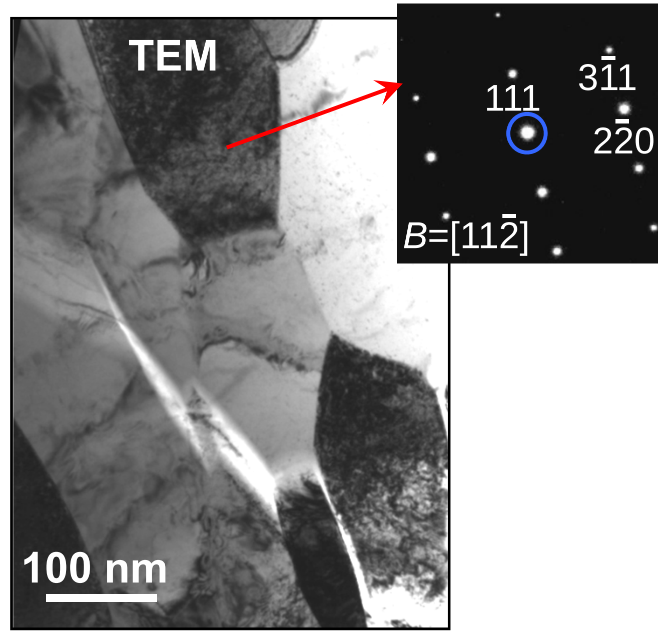
$Y_2O_3.2ZrO_2$(*ss*) APS TBCs

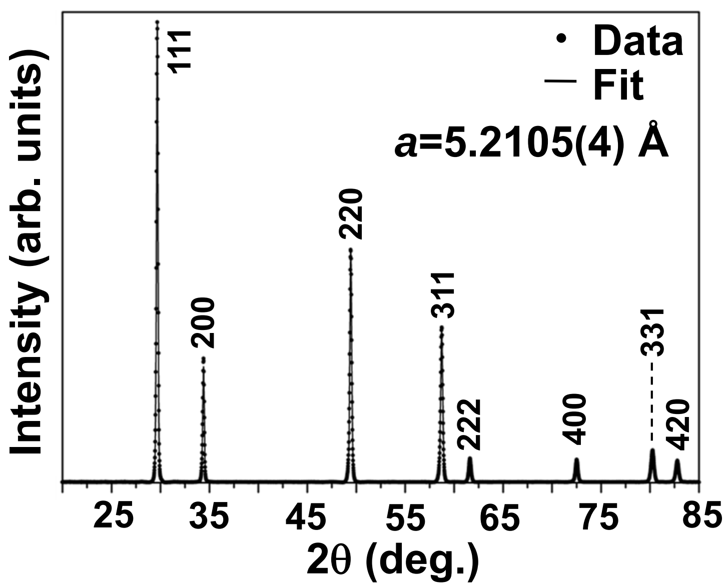
Single-Phase Cubic (Fluorite)



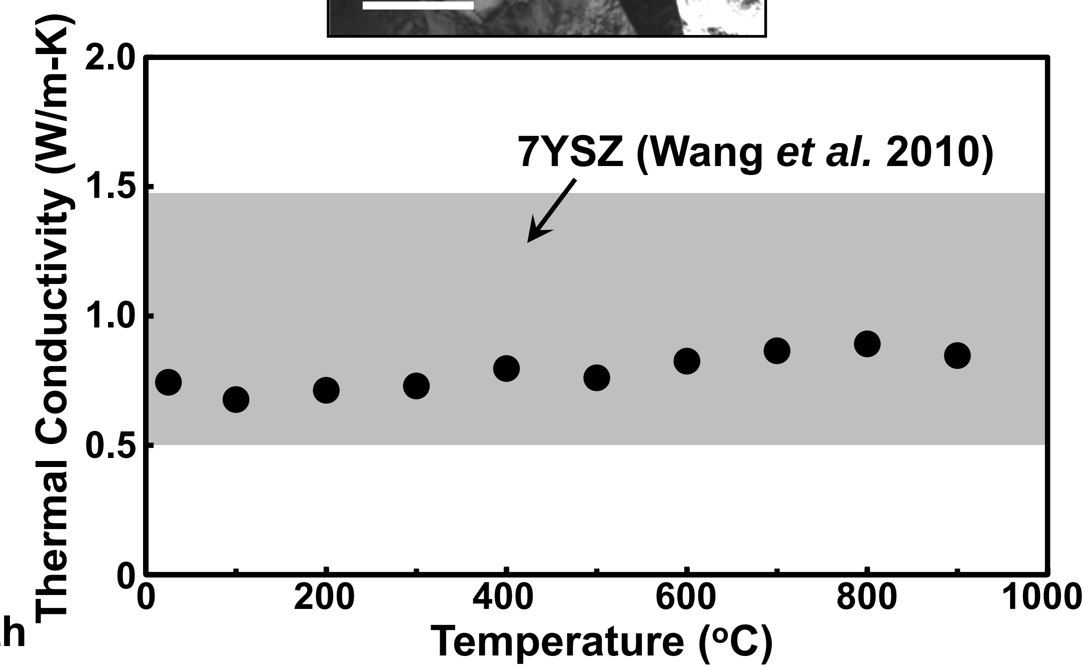
11.4% Porosity

~300 μm Thickness



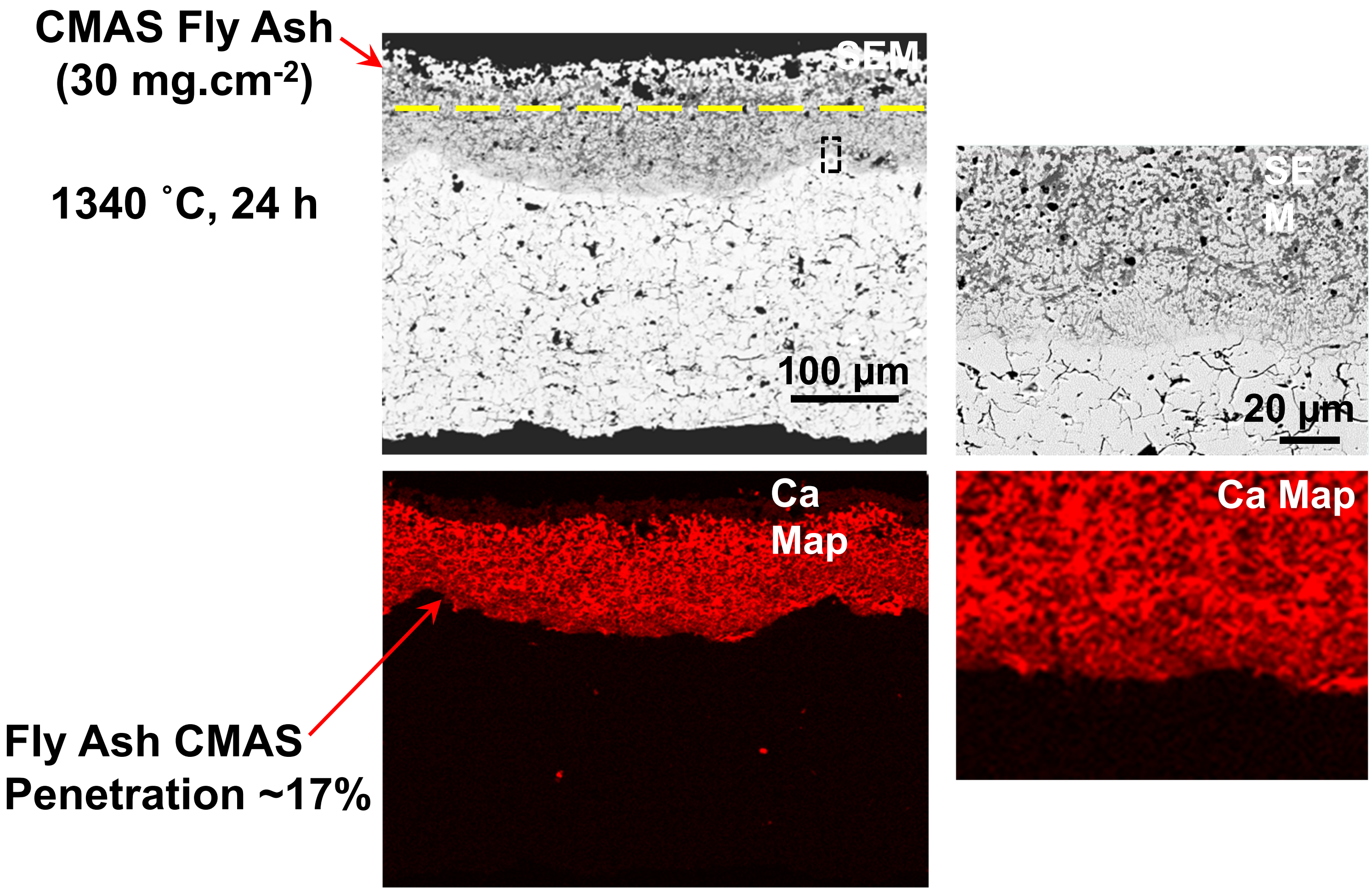


In Collaboration with Prof. S. Sampath



***J. Am. Cer. Soc*, 2015**

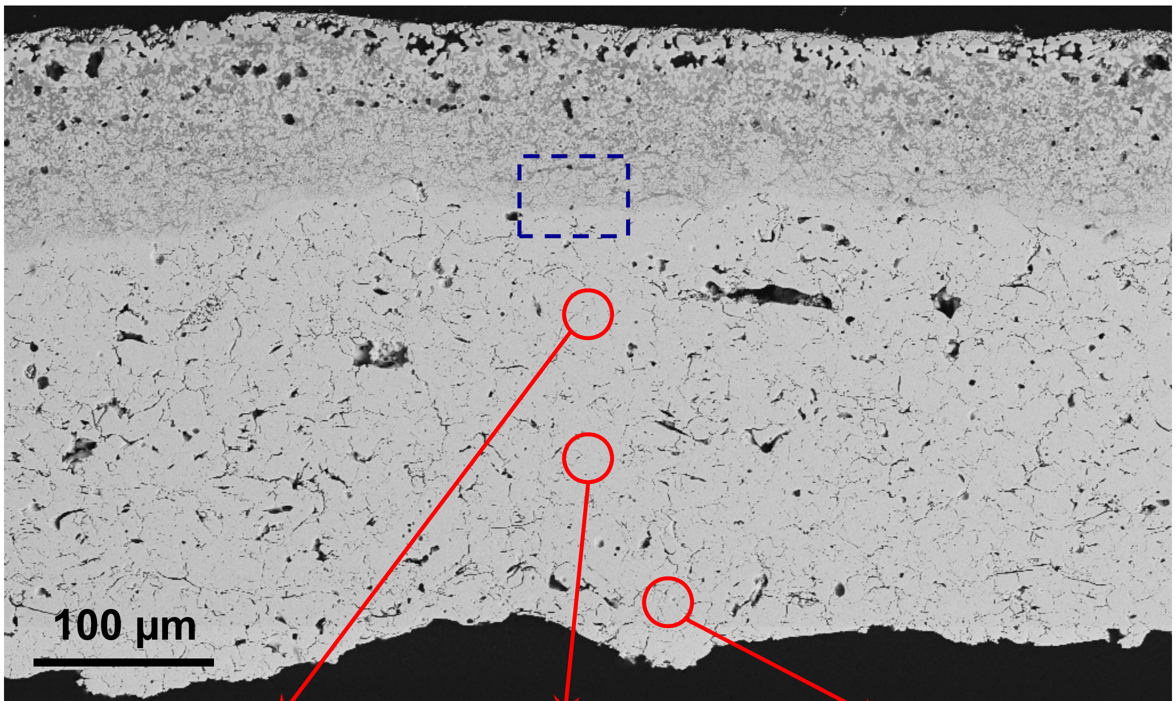
$Y_2O_3.2ZrO_2$(*ss*) APS TBCs: Fly Ash CMAS



***J. Am. Cer. Soc*, 2015**

$Y_2O_3.2ZrO_2$(*ss*) APS TBCs: Fly Ash CMAS

EDS Composition
Atom % Cation Basis



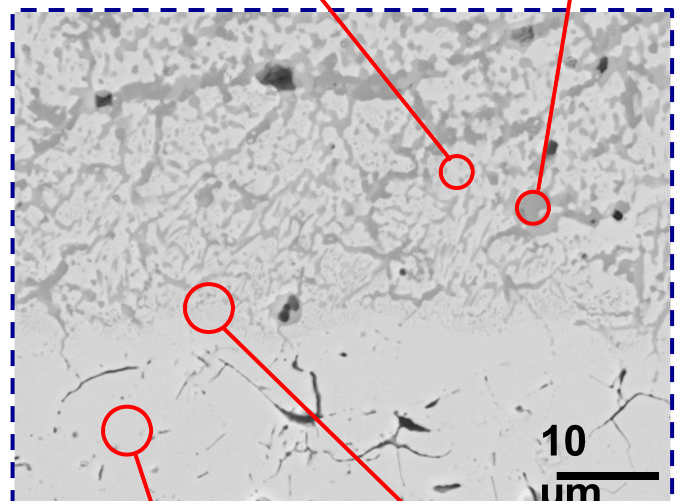
Y	54
Zr	46

Y	53
Zr	47

Y	53
Zr	47

Al	2.5
Si	13.5
Ca	7
Y	40
Zr	37

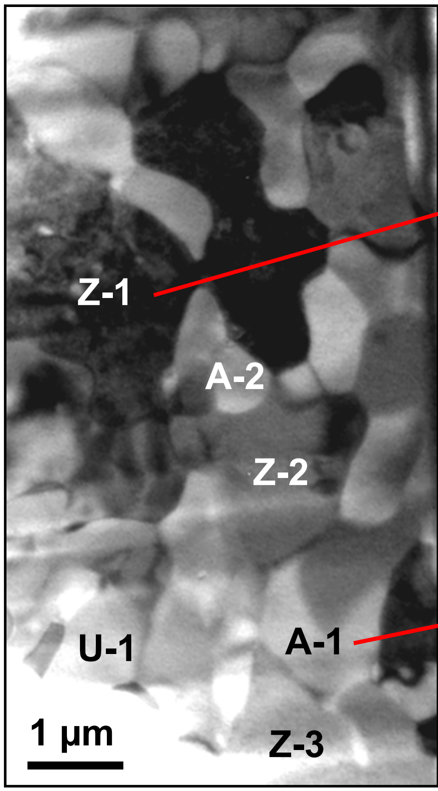
Mg	4
Al	14
Si	23.5
Ca	13.5
Fe	1.5
Y	35
Zr	8.5

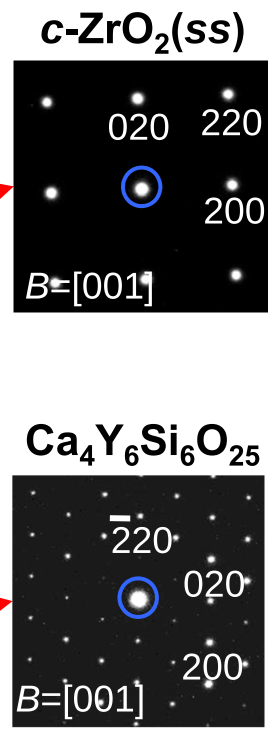


Y	56
Zr	44

Si	6.5
Ca	4.5
Y	47
Zr	42

$Y_2O_3.2ZrO_2$(*ss*) TBC/Fly Ash CMAS





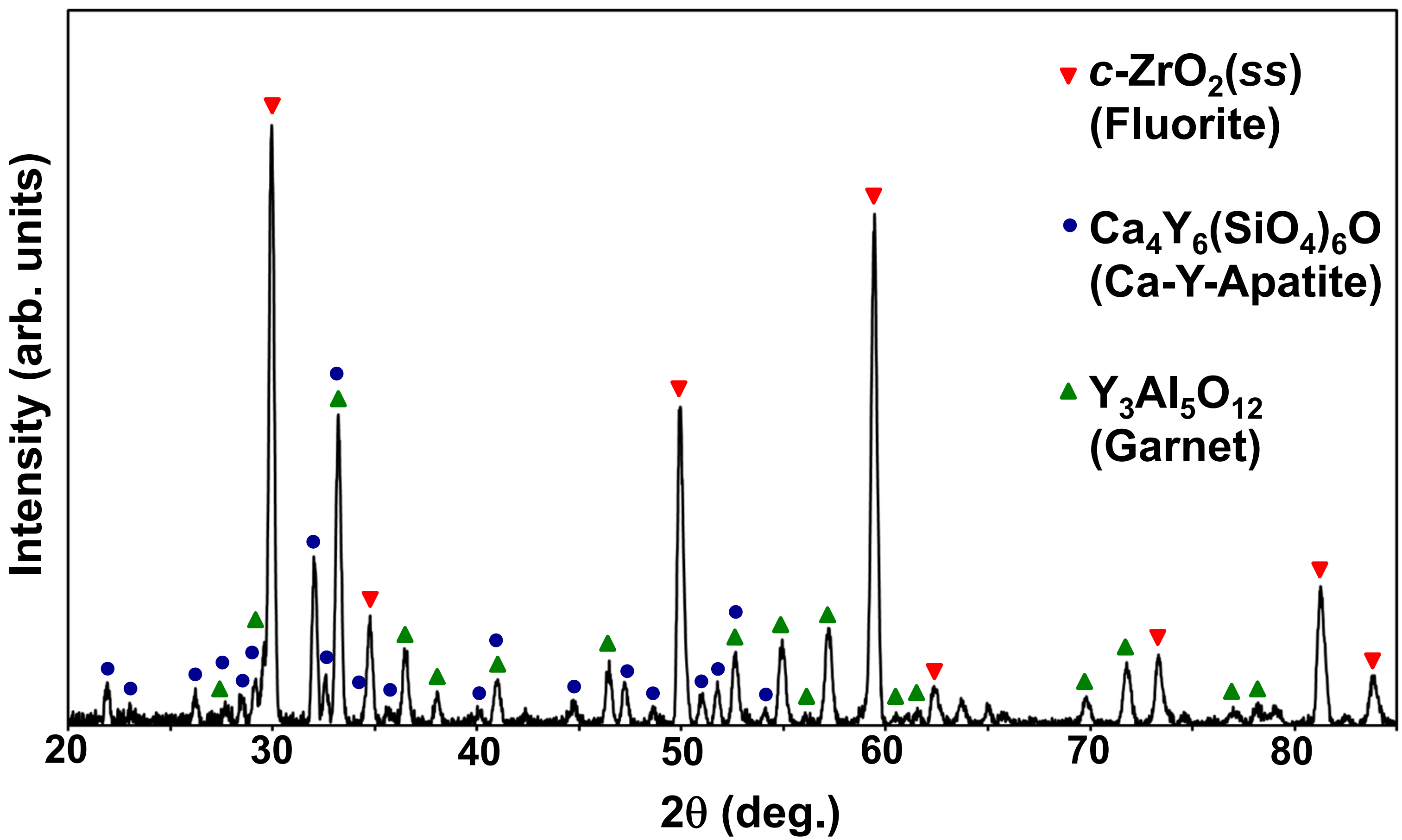
At.%	Λ	Ca	Si	Y	Zr	Al
$Y_2O_3.2ZrO_2$	0.99	-	-	50.0	50.0	-
$Ca_4Y_6(SiO_4)_6O$	0.75	25.0	37.5	37.5	-	-
Z-1	0.99	-	-	37	63	-
Z-2	0.99	-	-	44	57	-
Z-3	0.99	3	-	35	62	-
A-1	0.72	14	45	41	-	-
A-2	0.71	14	47	39	-	-
U-1	0.74	30	30	24	5	7

J. Am. Cer. Soc, 2015

* **Primary Phases in Arrest Region:**
Y-Depleted *c*-ZrO_2(*ss*) + Ca-Y-Apatite ($Ca_4Y_6(SiO_4)_6O$)

$Y_2O_3.2ZrO_2$(*ss*) Powder/Fly Ash CMAS

*** XRD of Powder Mixture (50:50 by wt.) Heat-Treated at 1340 ˚C, 24 h**



CMAS Damage Mitigation

* Exfoliation of TBC Grains by CMAS, Vigorous Reaction (ΔΛ)

* Large Amount of Solute in $Y_2O_3.2ZrO_2$(*ss*): Y:Zr :: 1:1 (Y:Zr :: 0.08:1 in 7YSZ)

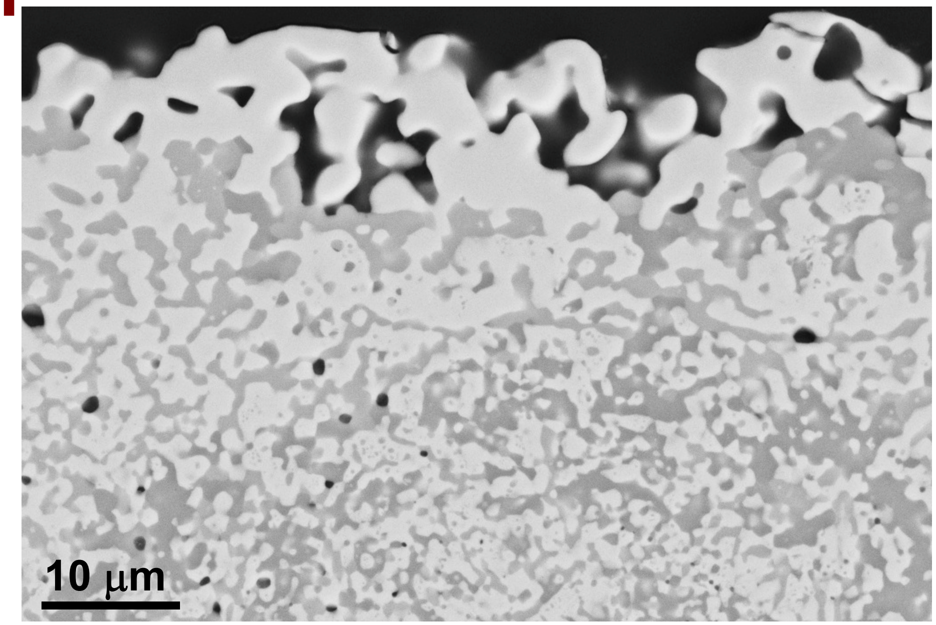
* Rapid Accumulation of Y in CMAS Glass Locally Over Short Penetration Depth

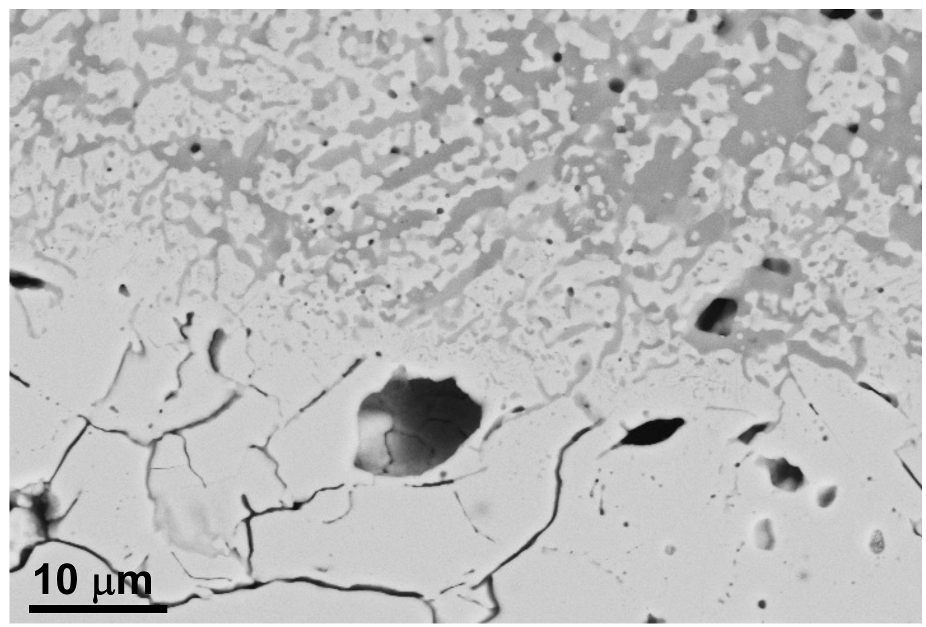
* Rapid Crystallization at Temp. of Modified CMAS to Ca-Y-Apatite, Seals TBC, Arrests CMAS Front

* Residual CMAS Likely Stable in Contact with Apatite Locally

* Dynamic Process, Dominated by Local Compositions

* Controlled by Nucleation Rate



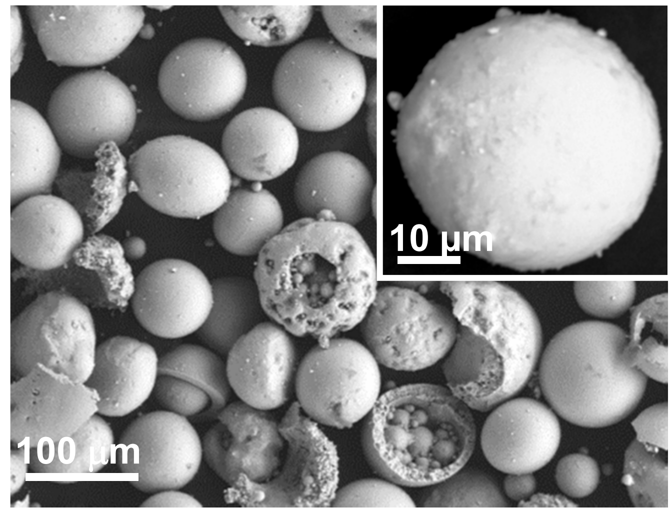


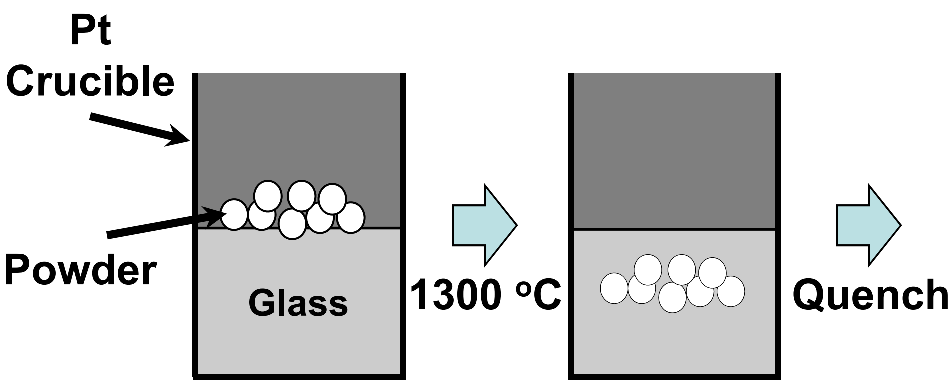
J. Am. Cer. Soc, 2015

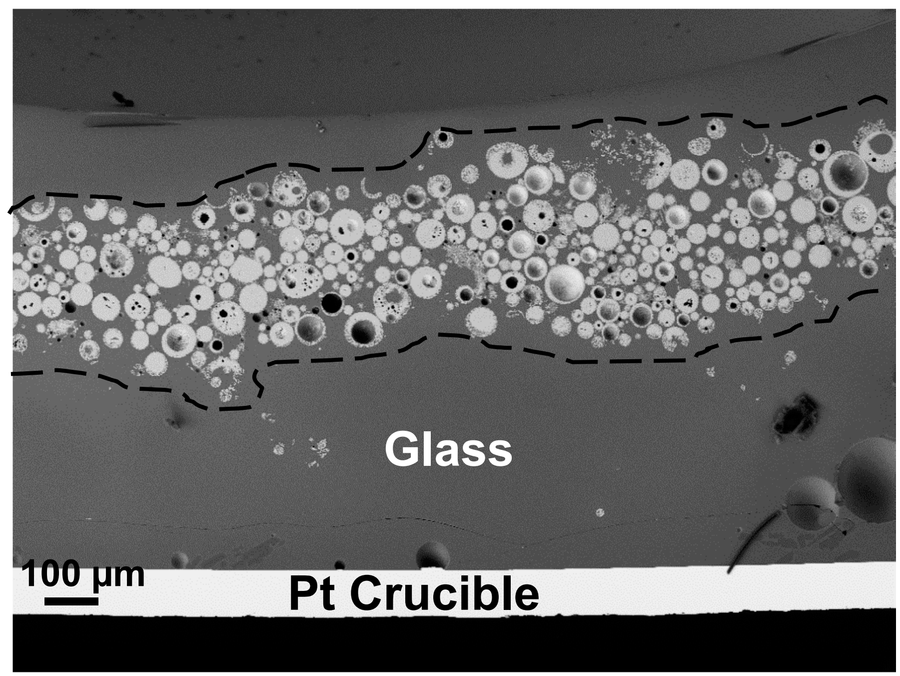
"Model" Experiments

* Powder Used for APS
* 1300 $^{o}C \rightarrow$ 1, 4, 8, 24 hrs
* CMAS Glass Λ=0.64
* Powders – 15 wt.% of CMAS Glass (Fixed Volume)

$Y_2O_3 \cdot 2ZrO_2$ Powder

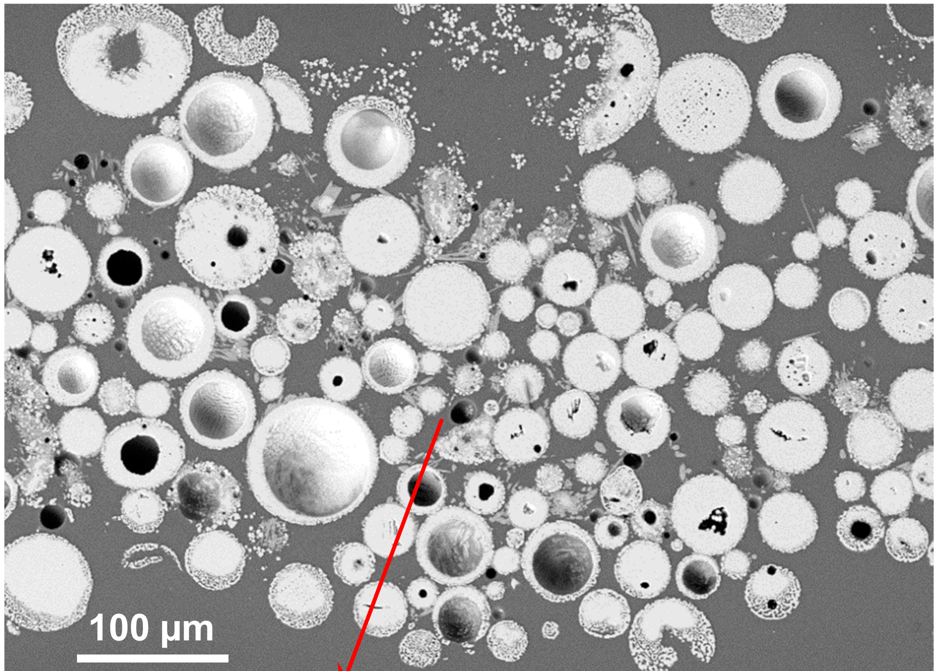






"Model" Experiments

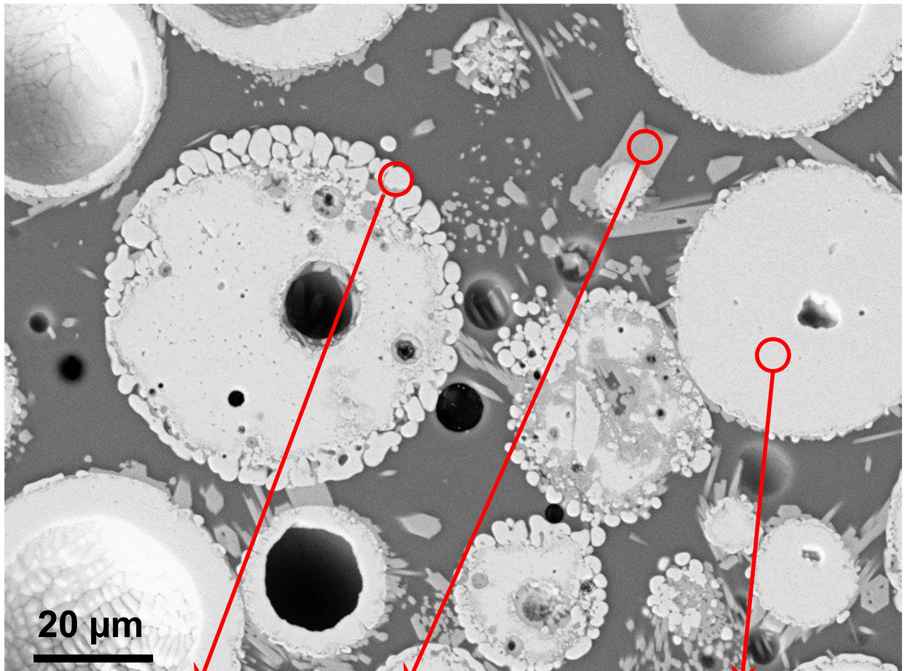
1300 ˚C, 1 h



SiO_2	44.9
MgO	4.5
$AlO_{1.5}$	9.7
CaO	31.6
$YO_{1.5}$	6.2
ZrO_2	3.0

Glass

EPMA (WDS) Composition Mol%



SiO_2	0.7
MgO	0.2
CaO	2.5
$YO_{1.5}$	20.8
ZrO_2	75.7

c-ZrO_2

SiO_2	36.5
MgO	0.4
CaO	19.2
$YO_{1.5}$	38.2
ZrO_2	5.6

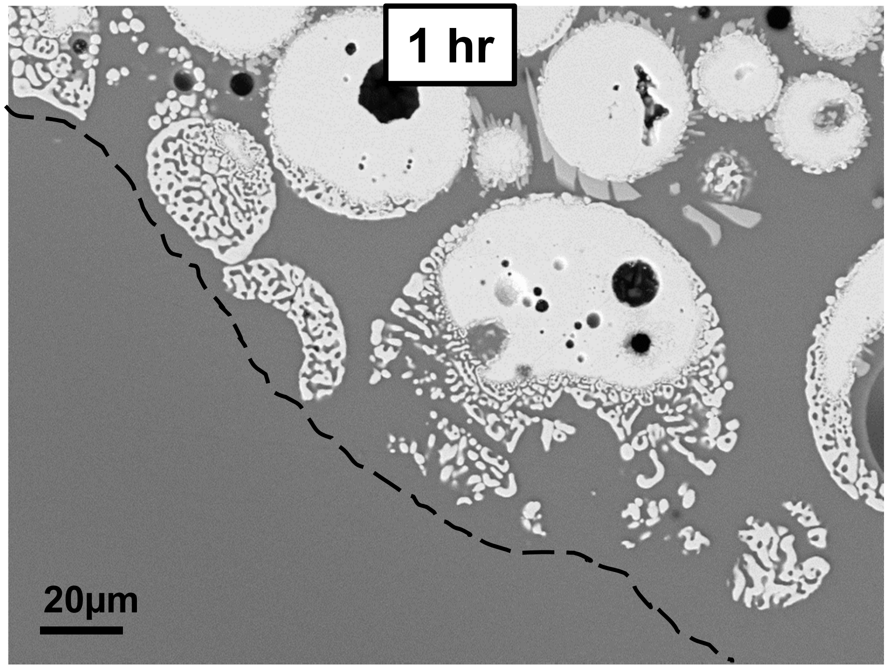
$Ca_4Y_6(SiO_4)_6O$

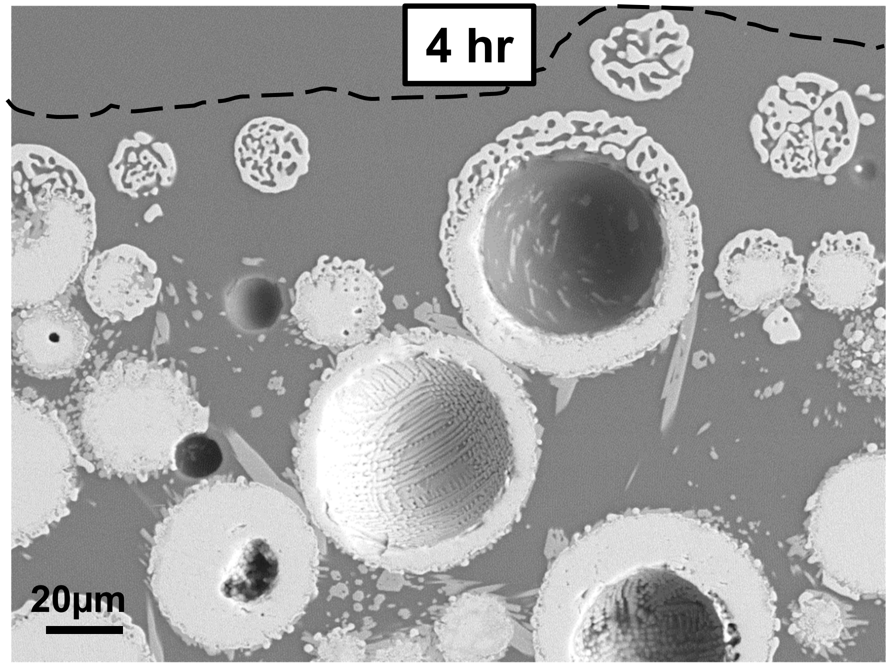
SiO_2	0.6
$AlO_{1.5}$	0.2
CaO	0.4
$YO_{1.5}$	46.7
ZrO_2	52.6

$Y_2O_3 \cdot 2ZrO_2$

J. Am. Cer. Soc., submitted

"Model" Experiments

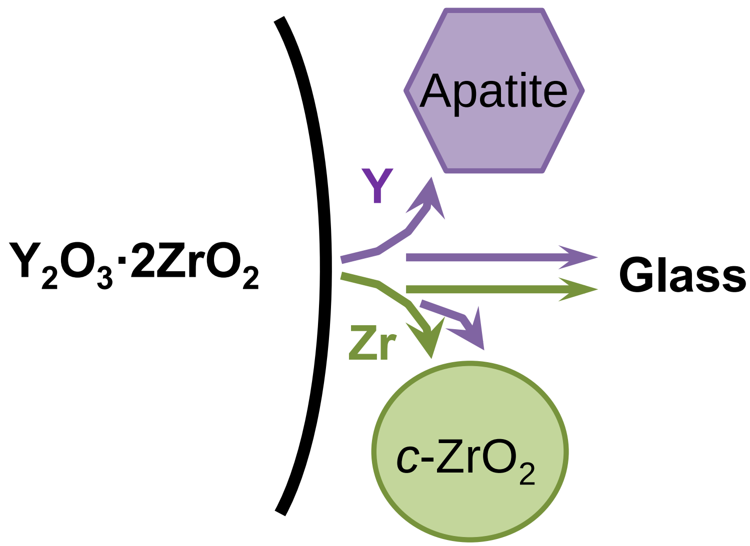


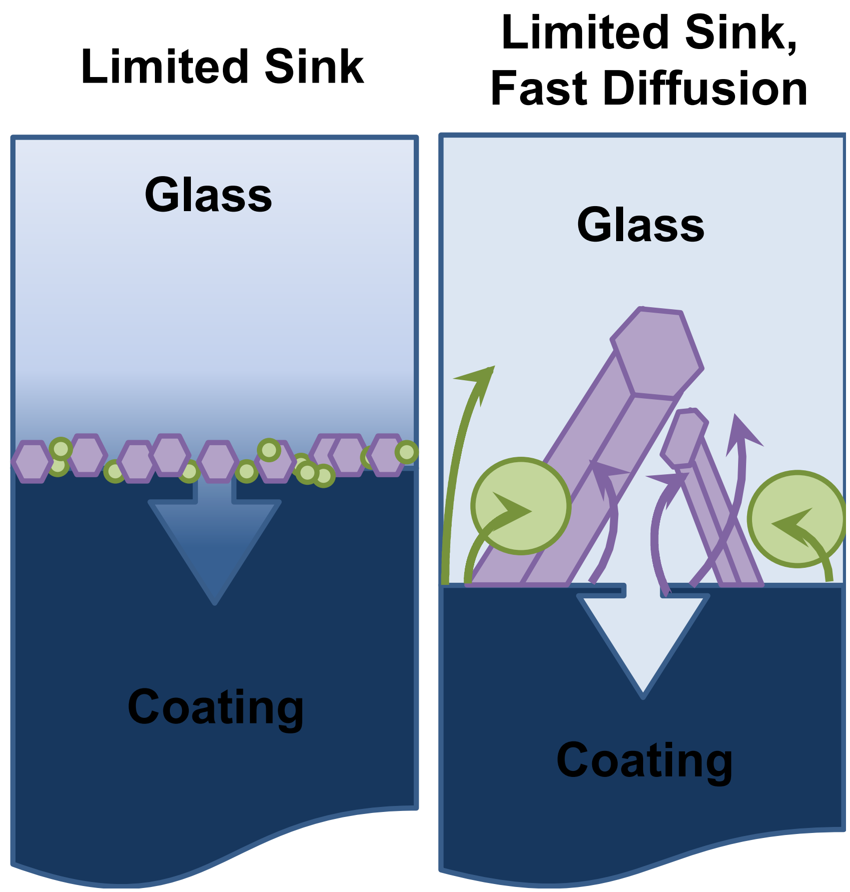


* No Large Apatite Grains/Rods at Periphery

* *c*-ZrO_2 Experience Significant Grain Growth

“Model” Experiments





*** Dissolution at the Surface**

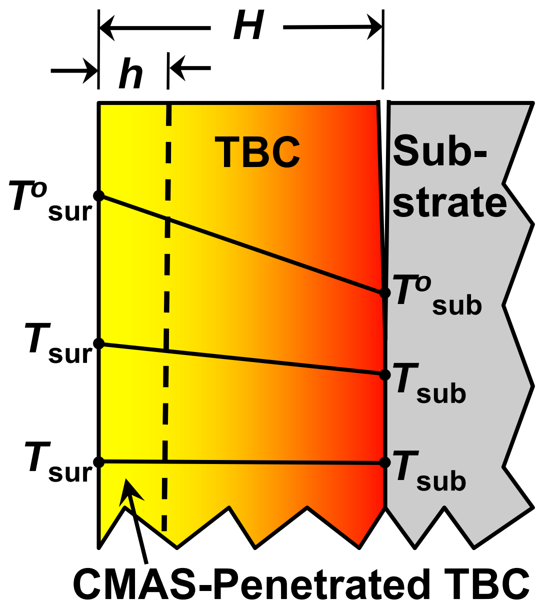
*** Local Fluctuation Induces Nucleation (*c*-ZrO_2 and Apatite)**

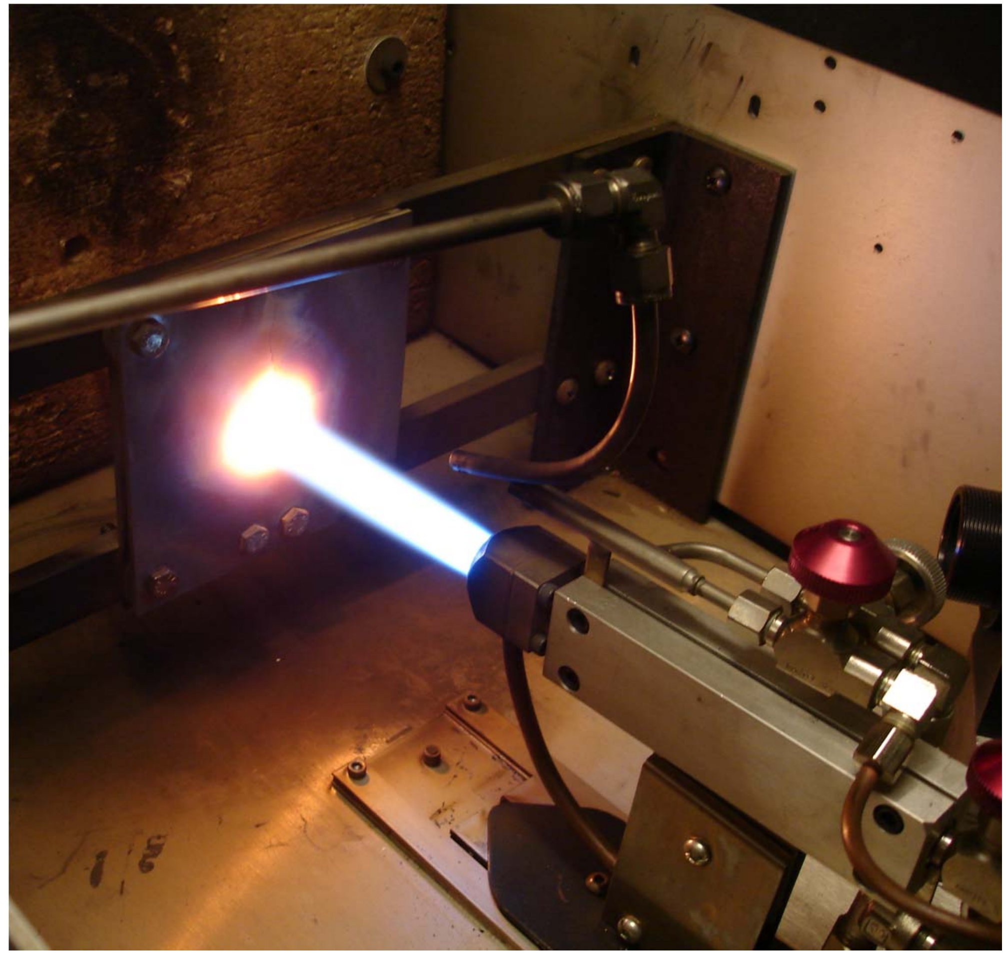
*** Easy Y Diffusion into Glass Allows for Grain Growth**

*** Limited Diffusion Allows for Nucleated Grains — CMAS Arrest**

J. Am. Cer. Soc., submitted

Mechanics of CMAS-Penetrated TBCs





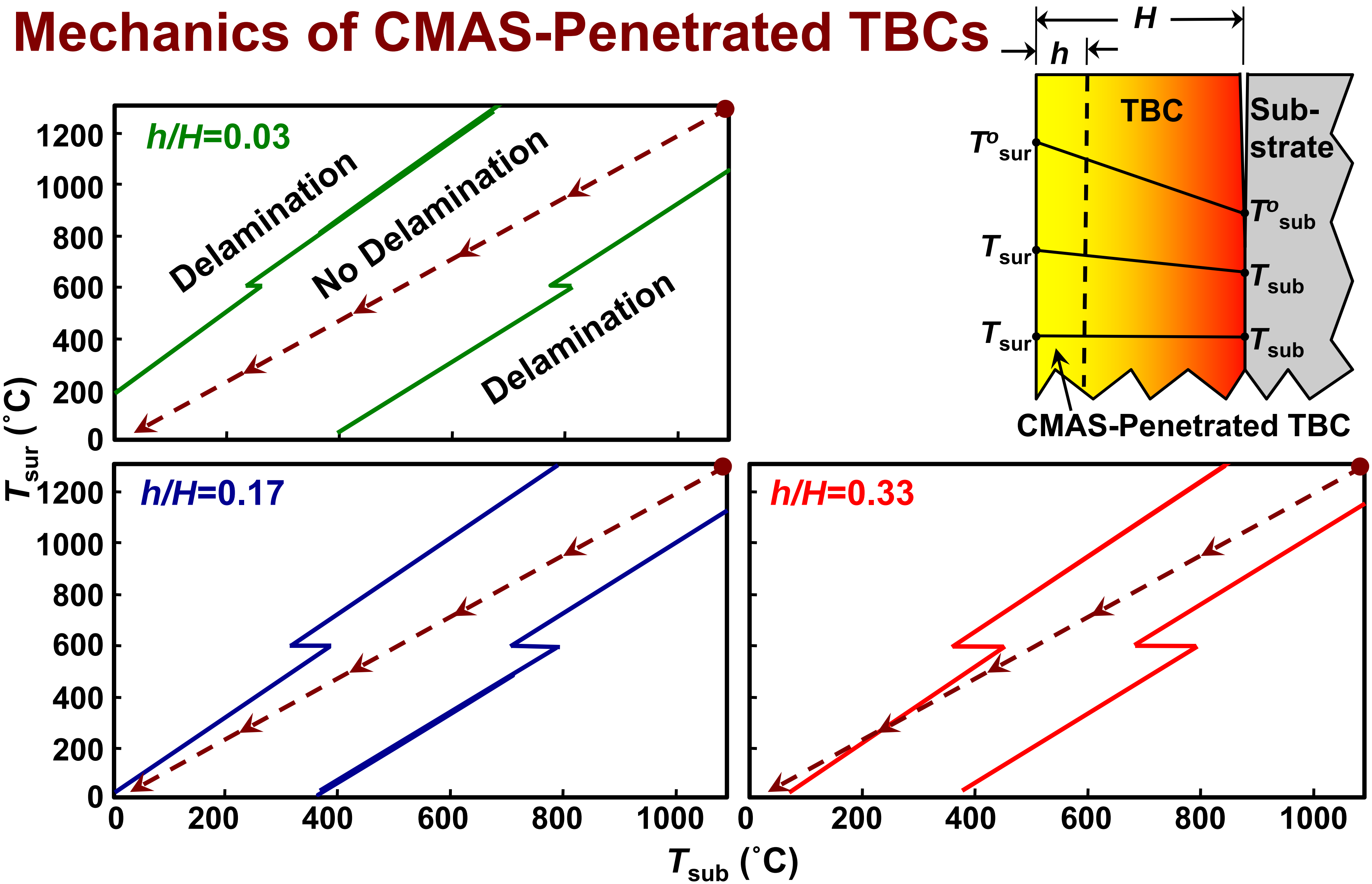
* Partial CMAS Penetration into TBCs Under Thermal Gradient

* Include *t->m* Transformation Strain in Evans-Hutchinson Model

* Various CMAS-Penetration Depths: *h/H* = 0, 0.03, 0.17, 0.33

* Some Analytical Calculations

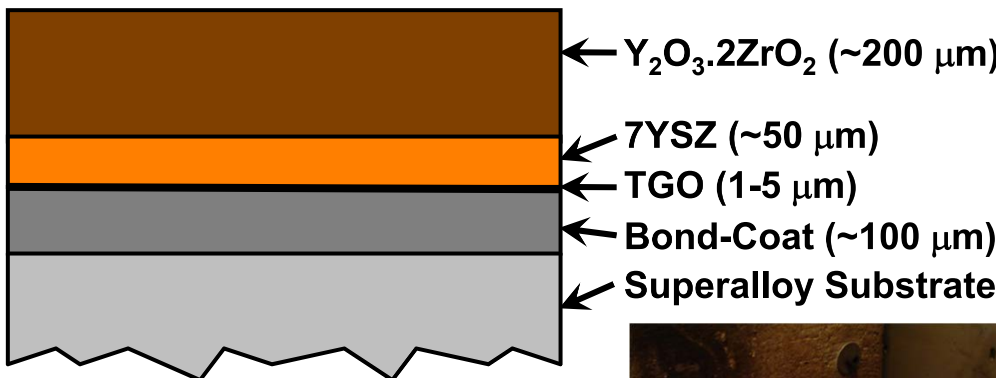
Mechanics of CMAS-Penetrated TBCs



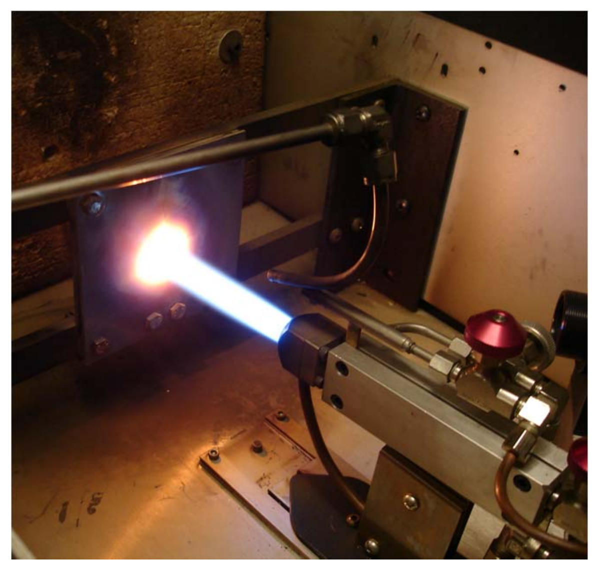
*** Reduced CMAS Penetration (*h/H*) Prevents TBC Failure**

Ongoing Work

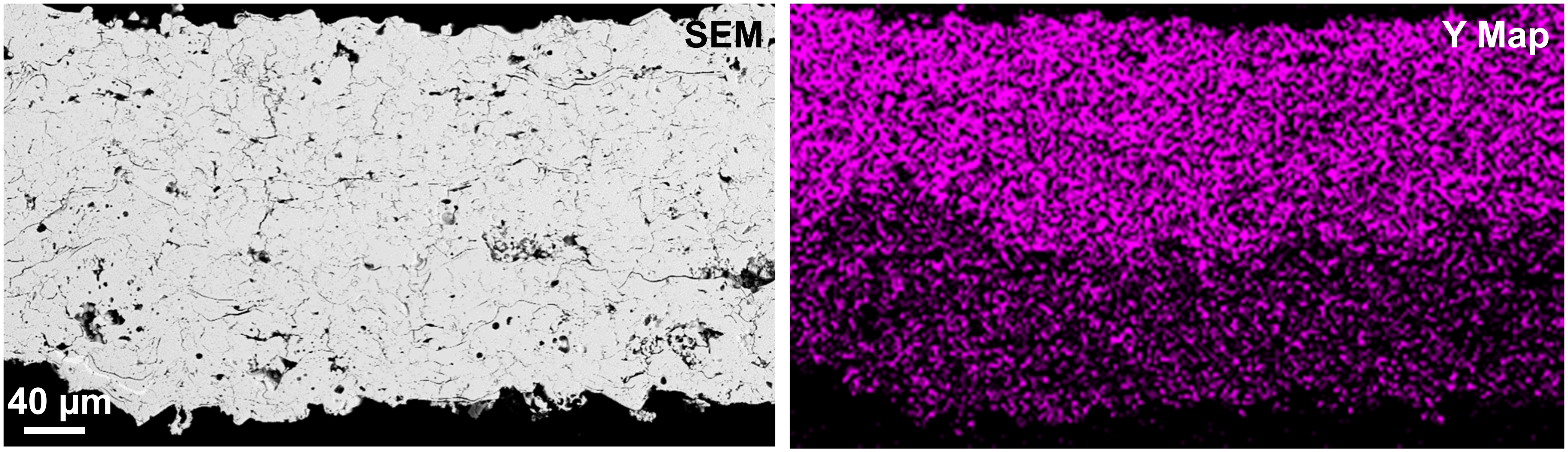
* $Y_2O_3.2ZrO_2$(*ss*) Toughness ~15 $J.m^{-2}$
* 7YSZ Toughness ~30 $J.m^{-2}$ (*t'*-ZrO_2 Ferroelastic Toughening)
* Exploit High Toughness of 7YSZ Near Metal/Ceramic Interface
* Bi-Layer APS $Y_2O_3.2ZrO_2$-7YSZ TBCs
  - CMAS-Resistant Top Layer, High Toughness Bottom Layer



* Testing of Bi-Layer TBCs and 7YSZ TBCs
  - Gradient Rig
  - Fly Ash CMAS and Water Injection
* Characterization of Tested TBCs
  - Understanding of Damage and Mitigation Mechanisms
* Characterization of Tested TBCs



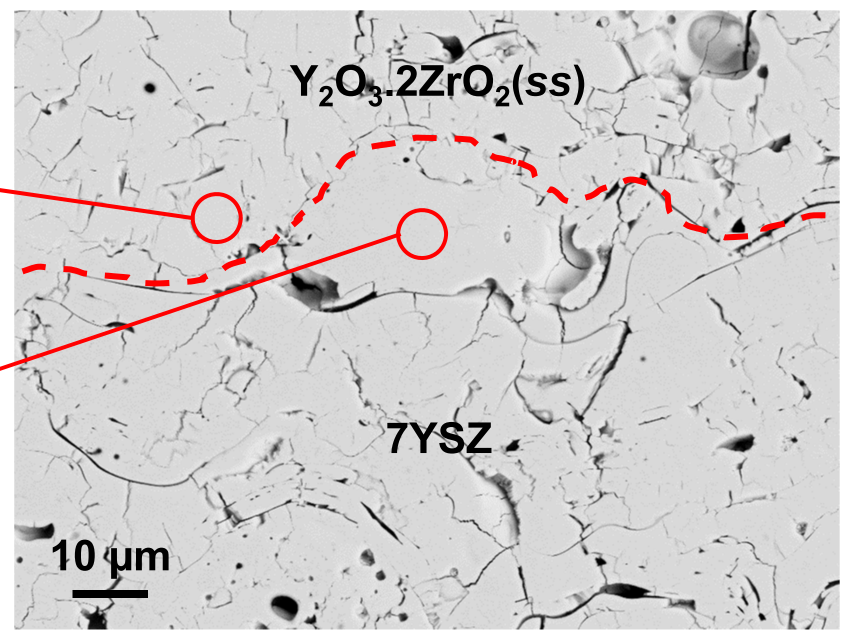
$Y_2O_3.2ZrO_2$(*ss*)-7YSZ Bi-Layer APS TBCs



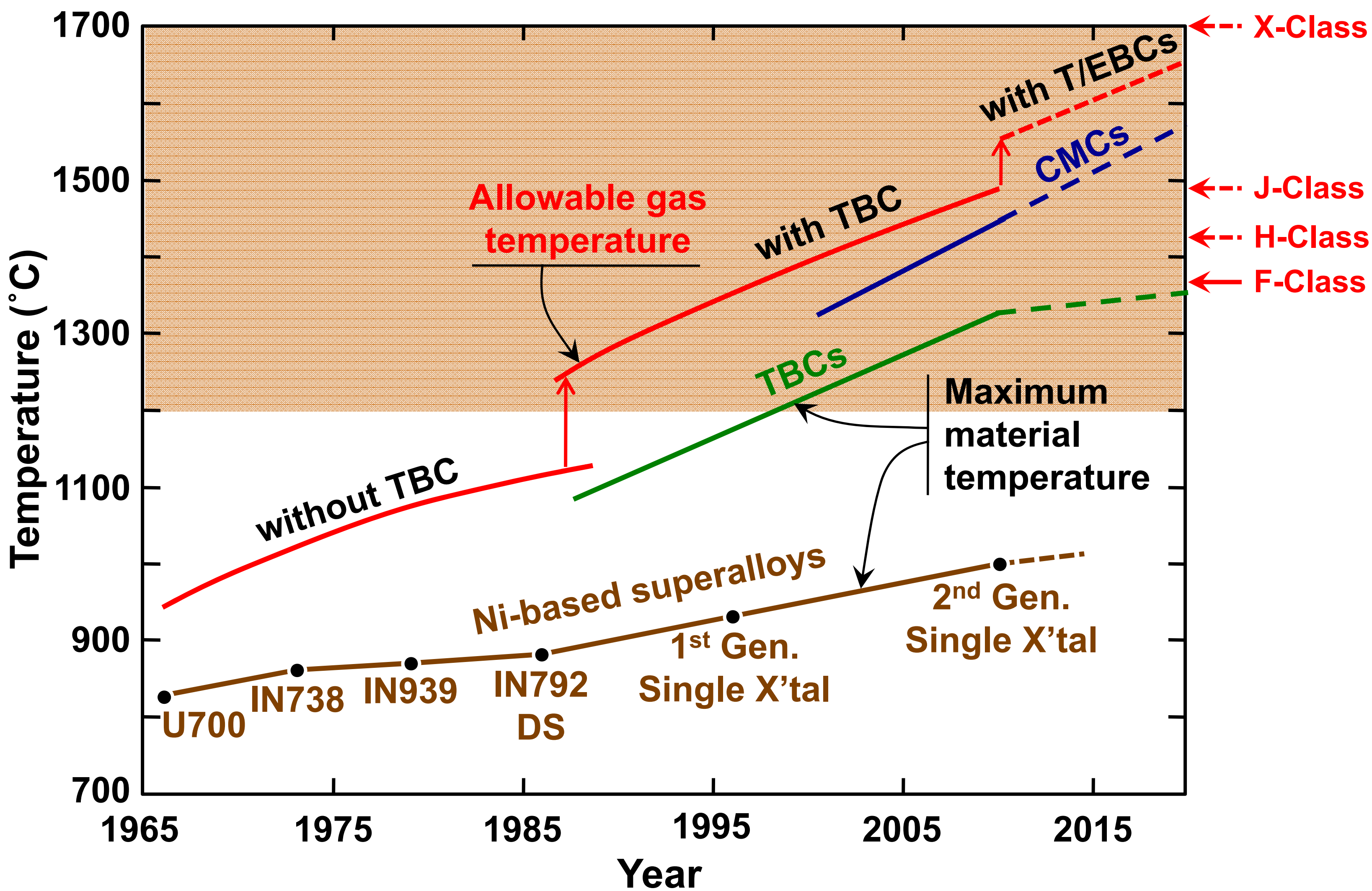
Y	53
Zr	47

Y	9
Zr	91

EDS Composition
Atom % Cation Basis



Outlook

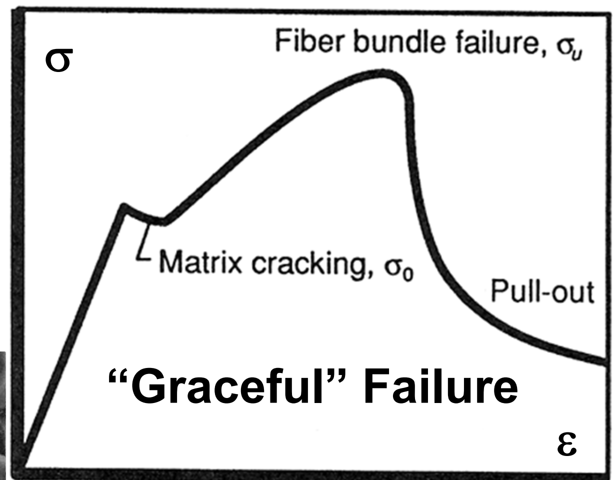


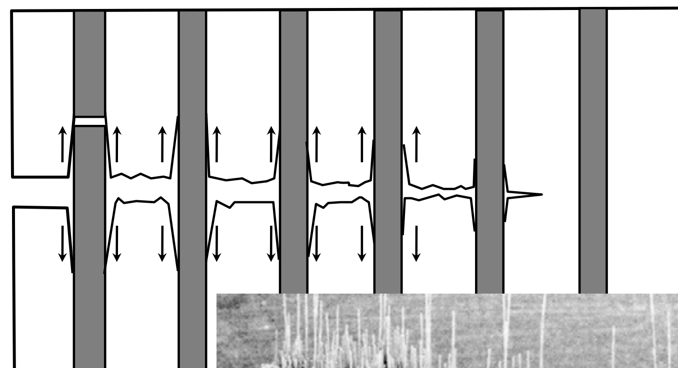
* Ceramic Matrix Composites (CMCs) with Environmental Barrier Coatings (EBCs)

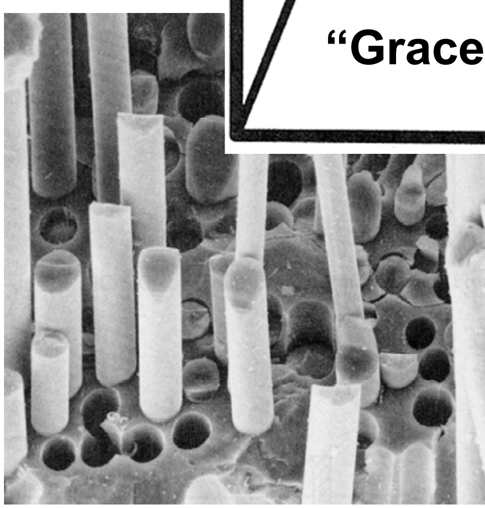
* Need Resistance to CMAS in EBCs

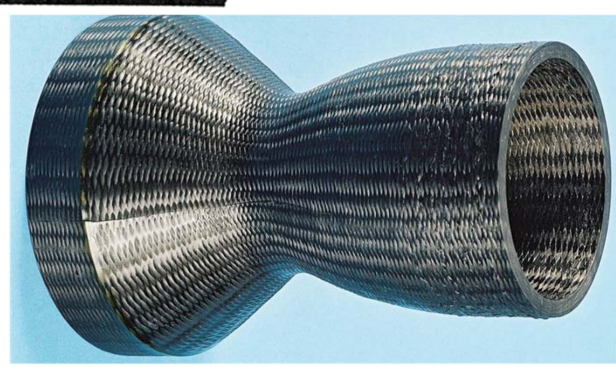
Ceramic Matrix Composites

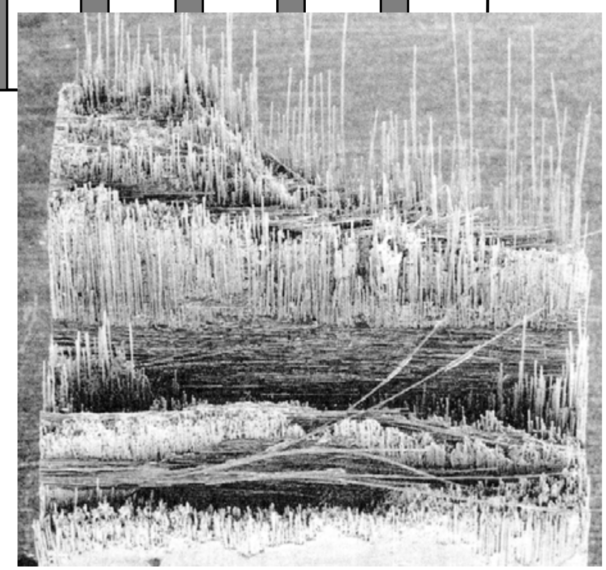
* SiC/SiC Fiber-Reinforced CMCs Most Suitable
    - Damage Tolerance, Notch-Insensitivity
    - High-Temperature Capability
    - Oxidation Resistance
* Mechanical Properties/Performance Research in 1980s and 1990s
* Processing/Fabrication Limitations and Very High Cost





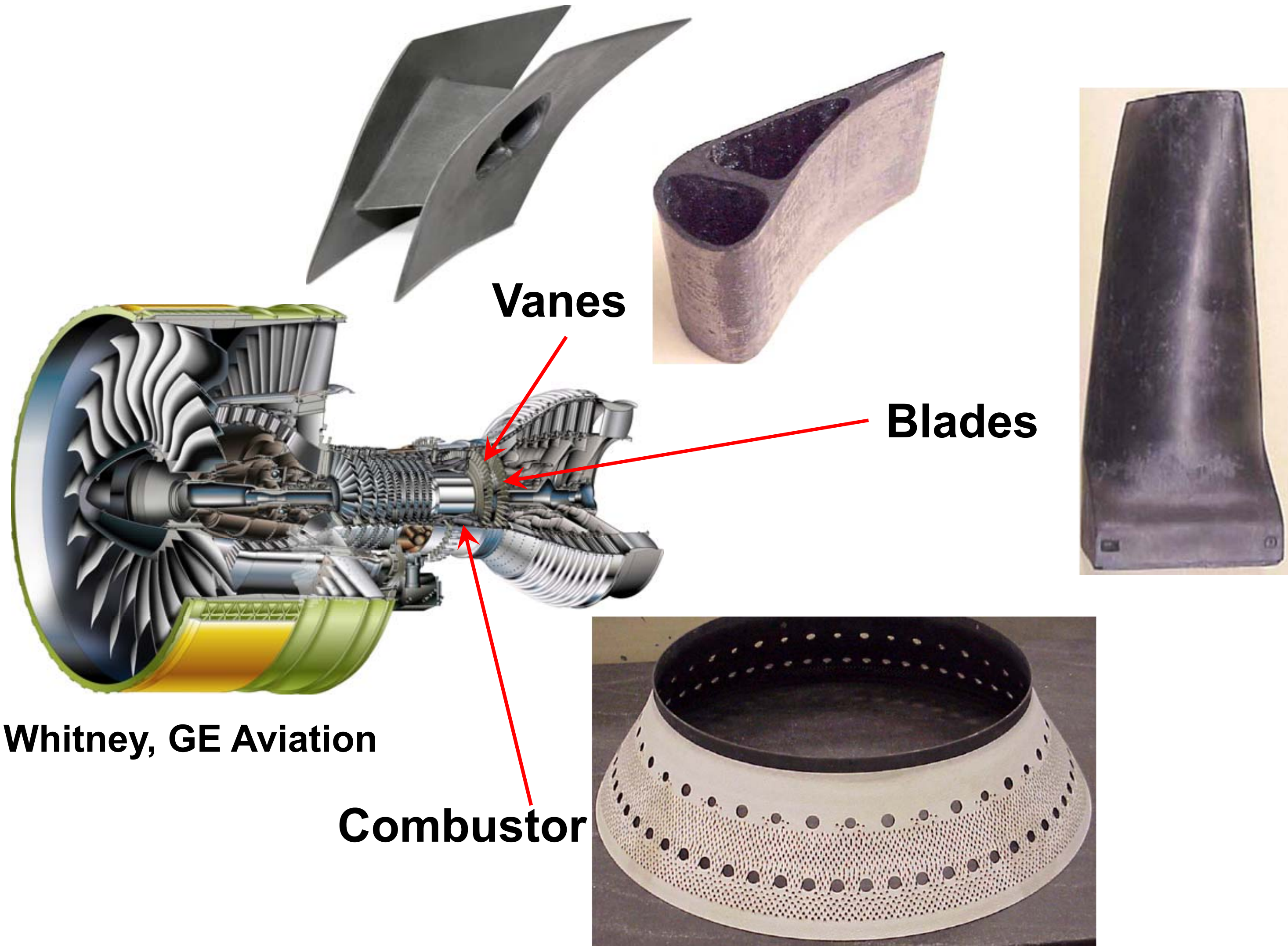






Ceramic Matrix Composites

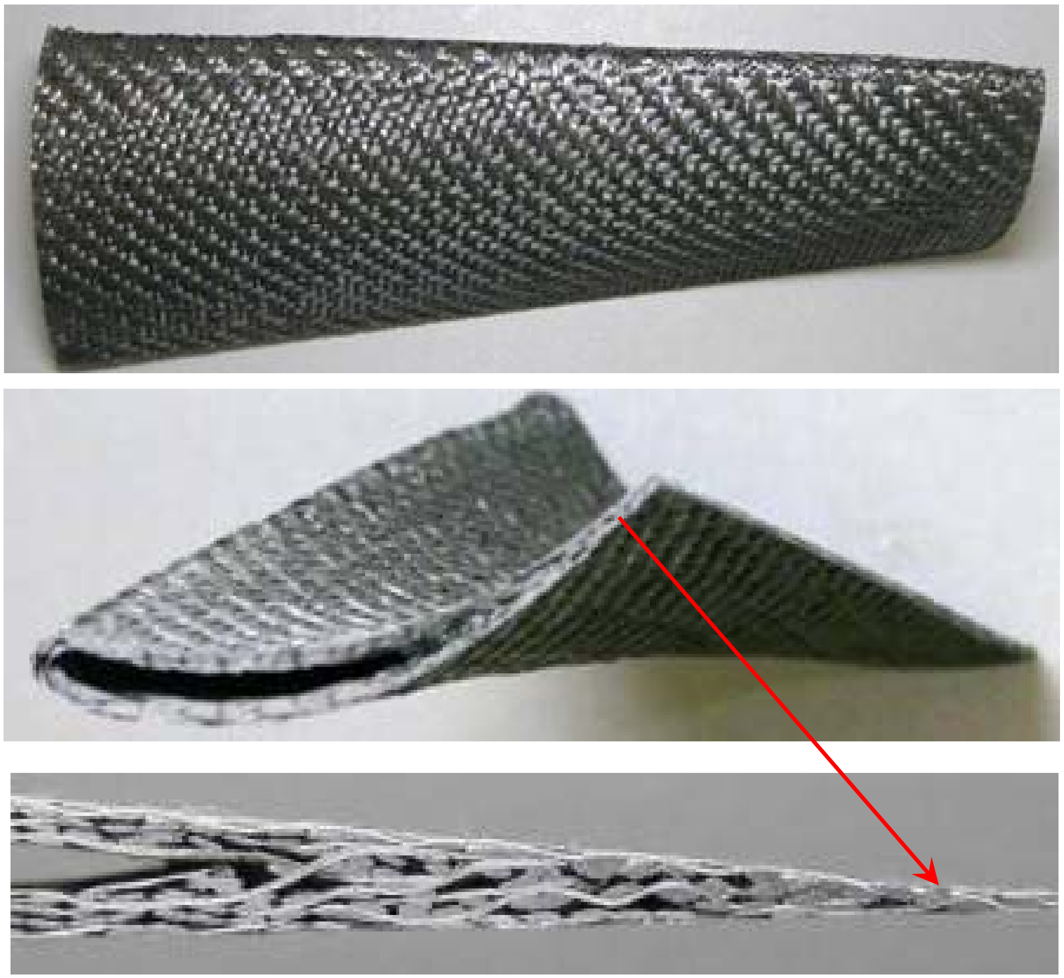
* Processing/Fabrication has Improved and Cost is Reduced
* High Efficiency/Performance Demands, No Other Material Choices
* Significant Recent Effort in CMCs for Gas-Turbine Engines

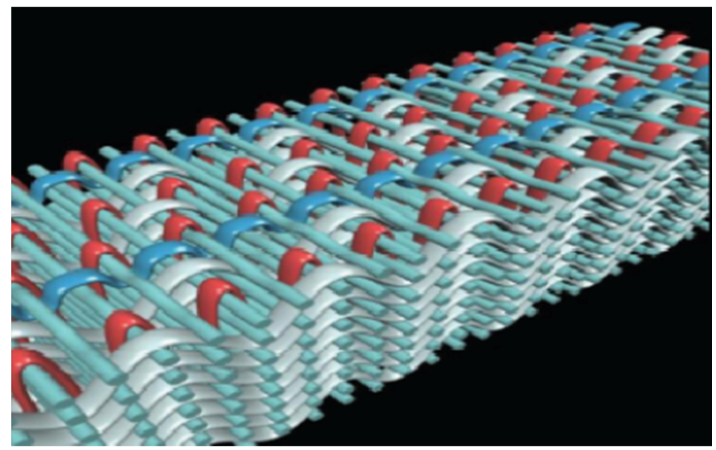


Pratt & Whitney, GE Aviation

Ceramic Matrix Composites

SiC/SiC 3-D Fiber-Reinforced CMC Hollow Blades

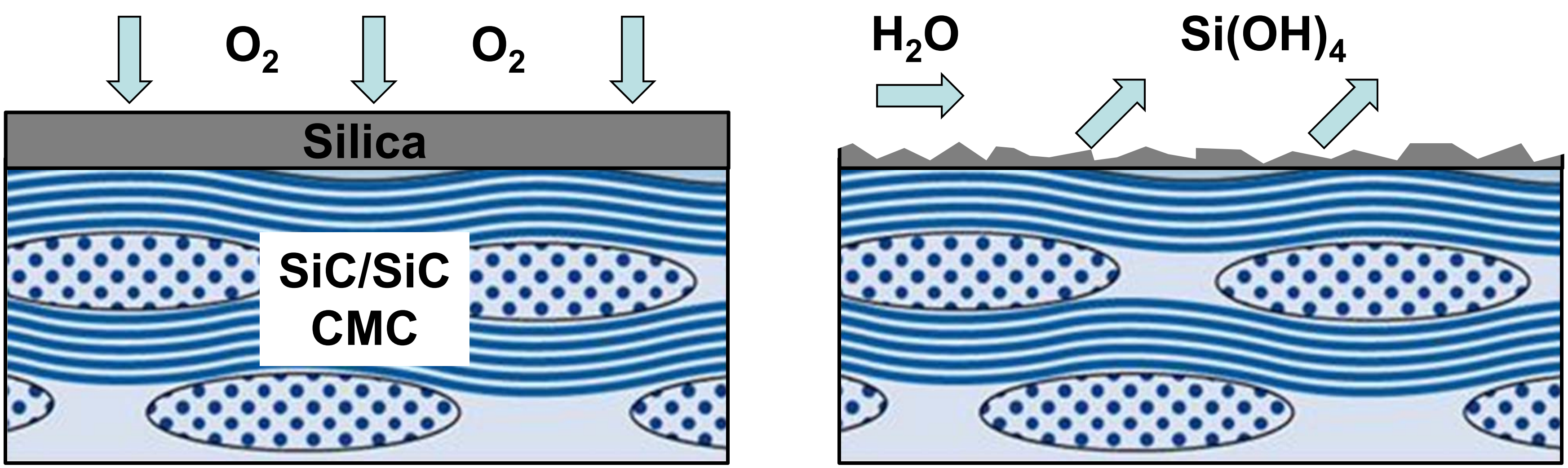




D.B. Marshall

Ceramic Matrix Composites

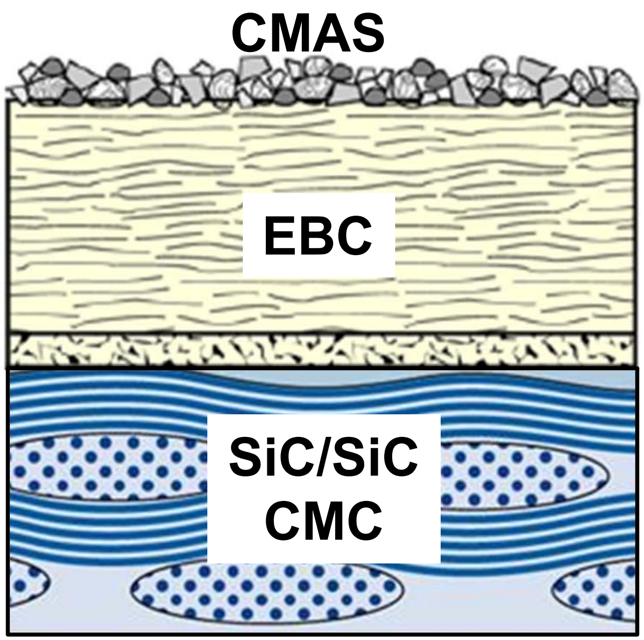
* Oxidation of SiC Produces Protective Silica Layer
* But Water Vapor in Engine Environment at High Velocity Results in Volatilization of the Silica Layer
* Requires EBCs for Protection

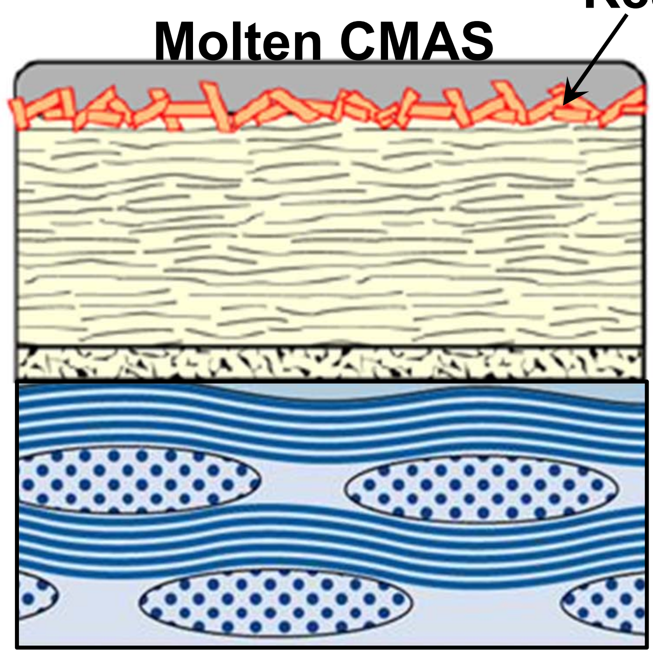


E. Opila

CMAS-Resistant EBCs

* Dense Coatings; Good Thermal-Expansion Match with CMCs; High-Temperature Stability
* Optical Basicity (OB) Concept Can be Applied to EBCs
* No Reactivity Between CMAS and EBC: Opposite of TBCs Case
* Match OBs of EBCs and Expected CMAS





C. Levi, H. Wadley

EBC-Coated
CMC Hollow
Blade

NASA

CMAS-Resistant EBCs

EBC Ceramics	Λ	$\Delta\Lambda$ (CMAS Λ 0.64)	Reference
$Gd_4Al_2O_9$	0.99	0.35	Fu *et al.*, 2011
$Y_4Al_2O_9$	0.87	0.23	Fu *et al.*, 2011
$GdAlO_3$	0.79	0.15	Fu *et al.*, 2011
Y_2SiO_5	0.79	0.15	Grant *et al.*, 2010
Yb_2SiO_5	0.76	0.13	Toohey *et al.*, 2011
$YAlO_3$	0.70	0.06	Hazel *et al.*, 2008
$Y_2Si_2O_7$	0.70	0.06	Ahlborg *et al.*, 2013
$Yb_2Si_2O_7$	0.68	0.04	Toohey *et al.*, 2011
$Sc_2Si_2O_7$	0.66	0.02	Liu *et al.*, 2013

One of the Most CMAS-Resistant EBCs

Summary

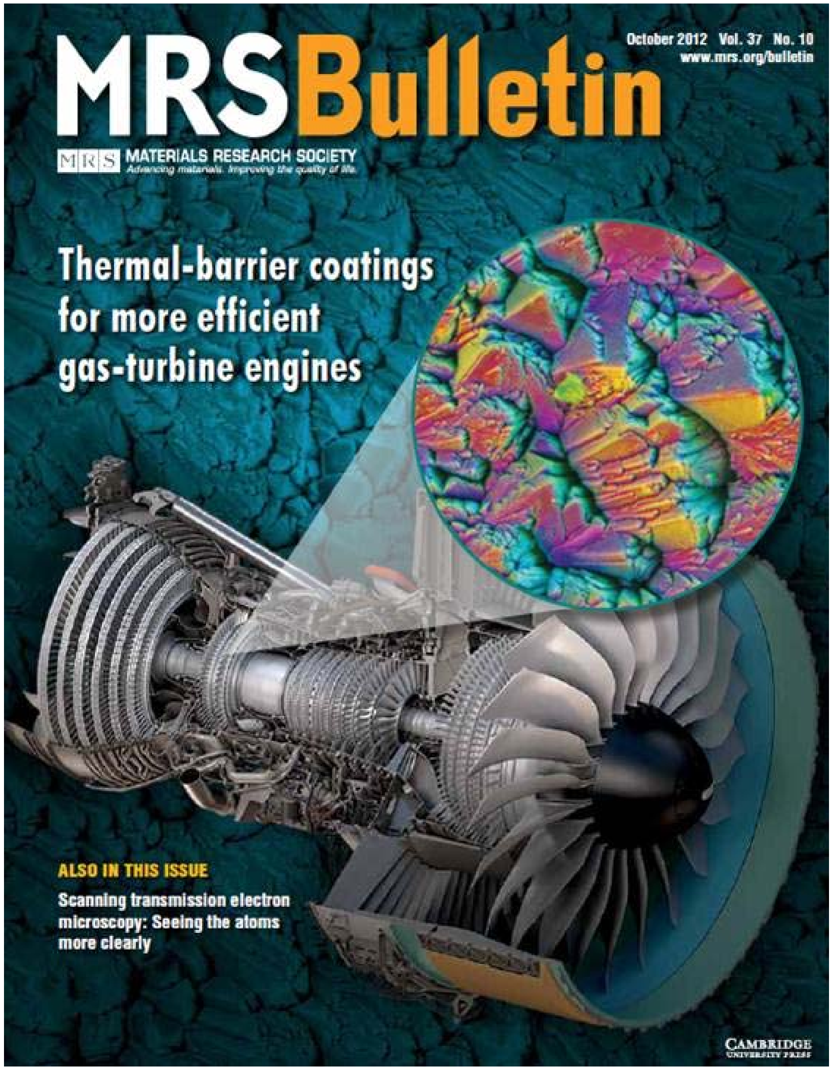
* Molten CMAS attack of TBCs is a growing issue with rising temperatures in both aero and power gas-turbine engines.
* 7YSZ TBCs are not well-suited to repel fly ash CMAS attack.
* The Optical Basicity concept can be used to screen CMAS-resistant TBC compositions.
* "Model" experiments indicate that high "solute" content, especially Y^{3+}, in TBCs is necessary for mitigation of attack. Other TBC ceramics?
* Demonstrated processing and fly ash CMAS-resistance of $Y_2O_3.2ZrO_2$ APS TBCs. Elucidated mitigation mechanisms.
* Gradient testing is necessary to capture thermo-chemo-mechanical response of partially-penetrated TBCs, coupled with modeling.
* Optimization of CMAS resistance and other required properties in TBCs is necessary: bi-layer TBCs.
* The Optical Basicity concept could be applied to screening CMAS-resistant EBC compositions.
* Resistance to molten CMAS will remain a challenge as gas-turbine engine operating temperatures continue to increase.

Recent TBC Publications

* D.R. Clarke, M. Oechsner, and N.P. Padture, "Thermal-Barrier Coatings for More Efficient Gas-Turbine Engines," *MRS Bulletin*, 37 [10] 891-8 (2012).
* J.M. Drexler, A.L. Ortiz, and N.P. Padture, "Composition Effects of Thermal Barrier Coating Ceramics on Their Interaction with Molten Ca–Mg–Al–Silicate (CMAS) Glass," *Acta Materialia*, 60 [15] 5437-47 (2012).
* J.M. Drexler, C.-H. Chen, A.D. Gledhill, K. Shinoda, S. Sampath, and N.P. Padture, "Plasma Sprayed Gadolinium Zirconate Thermal Barrier Coatings that Are Resistant to Damage by Molten Ca-Mg-Al-Silicate Glass," *Surface and Coatings Technology*, 206 [19-20] 3911-6 (2012).
* B.S. Senturk, H.F. Garces, A.L. Ortiz, G. Dwivedi, S. Sampath, and N.P. Padture, "CMAS-Resistant Plasma Sprayed Thermal Barrier Coatings Based on Y_2O_3-Stabilized ZrO_2 with Al^{3+} and Ti^{4+} Solute Additions," *Journal of Thermal Spray Technology*, 23 [8] 708-15 (2014).
* A.R. Krause, B.S. Senturk, H.F. Garces, G. Dwivedi, A.L. Ortiz, S. Sampath, and N.P. Padture, "$2ZrO_2 \cdot Y_2O_3$ Thermal Barrier Coatings Resistant to Degradation by Molten CMAS: Part I, Optical Basicity Considerations and Processing," *Journal of the American Ceramic Society*, 97 [12] 3943-9 (2014).
* A.R. Krause, B.S. Senturk, and N.P. Padture, "$2ZrO_2 \cdot Y_2O_3$ Thermal Barrier Coatings Resistant to Degradation by Molten CMAS: Part II, Interactions with Sand and Fly Ash," *Journal of the American Ceramic Society*, 97 [12] 3950-7 (2014).
* H.F. Garces, B.S. Senturk, and N.P. Padture, "*In Situ* Raman Spectroscopy Studies of High-Temperature Degradation of Thermal Barrier Coatings by Molten Silicate Deposits," *Scripta Materialia*, 76 29-32 (2014).

Thermal-barrier coatings for more efficient gas-turbine engines

David R. Clarke, Matthias Oechsner, and Nitin P. Padture, Guest Editors



Processing science of advanced thermal-barrier systems

Sanjay Sampath, Uwe Schulz, Maria Ophelia Jarligo, and Seiji Kuroda

Testing and evaluation of thermal-barrier coatings

Robert Vaßen, Yutaka Kagawa, Ramesh Subramanian, Paul Zombo, and Dongming Zhu

Low thermal conductivity oxides

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Multifunctional coating interlayers for thermal-barrier systems

T.M. Pollock, D.M. Lipkin, and K.J. Hemker

Environmental degradation of thermal-barrier coatings by molten deposits

Carlos G. Levi, John W. Hutchinson, Marie-Hélène Vidal-Sétif, and Curtis A. Johnson

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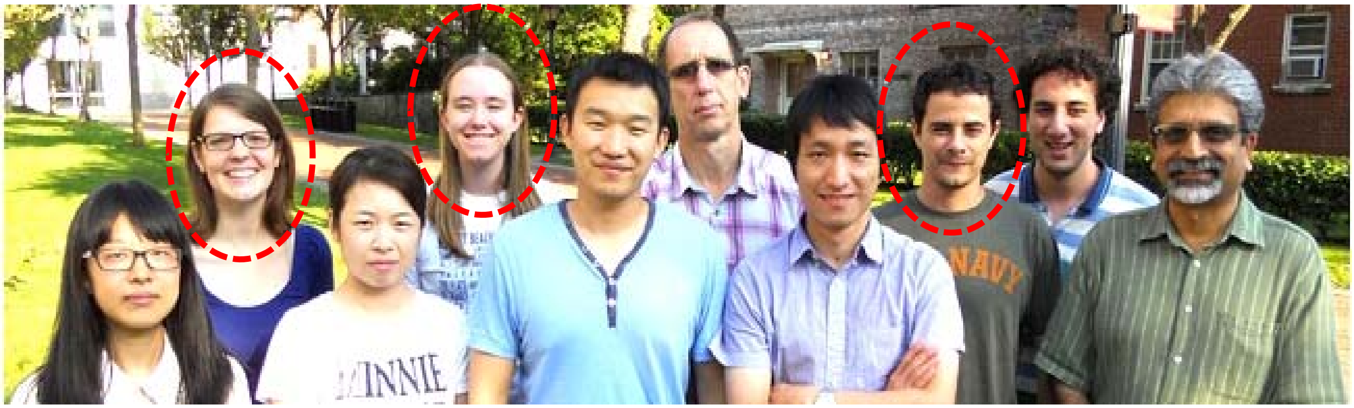

Thanks!