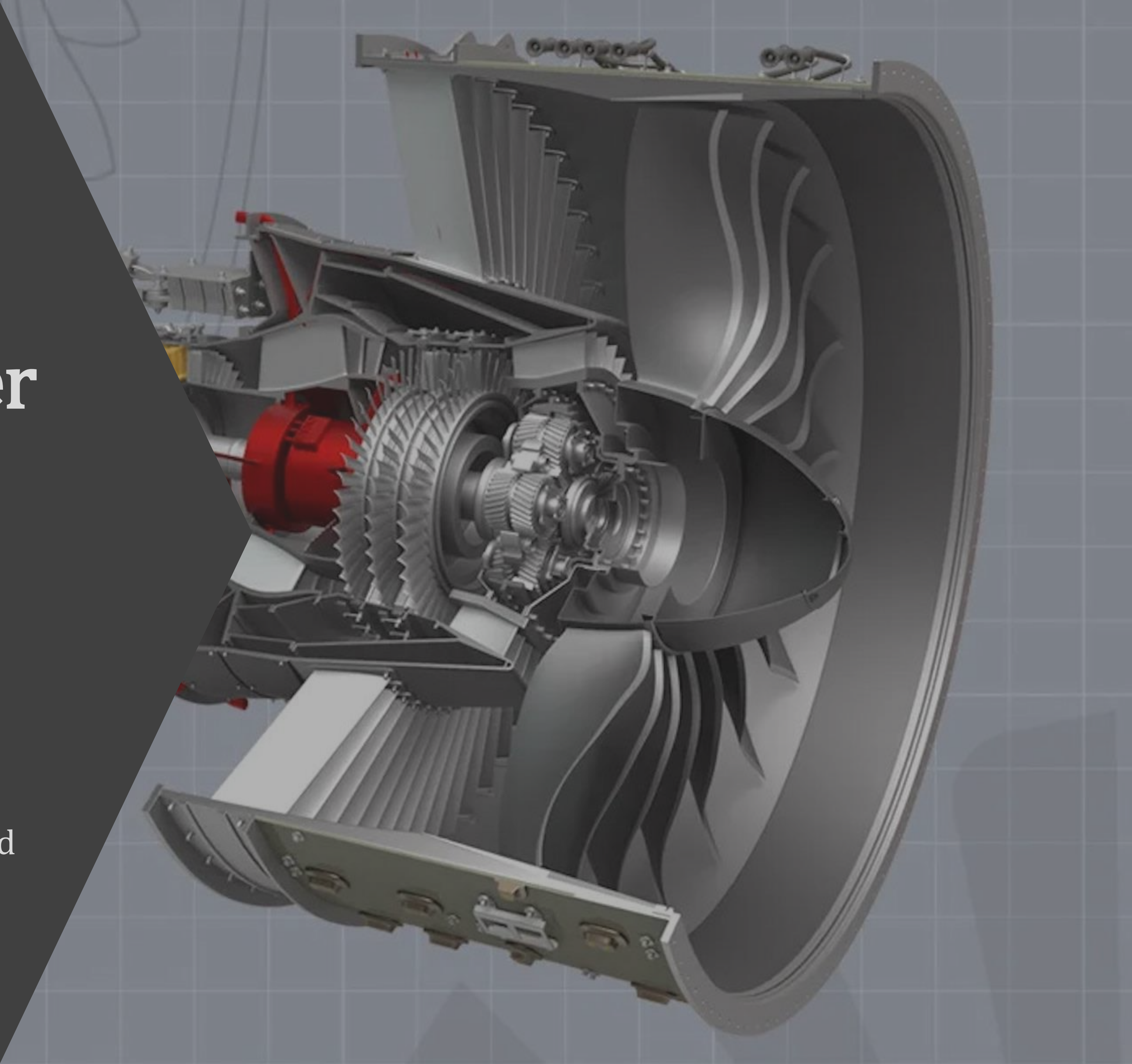
National Aeronautics and
Space Administration

Advanced Environmental Barrier Coating Testing and Development for Gas Turbine Engines



Penn State College of Engineering
Center for Gas Turbine Research, Education, and Outreach

November 7, 2024

John H. Glenn Research Center – Cleveland, OH

- Groundbreaking in 1940 in the National Advisory Committee on Aeronautics (NACA) as the Aircraft Engine Research Laboratory (AERL)
- Became a part of NASA in 1958
- Expertise in several fields contributing to agency missions and goals
  - Power, Energy Storage and Conversion
  - Aircraft Propulsion
  - Space Propulsion and Cryogenic Fluids Management
  - Communications Technology Development
  - Physical Sciences and Biomedical Technologies in Space
  - **Materials and Structures for Extreme Environments**

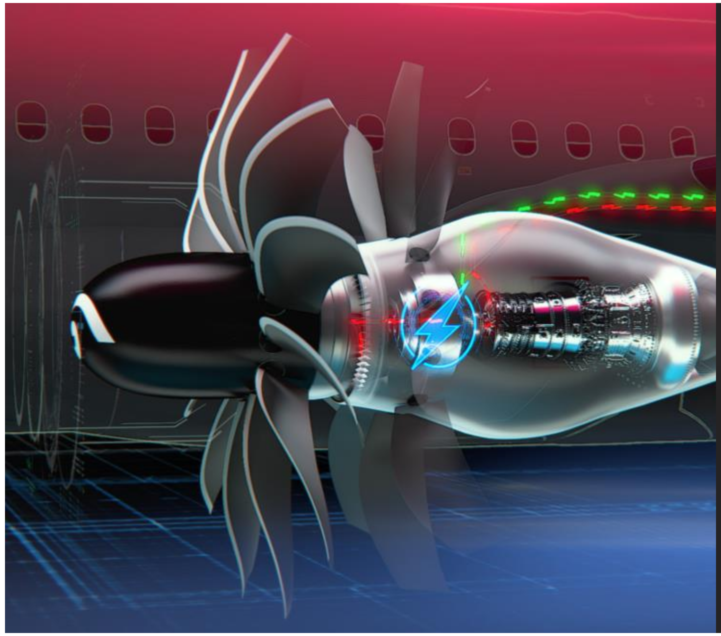
Aeronautics Research Mission Directorate

All U.S. commercial aircraft and air traffic control facilities incorporate NASA-developed technology. That heritage continues at NASA, where the first “A” stands for Aeronautics, and the efforts to safely and sustainably transform aviation for the 21st century are managed by the agency’s Aeronautics Research Mission Directorate (ARMD).

- **Advanced Air Vehicles Program**
- Airspace Operations and Safety Program
- Integrated Aviation Systems Program
- **Transformative Aeronautics Concepts Program**
- Aerosciences Evaluation and Test Capabilities

NASA’s Sustainable Flight National Partnership: Net Zero Carbon Emissions by 2050

Aeronautics Research Mission Directorate



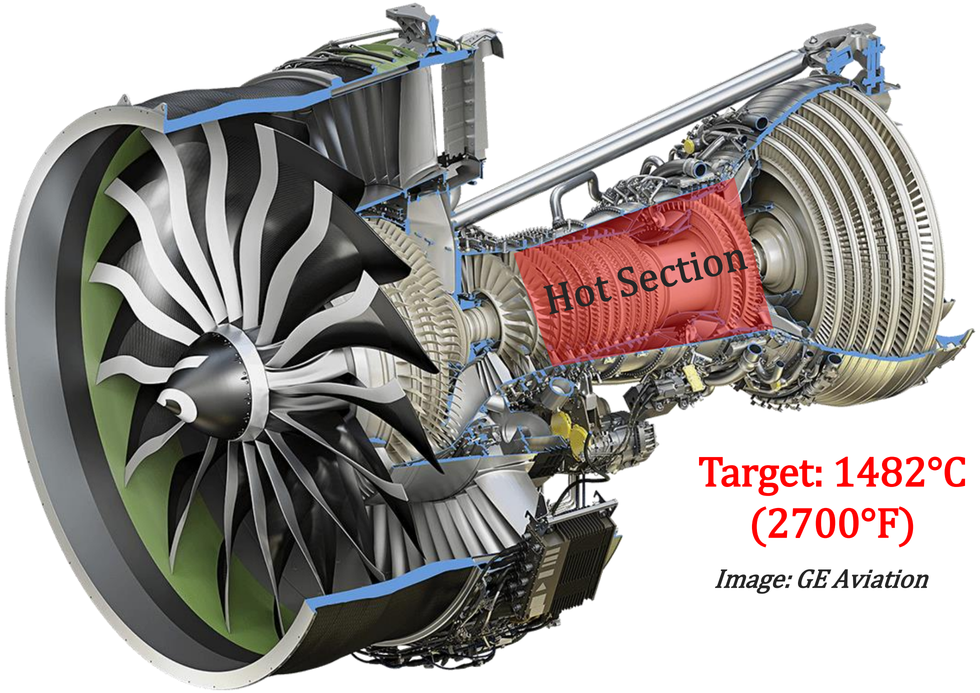
HyTEC (Hybrid Thermally Efficient Core) Project

- Design and demonstrate a jet engine that has a smaller core but produces equivalent thrust as engines being flown today on single-aisle aircraft.
- Smaller core technology aims to reduce fuel burn and emissions by an estimated 5 to 10%.

Transformational Tools and Technologies (TTT) Project

- encourages revolutionary concepts, environment for researchers to experiment with new ideas
- Promote converging advancements in aeronautics and non-aeronautics sectors

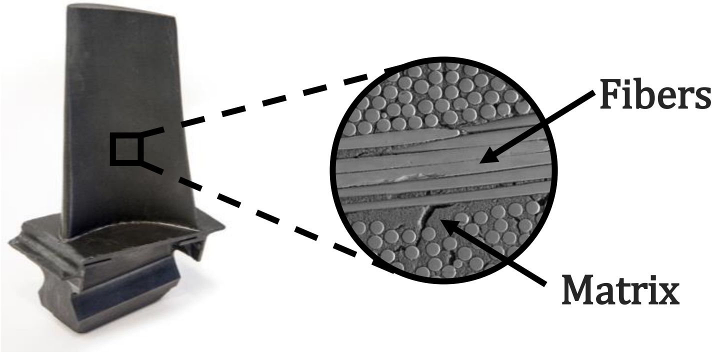
Protective Coatings for Gas Turbine Engines



Target: 1482°C (2700°F)

Image: GE Aviation

CMC Turbine Blade

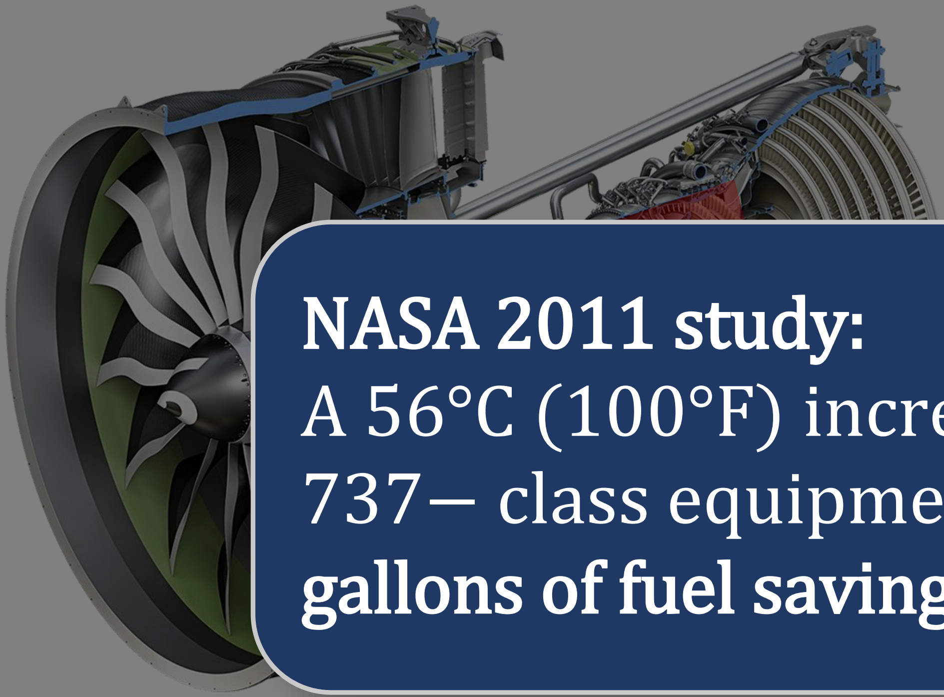


- Multi-decade development push to replace metallic airplane components with **lightweight composite materials**
  - Boeing 787 Dreamliner – Carbon-fiber composite fuselage
- Replacement of Ni-based superalloy engine components with SiC-based ceramic matrix composites (CMCs) to **increase turbine engine efficiency (incorporated into aero engines in 2016)**
  - Lower (1/3) density than conventional metal-based components
  - Allow for higher operating temperatures (>1200°C)

$$\varepsilon = 1 - \frac{T_C}{T_H}$$

- **6% increase in fuel efficiency savings of ~$400,000 per plane per year**

Protective Coatings for Gas Turbine Engines



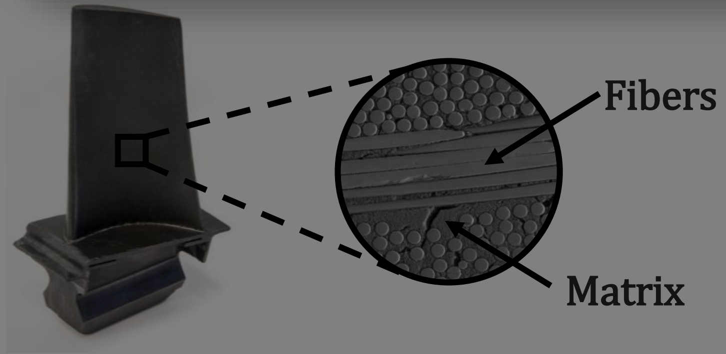
- Multi-decade development push to replace metallic airplane components with **lightweight composite materials**
    - Boeing 787 Dreamliner – Carbon-fiber composite

NASA 2011 study:
A 56°C (100°F) increase in material capability in the 737– class equipment alone could provide **758 million gallons of fuel savings for the US market per year.**

ponents with
increase
aero engines

al-based
components

CMC Turbine Blade



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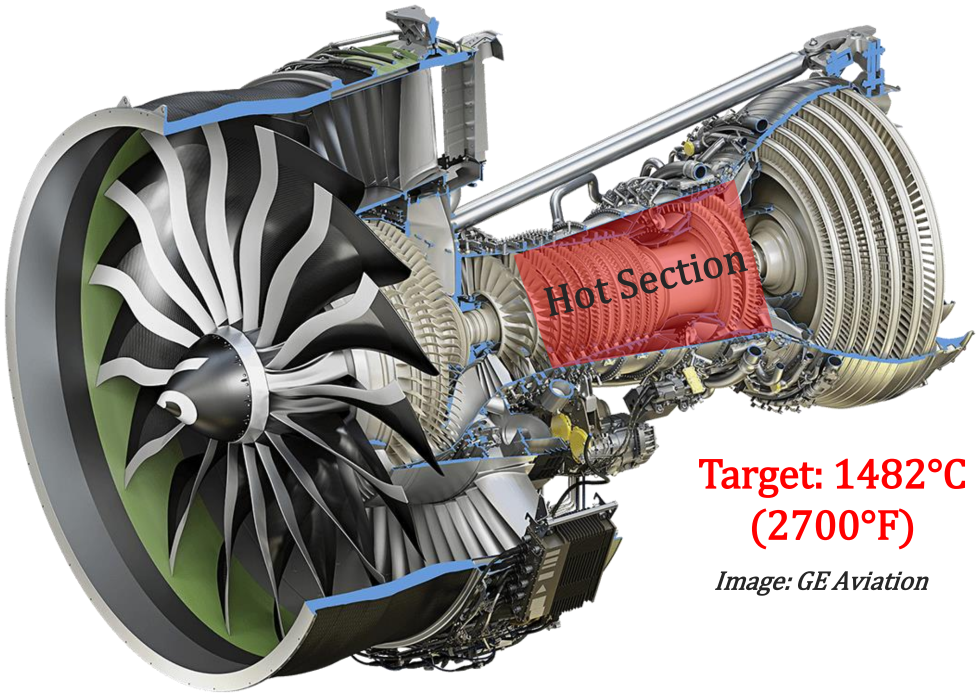
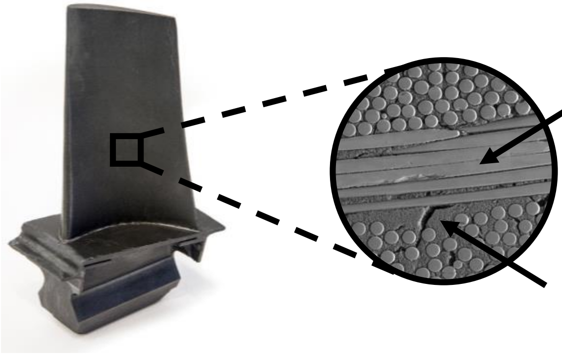


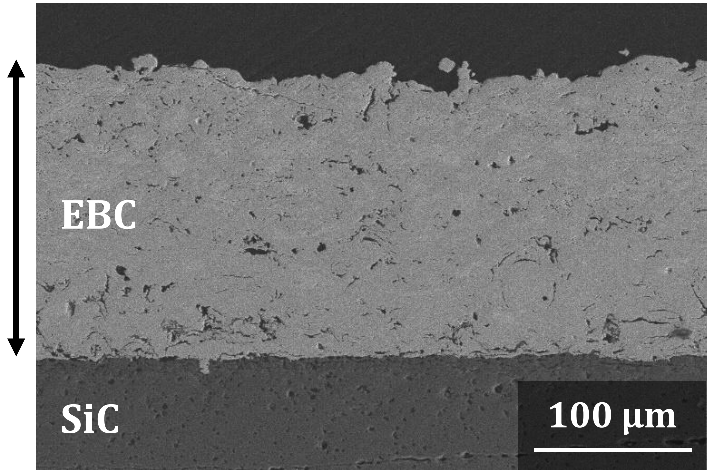
Target: 1482°C (2700°F)

Image: GE Aviation

- Silicon carbide (SiC) CMCs susceptible to environmental attack at temperatures >800°C in oxygen and water vapor
  - Silica (SiO_2) scale formation that volatilizes in H_2O environment
  - Surface recession
- Require **environmental barrier coatings (EBCs)** to protect CMC component from harsh environment

CMC Turbine Blade





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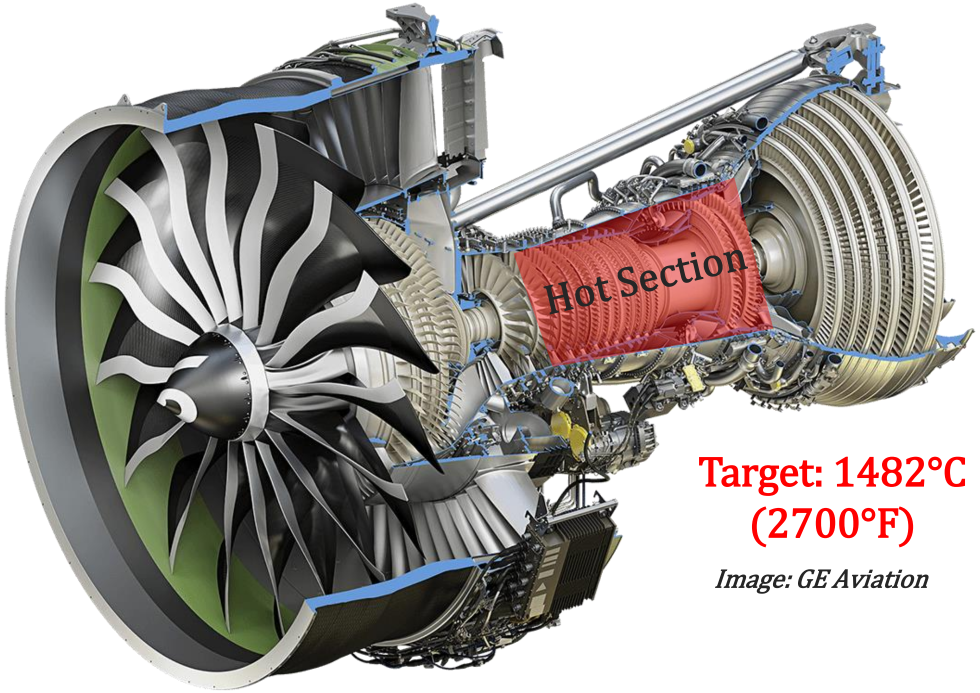

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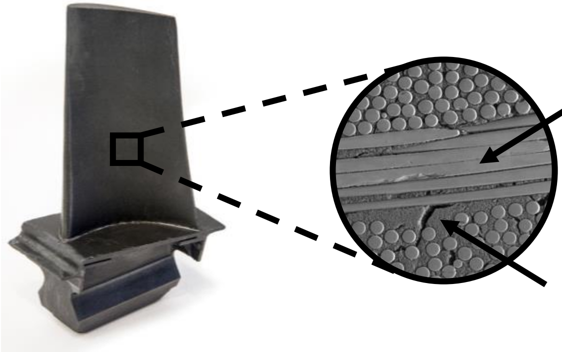
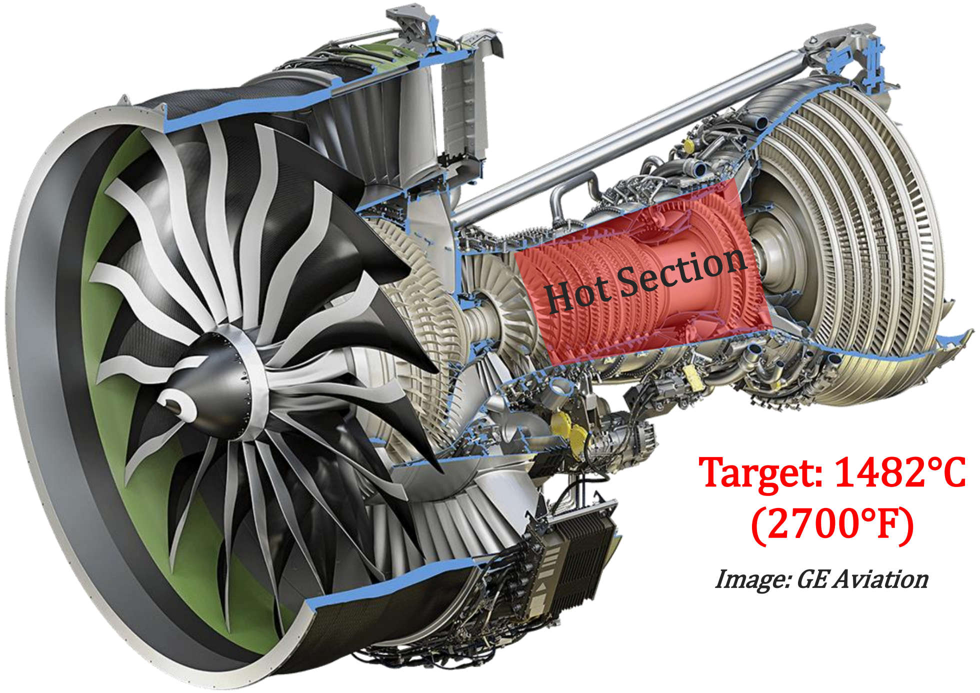


Intrinsic Material Selection Criteria

- **Coefficient of thermal expansion (CTE)**
- **Sintering resistance**
- **Low H_2O and O_2 diffusivity/solubility**
- **Phase Stability**
- **Low Modulus**
- **Limited coating interaction**

Protective Coatings for Gas Turbine Engines



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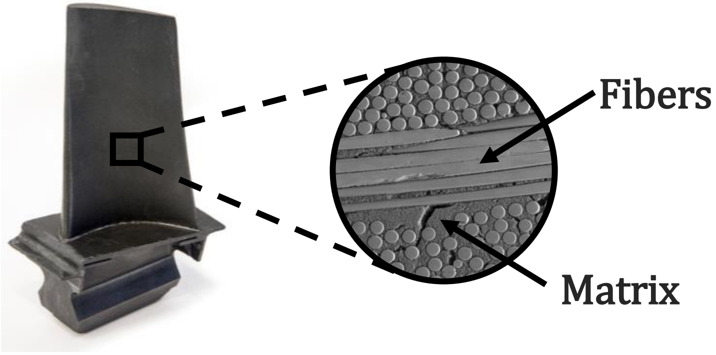


Turbine Engine Requirements

SiC Recession: Fuel-lean mixture - P_{total} ~ 6 atm, v ~ 20 m/s

Time [hours]	1,200℃ [µm/side]	1,300℃ [µm/side]	1,400℃ [µm/side]
100	6.187	11.01	18.29
1,000	61.87	110.1	182.9
10,000	618.7 (~0.62 mm)	1101 (~1.1 mm)	1829 (~1.8 mm)

SiC Recession: Fuel-rich mixture - P_{total} ~ 6 atm, v ~ 20 m/s

Time [hours]	1,200℃ [µm/side]	1,300℃ [µm/side]	1,400℃ [µm/side]
100	10.67	25.94	56.69
1,000	106.7	259.4	566.9
10,000	1067 (~1.1 mm)	2594 (~2.6 mm)	5669 (~5.7 mm)

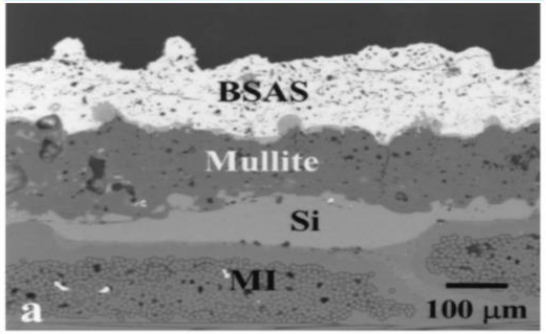
- Current engines require materials to have durability >10,000 hours
- Supersonic turbine engines require 6,000 – 9,000 hours at max temperature

EBC Development History

- Gen I EBC developed at NASA GRC in collaboration with GE and P&W

- BSAS/Mullite/Silicon multilayer
  - Low SiO_2 activity
  - Good CTE match

NASA Gen I EBC System



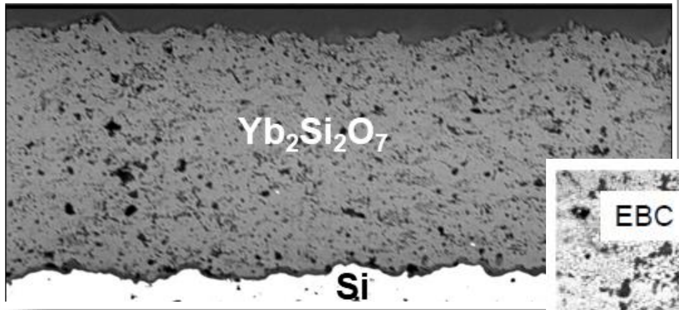
Mullite: $(3Al_2O_3{:}2SiO_2)$

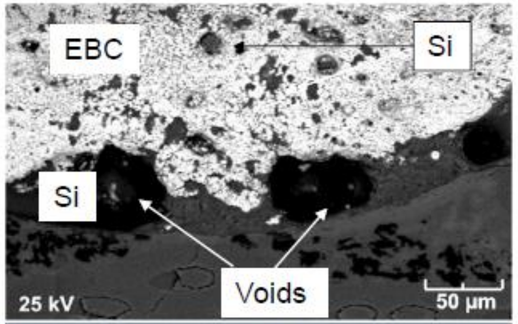
BSAS: $1-xBaO \bullet xSrO \bullet Al_2O_3 \bullet 2SiO_2$, $0<x<1$

- Silicon (Si) bond coat added to improve adhesion and oxidation resistance

- Gen II EBC developed at NASA GRC in early 2000s
  - Rare earth silicate-based system
  - RE_2SiO_5, $RE_2Si_2O_7$
  - RE = Y, Yb, Sc, Lu, etc.
  - Higher thermodynamic stability compared to Gen I EBC systems
  - Upper use temperature limited by Si bond coat ($T_m \sim 1410°C$)

NASA Gen II EBC System





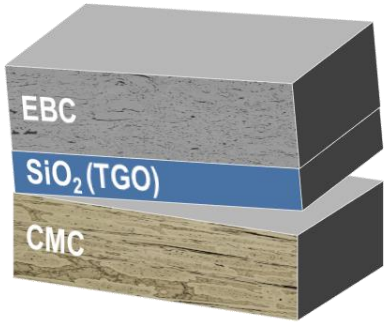
Si bond coat failure (1370°C)

Environmental Barrier Coating Failure Modes

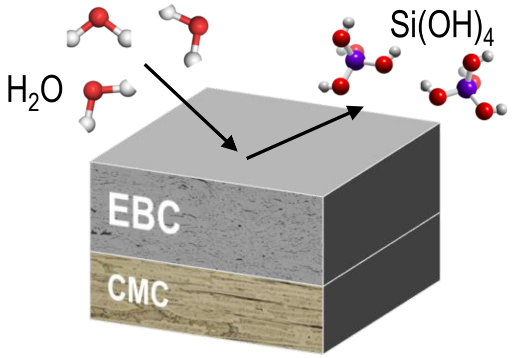
Testing of EBC systems is critical

Individual mechanisms must be well understood before evaluating combinatorial effects

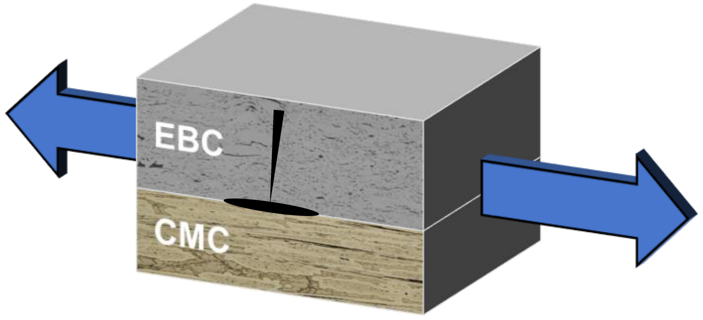
Synergies between extrinsic failure modes determine EBC lifetime and design requirements



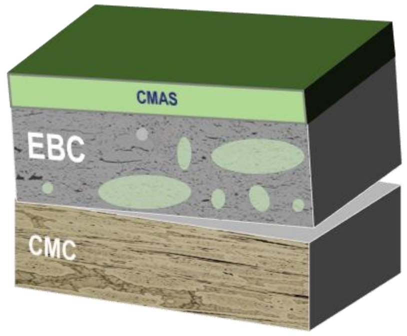
Steam Oxidation



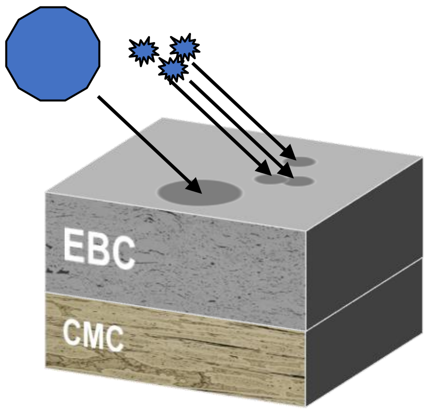
Hydroxide Formation/Recession



Thermomechanical Durability

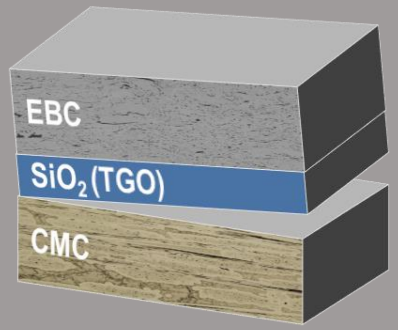


Molten Silicate Attack and Infiltration



Erosion and FOD

Environmental Barrier Coating Failure Modes



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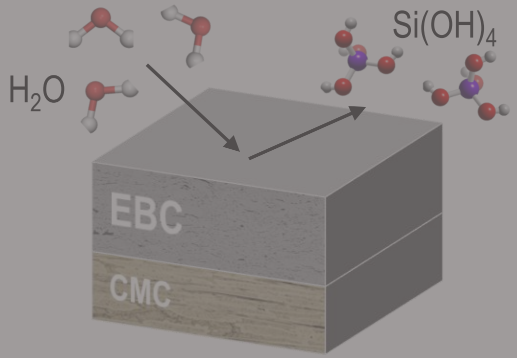

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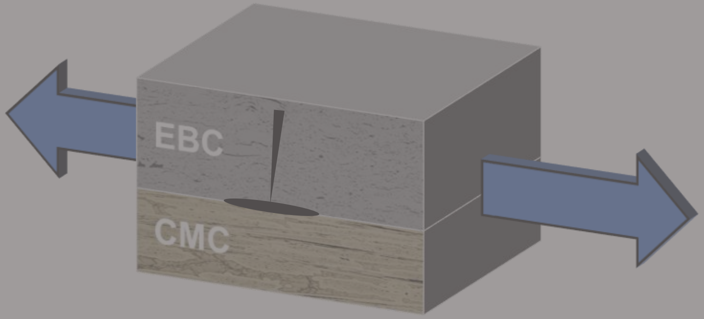

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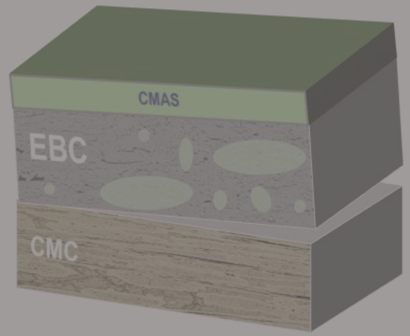

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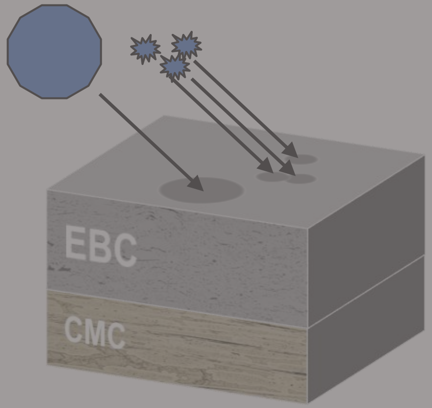
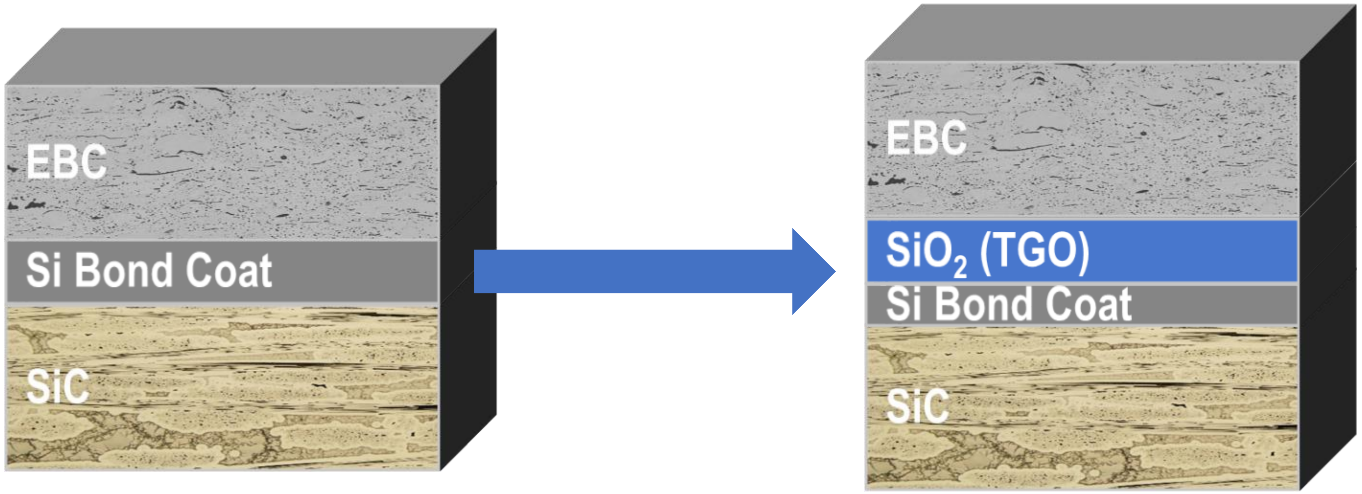


Erosion and FOD

Steam Oxidation

- Limiting the formation and growth of SiO_2 layer is critical to long-life and durability requirements
- Thermally grown oxide (TGO) layer is the weak link in coating system due to CTE mismatch and phase transformation
- Oxidation of Si-based ceramics (including Si) is an order of magnitude or more in steam versus dry air



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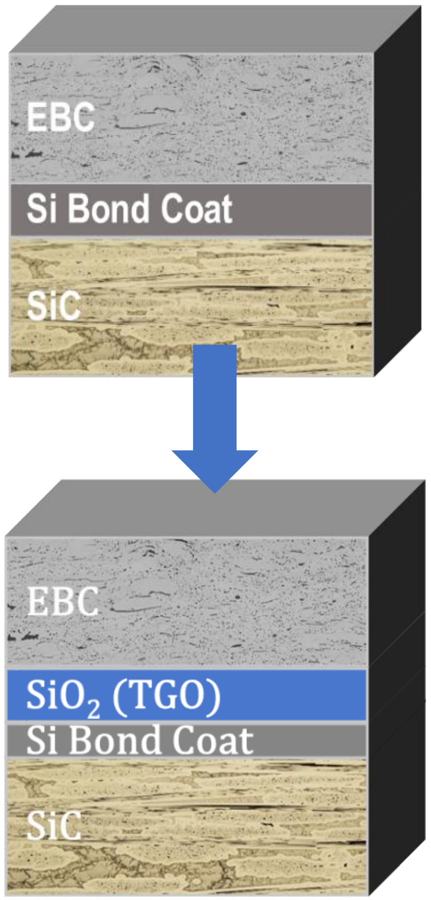
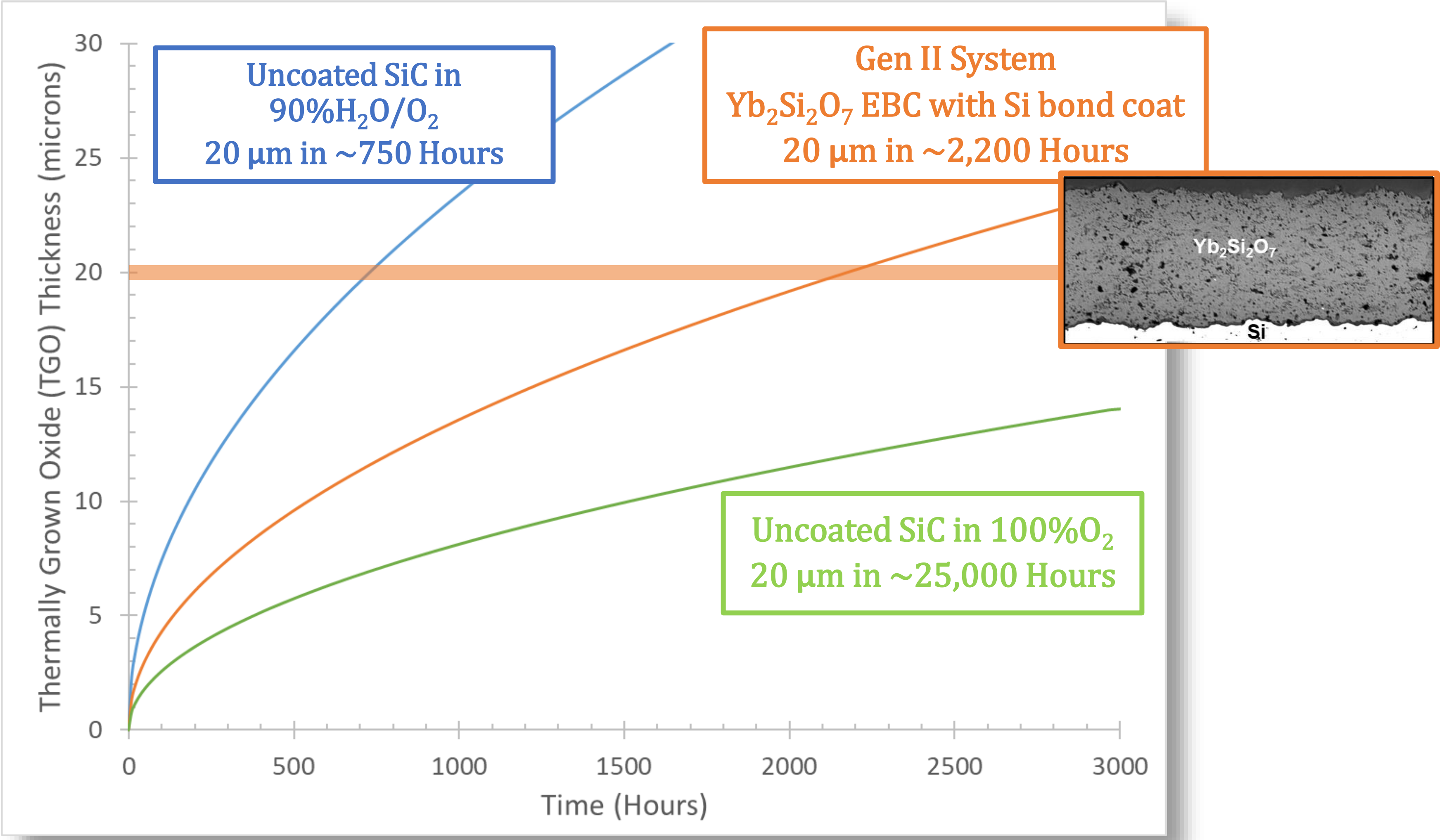
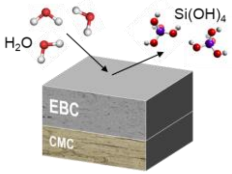




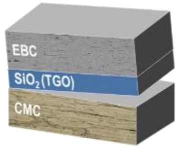
Steam Oxidation

Steam Cycling

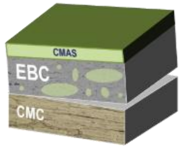
$P(H_2O) = 0.9atm$
$V = 10$ cm/s
$P_{total} = 1$ atm



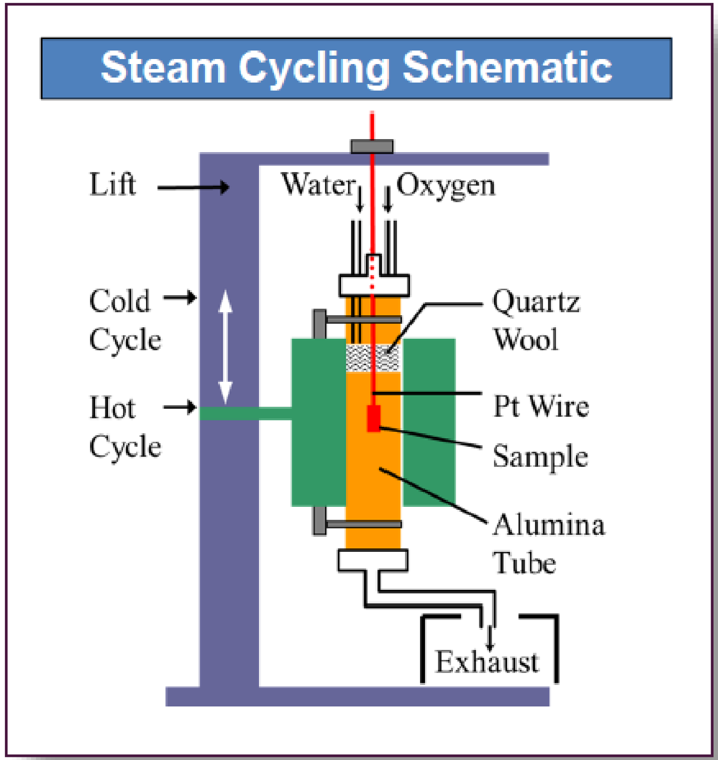
Recession



Oxidation



CMAS



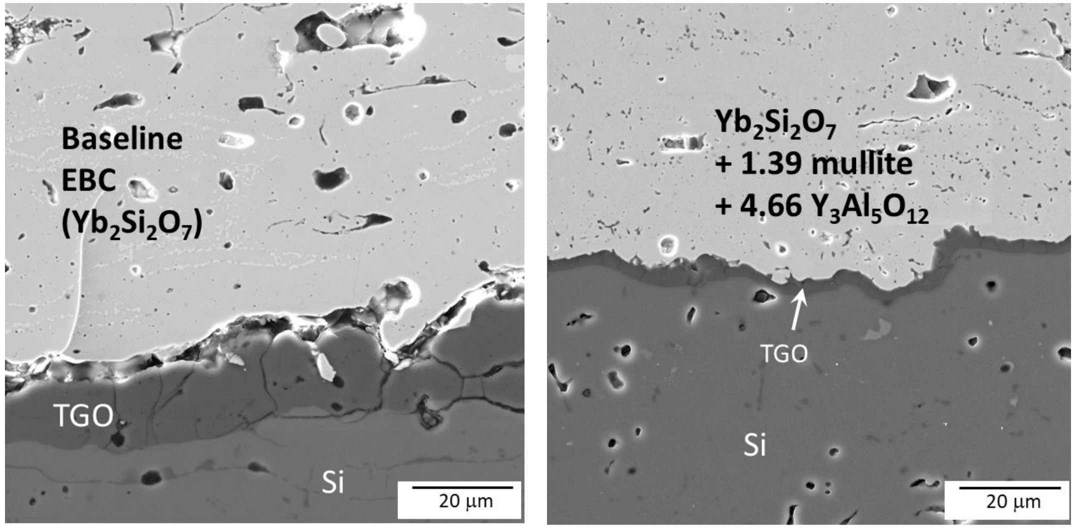
- Continuous cycling of samples at temperature forms thermally grown oxide (TGO) – SiO_2.
  - TGO is the weak interface
  - Life-limiting factor
- Steam oxidation provides 10x increase in TGO thickness versus dry air
- Cycling in 90% H_2O/O_2 is akin to 9 atm combustion environment

Steam Oxidation

- K. Lee (NASA) modified a $Yb_2Si_2O_7$ EBC with Al_2O_3, mullite, $Y_3Al_5O_{12}$, and TiO_2
  - Published in 2019
- APS 2-layer system consisting of a Si bond coat and the modified EBC topcoat
- Samples were cycled for up to 1000 hours in 90% H_2O / 10%O_2 at 1316°C

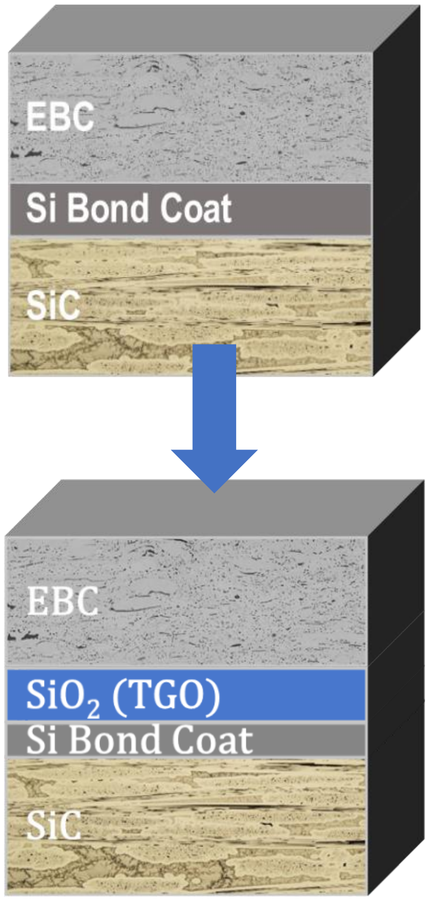
1 hour hot / 1000 cycles at 1316°C

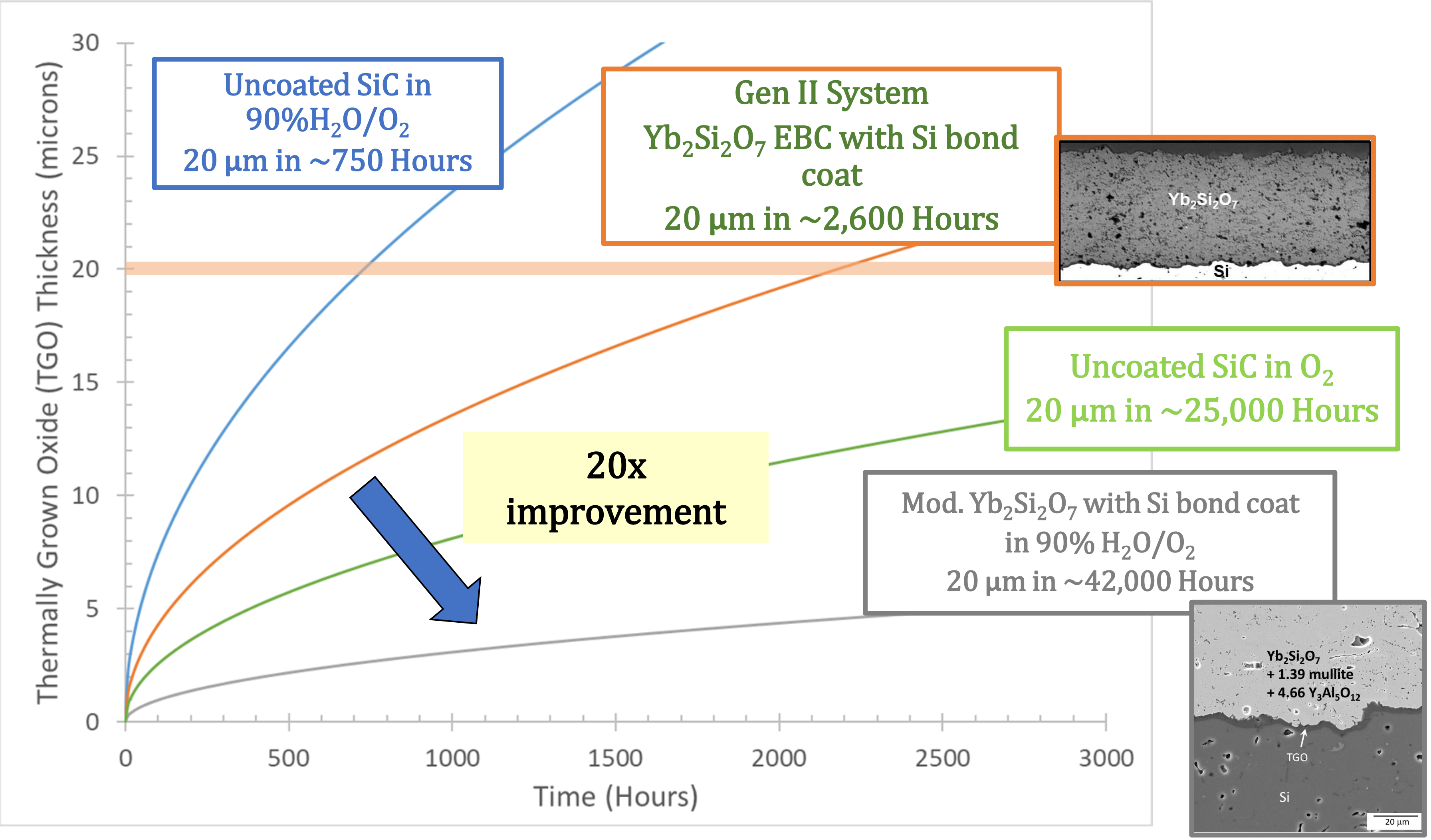
- Al_2O_3 and Al_2O_3-containing modifiers showed the largest reduction in TGO growth rate
  - TGO was shown to contain Al_2O_3
- Reduction in the TGO thickness translates to potentially **>20x** life improvement over baseline systems



K. Lee, J. Amer. Ceram. Soc., 2019; 102:1507-1521.

Steam Oxidation





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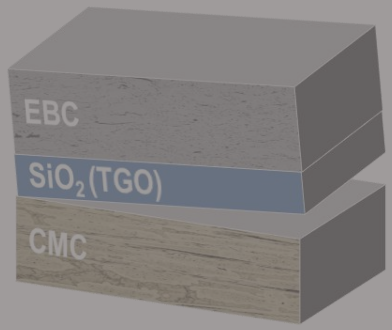

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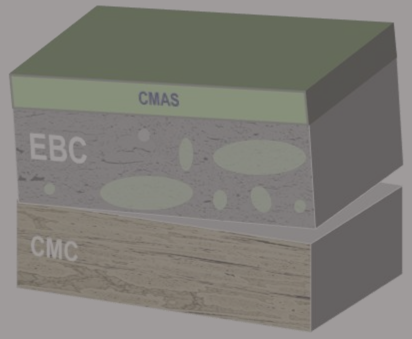

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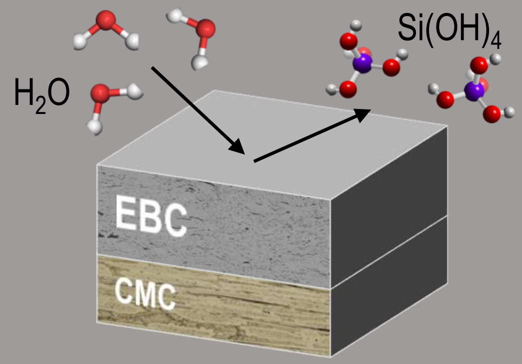
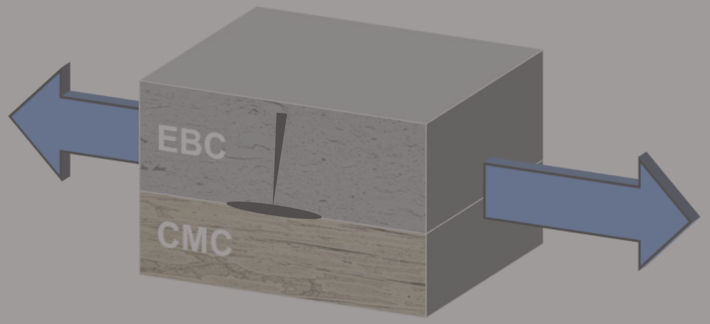
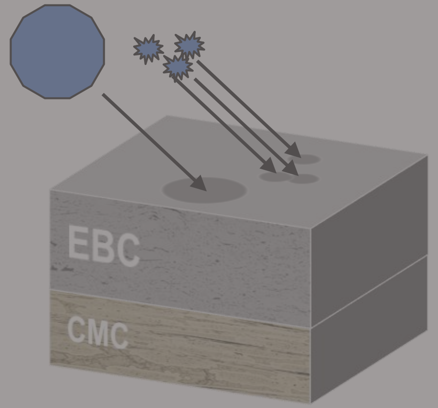


Hydroxide Formation/Recession

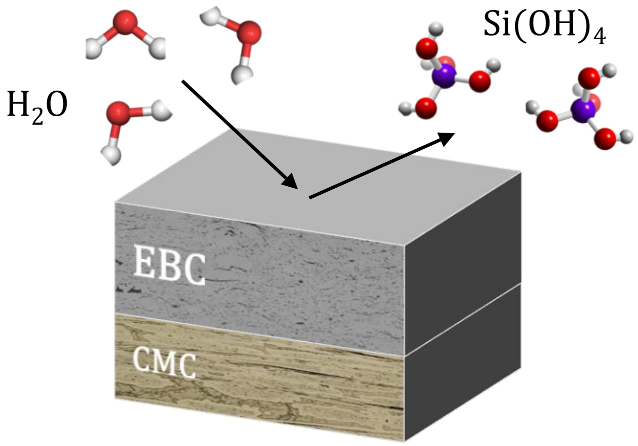


Thermomechanical Durability



Erosion and FOD

Hydroxide Formation/Recession



Hydroxide Formation/Recession

$$SiC + 3\,H_2O_{(g)} = SiO_2 + CO_{(g)} + 3H_{2(g)}$$

$$SiO_2 + 2H_2O_{(g)} = Si(OH)_{4(g)}$$

	Most Water Vapor Resistant
CTE too high ($>10\text{x}10^{-6}/°C$)	HfO_2
	ZrO_2 (YSZ)
	$2(Y_2O_3) \bullet 3(ZrO_2)$
CTE too high or anisotropic	$3(Y_2O_3) \bullet 5(Al_2O_3)$ (YAG)
	$Yb_2O_3 \bullet SiO_2$
	$Y_2O_3 \bullet SiO_2$
	$Al_2O_3 \bullet TiO_2$
Currently used CTE $\sim 4\text{-}6\text{x}10^{-6}/°C$	$Yb_2O_3 \bullet 2(SiO_2)$
	$Y_2O_3 \bullet 2(SiO_2)$
	$Ba(Sr)O \bullet Al_2O_3 \bullet 2(SiO_2)$ (BSAS)
Not protective	Al_2O_3
	TiO_2
	SiO_2
	Cr_2O_3
	Least Water Vapor Resistant

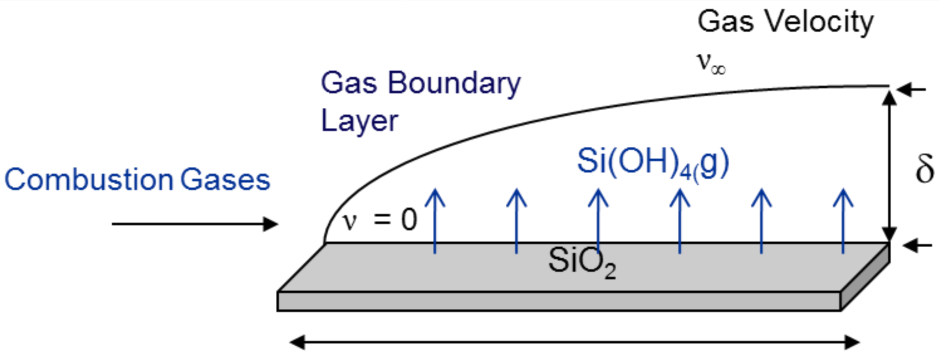
ASM Handbook, Volume 13B, Corrosion: Materials (#06508G), Environmental Performance of Nonmetallic Materials (574-575)

Hydroxide Formation/Recession

Fundamental Thermochemistry

Instrument	Measurements
Mass Spectrometry (2000°C)	Products, activities, vapor pressure, enthalpy of vaporization
TGA (1650°C air, 2400°C vacuum)	Wt. change, oxidation, reduction, vaporization
Drop Solution Calorimeter	Enthalpy of formation, reaction, and mixing

- Develop an understanding of high temperature material behavior from fundamental thermodynamics, chemistry, and kinetics.
- Experimental and computational methods.
- Modeling can be used to determine potential gaseous species



NASA GRC identified $Si(OH)_4$ product for reaction of SiC with moisture – reaction is life limiting to SiC/SiC durability in turbine engines.

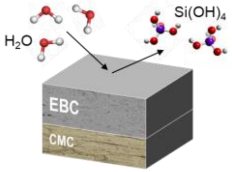
KEMS

Thermo-gravimetric Analysis (air/water/vacuum)

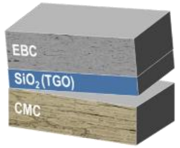
Calorimeter

Hydroxide Formation/Recession

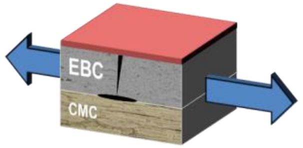
NG/O_2 Burner Rig
$P(H_2O)$ = 0.1 - 0.5 atm
V ~ 100 – 250 (est.) m/s
P_{total} = 1 atm



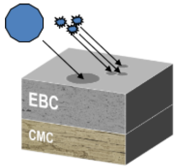
Recession



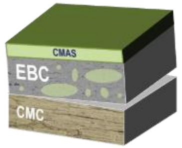
Oxidation



Thermomechanical



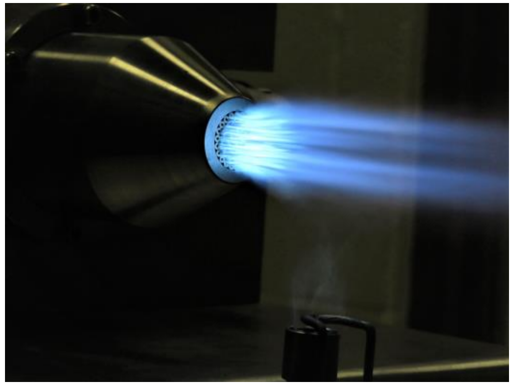
Erosion / FOD

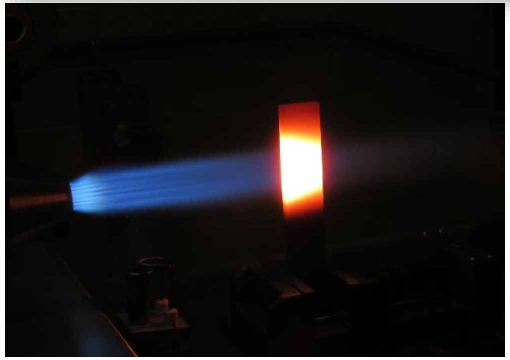


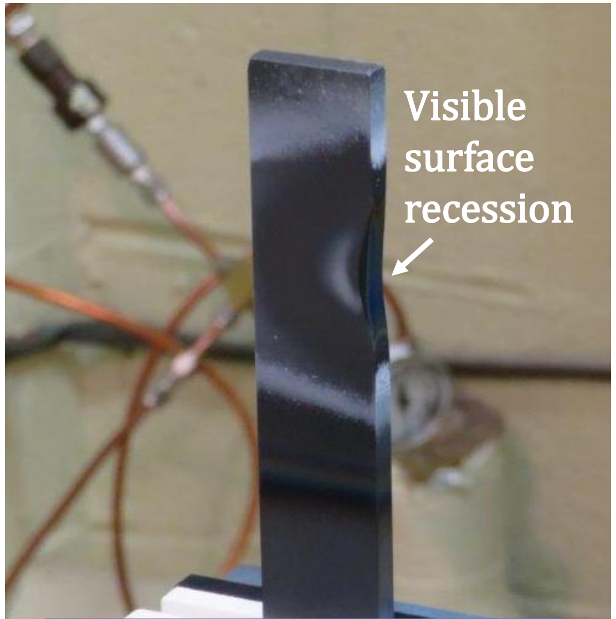
CMAS

Chemical Equilibrium Analysis (CEA)

- Peak adiabatic flame temperature – 4,986°F(~2,750°C)
- $P(H_2O)$ ~ 0.1 – 0.4 atm → P(total) = 1atm
- Gas velocity estimated: ~100 - 300 m/s
- High heat flux (up to ~200 W/cm^2)







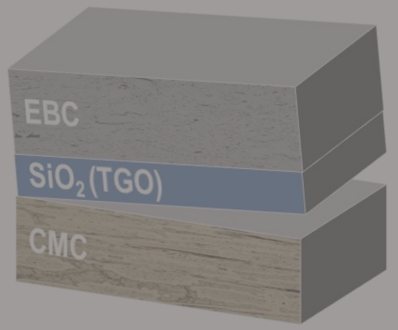
SiC Hexoloy SA – Recession
60 hours - 3000°F

Environmental Barrier Coating Failure Modes

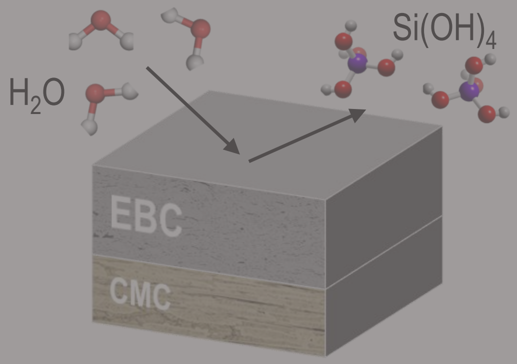
Testing of EBC systems is critical

Individual mechanisms must be well understood before evaluating combinatorial effects

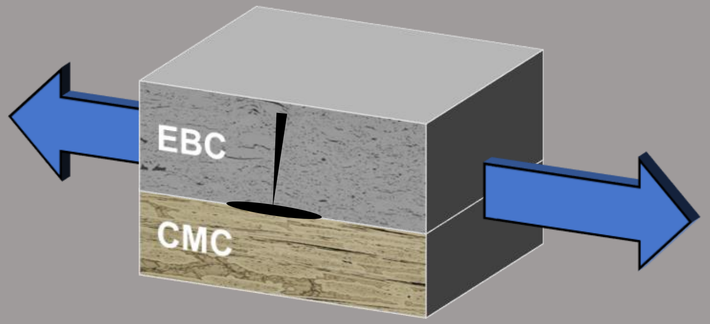
Synergies between extrinsic failure modes determine EBC lifetime and design requirements



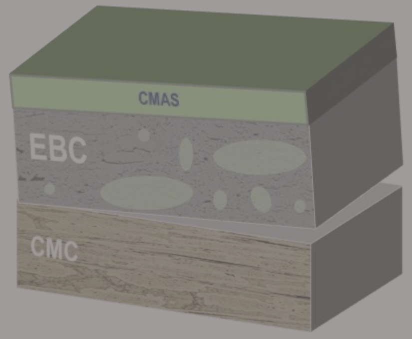
Steam Oxidation



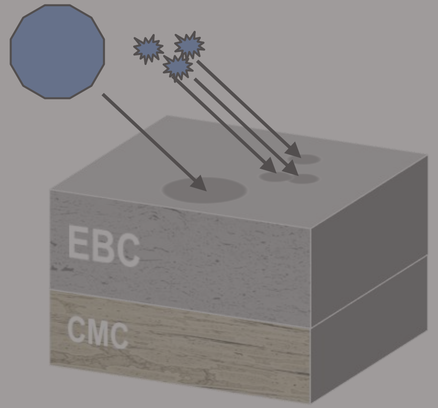
Hydroxide Formation/Recession



Thermomechanical Durability



Molten Silicate Attack and Infiltration

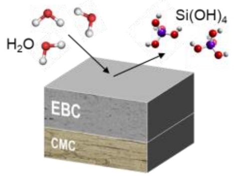


Erosion and FOD

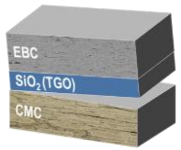
Thermomechanical Durability

High Heat Flux Laser

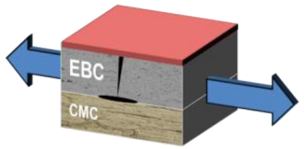
$P(H_2O) = \text{none}$
$V = \text{none}$
$P_{total} = 1\ \text{atm}$



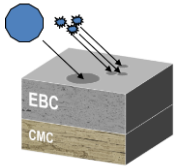
Recession



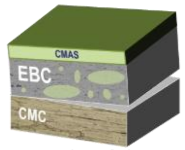
Oxidation



Thermomechanical

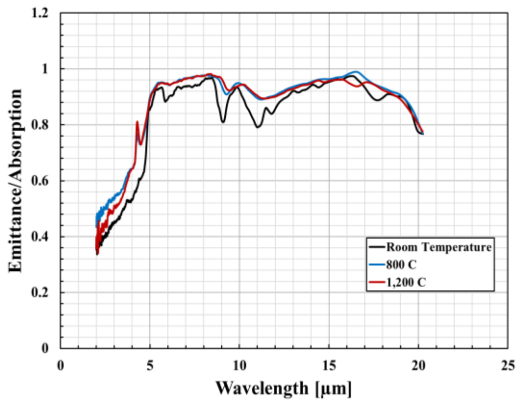


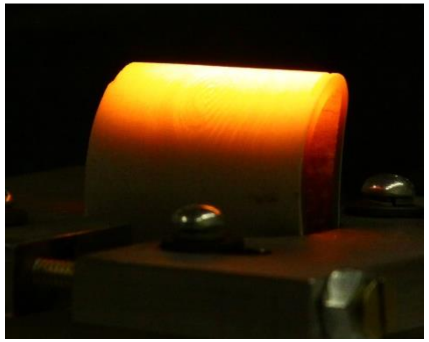
Erosion / FOD

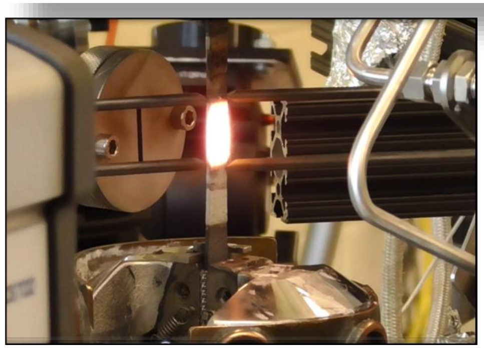


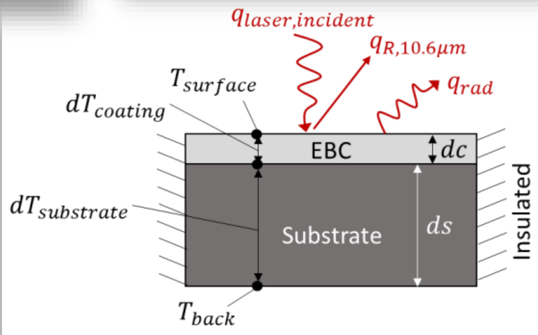
CMAS

- High-powered Carbon Dioxide (CO_2) lasers
  - 10.6 µm wavelength ideal for EBC candidate materials
  - High absorption
- Thermal or combined thermal-mechanical testing capabilities
- Surface temperatures > 3,000°F (1650°C) are achievable
- Incident heat flux up to 300 W/cm² (assuming 1 inch diameter spot size)

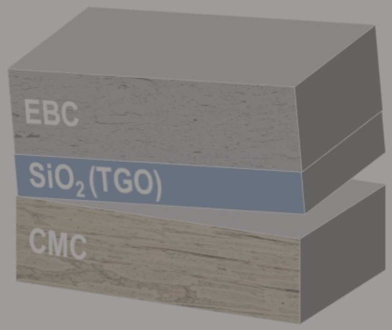




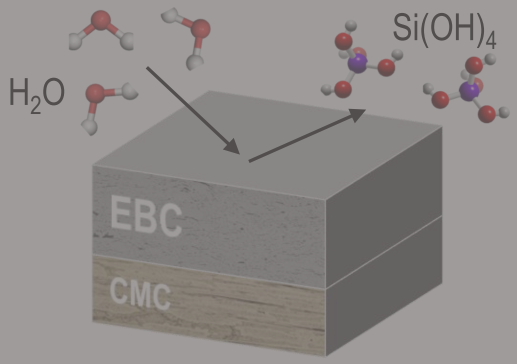




Environmental Barrier Coating Failure Modes



Steam Oxidation



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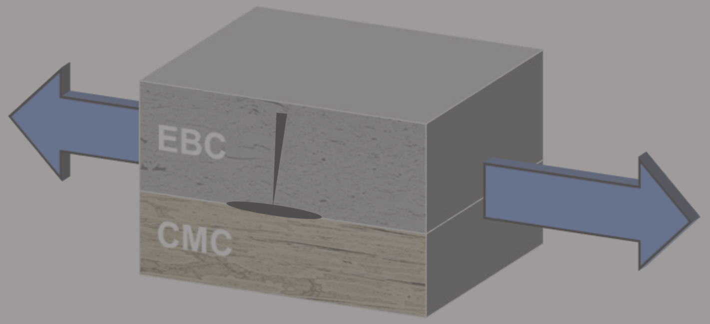
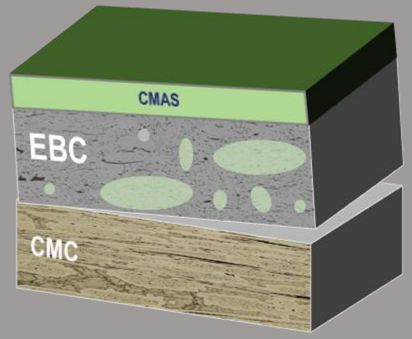
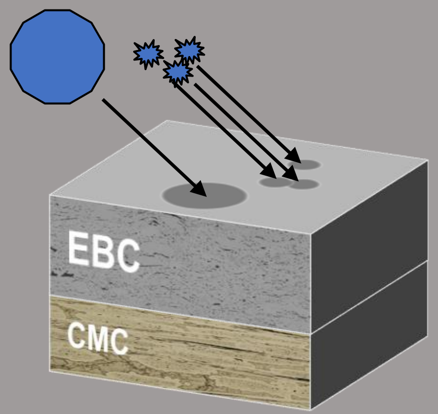


Thermomechanical Durability



Molten Silicate Attack and Infiltration



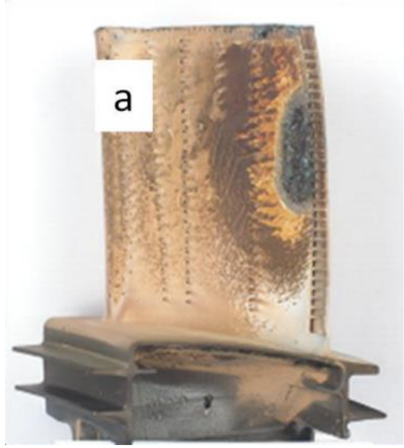
Erosion and FOD

Degradation by Particulate Ingestion

CMAS

- Particulates (i.e. sand, volcanic ash) ingested by engine melt into **Calcium-Magnesium-Alumino-Silicate (CMAS)** deposits above 1200°C
- Molten CMAS degrades T/EBCs (chemical + mechanical)
  - CMAS infiltration of T/EBC due to lowered CMAS viscosity at elevated temperatures → CTE mismatch
  - Thermochemical interactions of CMAS with T/EBC → spallation

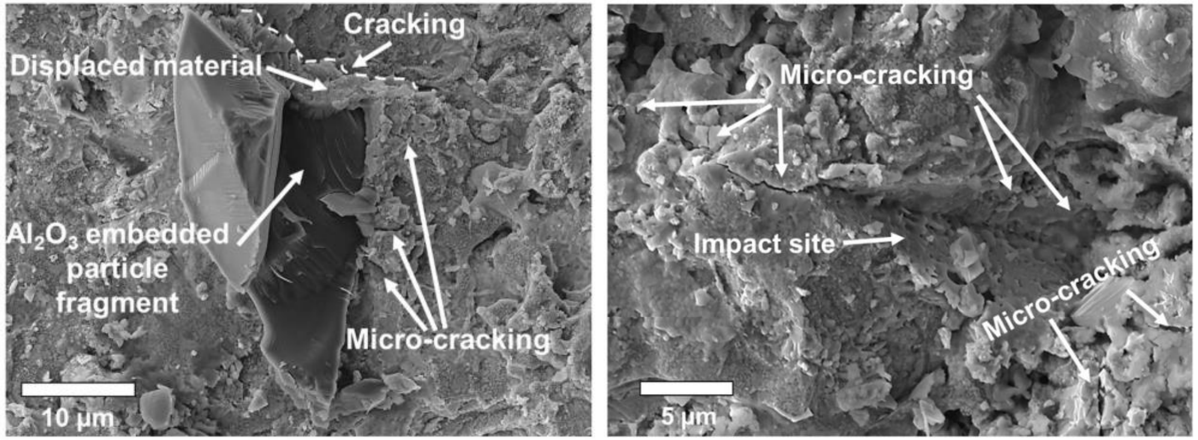
Eyjafjallajökull volcano eruption in Iceland (2010)



Damage on a turbine blade caused by CMAS >1200°C

Solid Particle Erosion

- Particulates (i.e. sand, volcanic ash) ingested by engine can **mechanically erode** T/EBCs at higher temperatures
- Brittle fracture dominated erosion response of T/EBCs at high temperature
  - Coating microstructure affects durability



Presby et al., *Ceramics International* **47** (2021)

Presby et al., *Coatings* **13** (2023)

Degradation by Particulate Ingestion

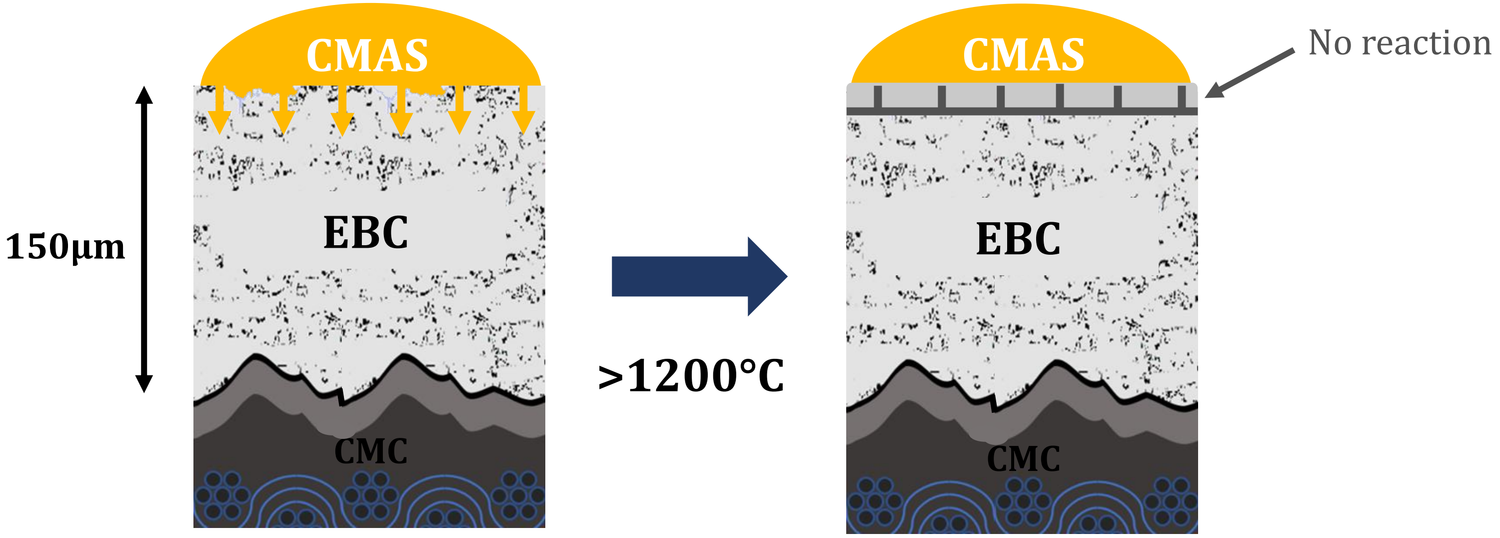
Relative Composition (mol%) of Sources and Deposits*

	SiO_2	CaO	MgO	$AlO_{1.5}$	FeO	CaO/SiO_2
Earth's Crust	65	6	6	10	4	0.093
Saudi Sand	93	1	< 1	4	< 1	0.011
Airport Runway Dust	75	5	2	15	4	0.067
Volcanic Ash	65	5	4	18	5	0.077
Fly Ash	40	5-20	5	20	5-20	0.125-0.5
Engine Deposits	**25-40**	**20-35**	**7-15**	**10-15**	**7-15**	**0.5-1.43**

Engine Deposits have a wide composition range!

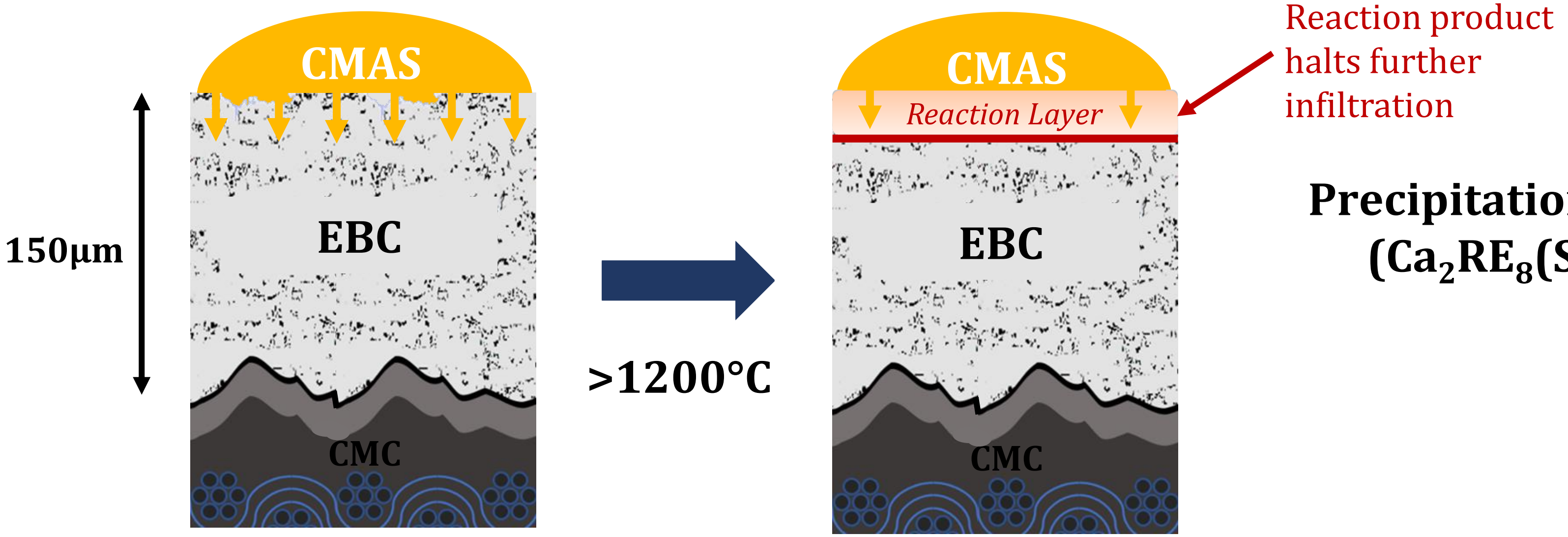
CMAS Mitigation Strategies

- *Minimize* reactivity of coating material with molten CMAS
  - Thermodynamic stability over reaction products



CMAS Mitigation Strategies

- *Minimize* reactivity of coating material with molten CMAS
  - Thermodynamic stability over reaction products
- *Maximize* reactivity of coating material with molten CMAS to induce crystallization
  - Crystallized reaction product barrier

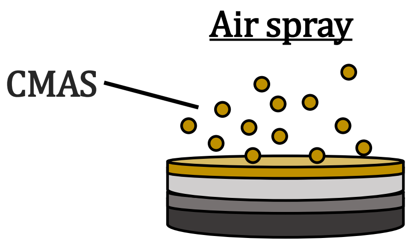


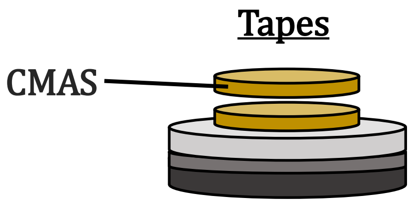
Precipitation of apatite ($Ca_2RE_8(SiO_4)_6O_2$)

Degradation by Particulate Ingestion

Testing Methods

Static CMAS Testing





Heat treatment in box furnace → thermodynamic assessment of reactivity

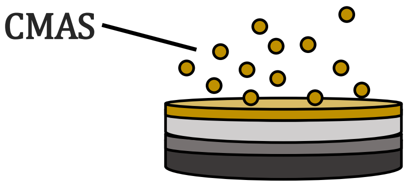
Degradation by Particulate Ingestion

Testing Methods

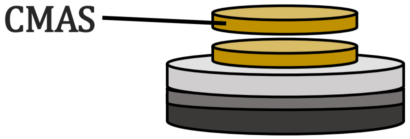
Engine Environment

Static CMAS Testing

Air spray

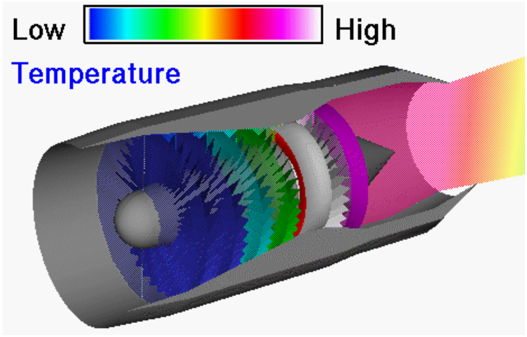


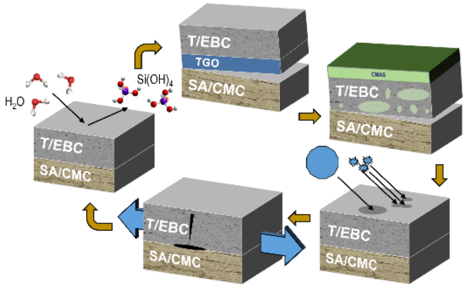
Tapes



Heat treatment in box furnace → thermodynamic assessment of reactivity

Dynamic, Non-equilibrium





Synergistic → Thermal cycling, gradients, water vapor combined will all affect coating durability

Degradation by Particulate Ingestion

Testing Methods

Engine Environment

Static CMAS Testing

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Heat treatment in box furnace → thermodynamic assessment of reactivity

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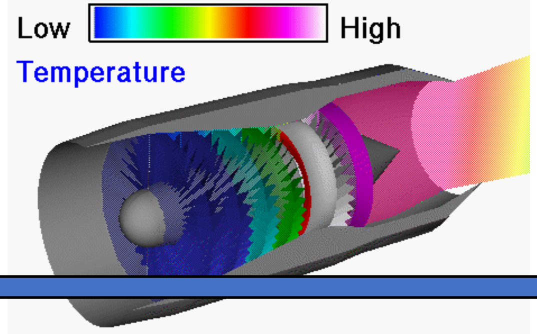
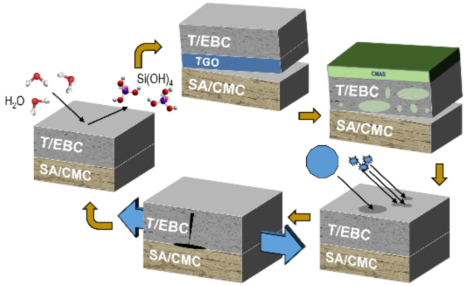




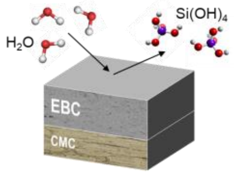
Synergistic → Thermal cycling, gradients, water vapor combined will all affect coating durability

- Laboratory scale testing in relevant environments
  - Induce coating damage observed in flight hardware
  - Standardize testing procedures for high temperature evaluation of particle interactions

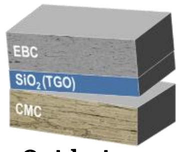
Mach 0.3-1 Jet-A Burner Rig Facility

Jet-A Burner Rig

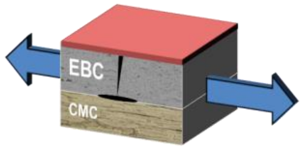
$P(H_2O) = 0.1$ atm
$V \sim 100 - 340$ m/s
$P_{total} = 1$ atm



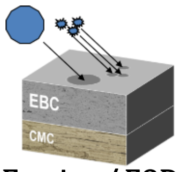
Recession



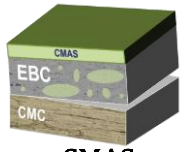
Oxidation



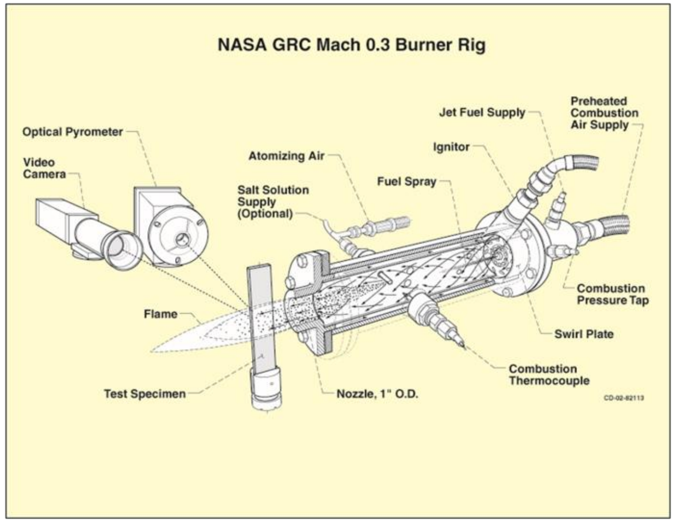
Thermomechanical



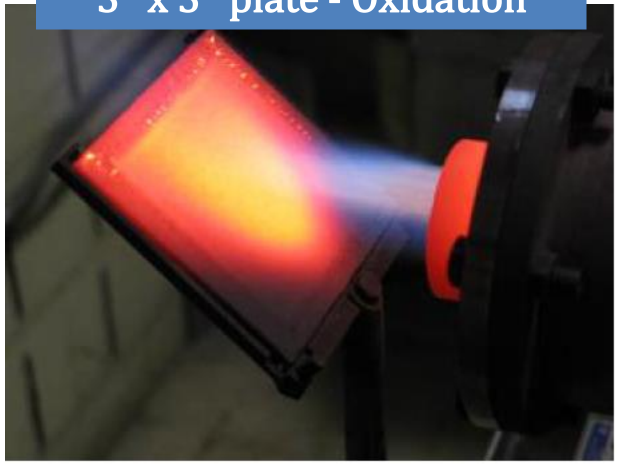
Erosion / FOD

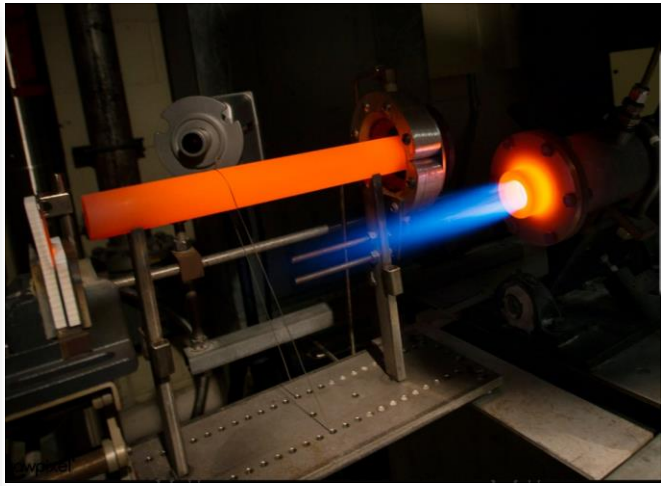


CMAS



3" x 3" plate - Oxidation





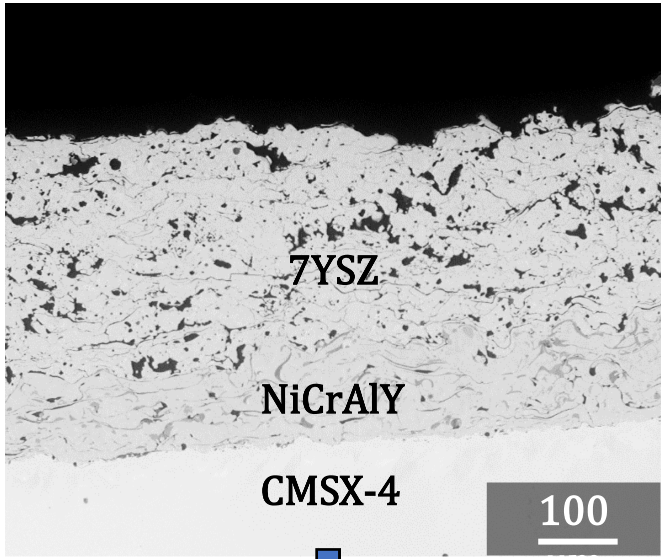
- Sample temperature: ~600 – 2700°F (~315 – 1482°C)
- Mach 0.3 – Mach 1.0 gas velocity (~100 – 340 m/s)
- ~10% water vapor (atmospheric pressure – 1atm)

- Jet-A/pre-heated air burner rig
- Coupon to sub-component scale testing
- Multiple mechanisms can be studied simultaneously

Fox, et. al. NASA/TM – 2011-216986

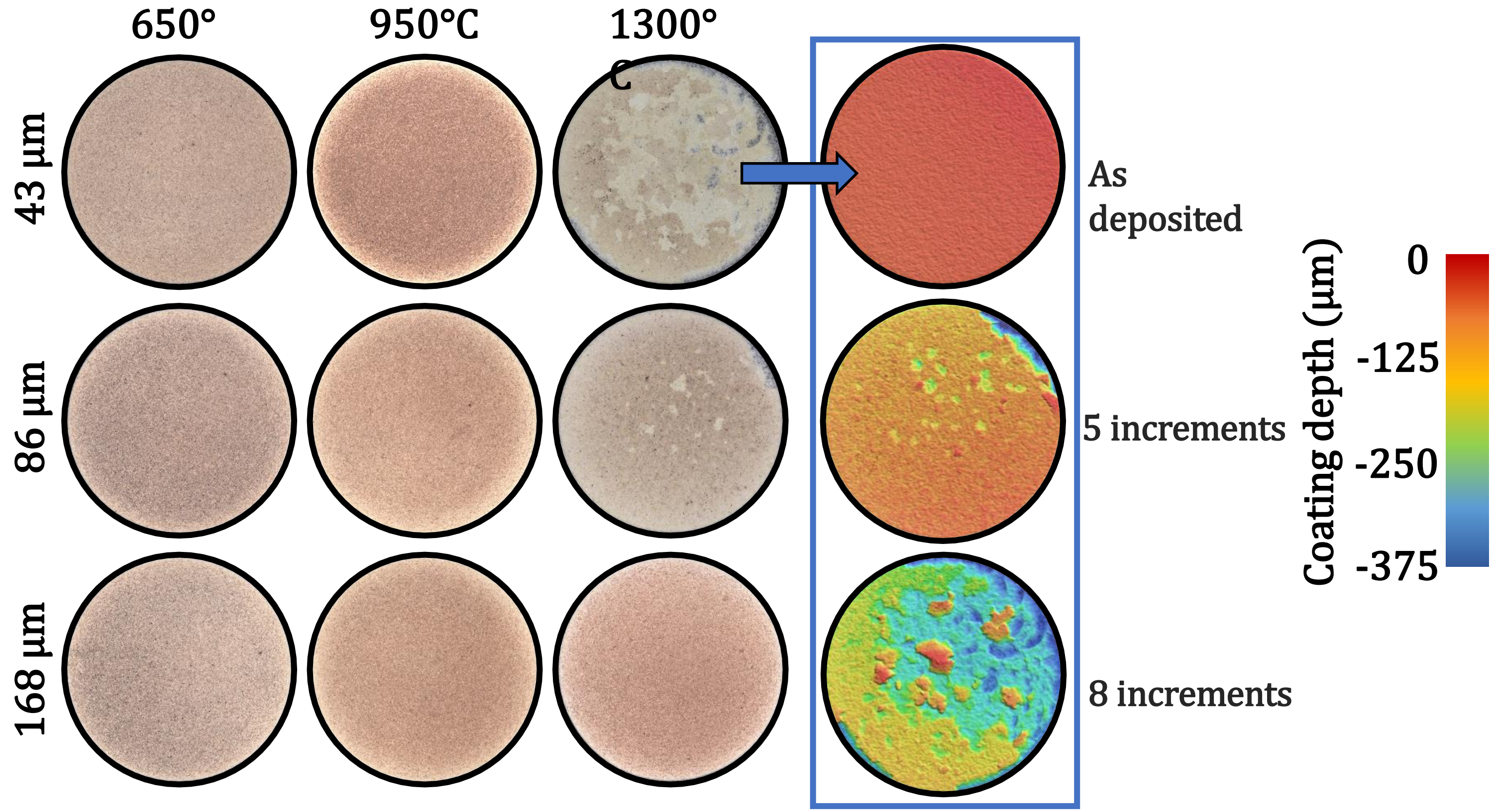
Degradation by Particulate Ingestion

7 wt.% Yttria-Stabilized Zirconia TBC



M. J. Maloney, courtesy of Pratt and Whitney

- Erosion Burner Rig Facility
  - Jet-A combustor
  - Variable fuel air ratio to achieve different temperatures
- SOA Air Plasma Sprayed ~250 μm 7YSZ TBC
  - CMSX-4 superalloy (25.4 mm diameter)
  - Particle degradation well documented in literature
- 30.67CaO–8.25MgO–12.81$AlO_{1.5}$–48.27SiO_2 (mol.%) glass frit melts at ~1240°C



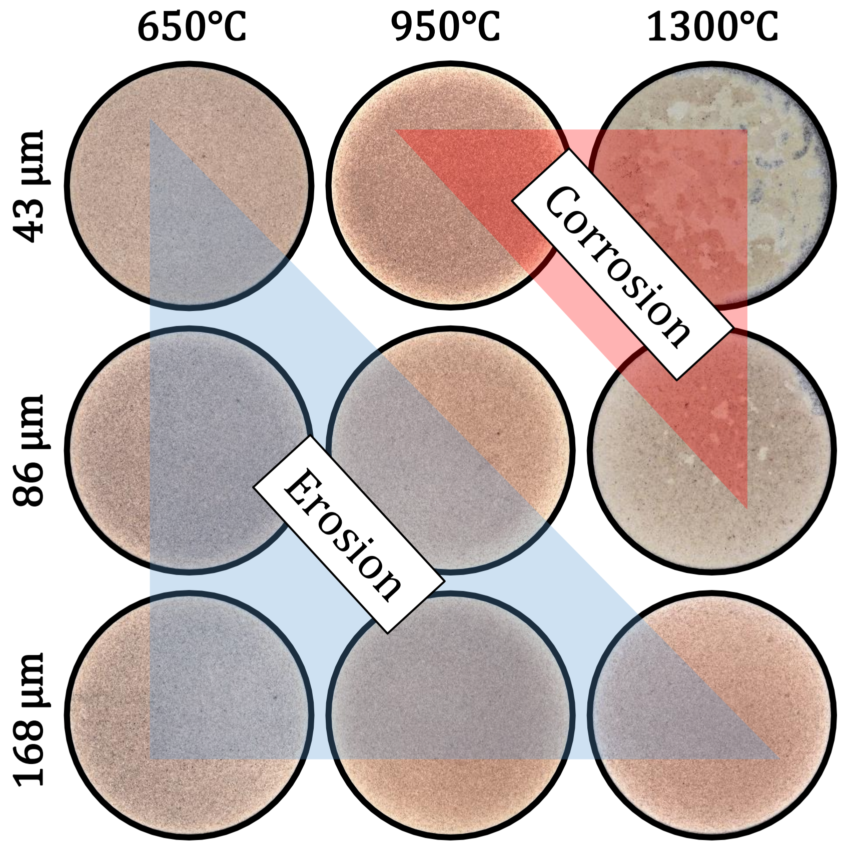
Stokes and Presby "A Dynamic Testing Approach for Particulate Erosion–Corrosion for Gas Turbine Coatings" *Journal of Engineering for Gas Turbines and Power* (2024)

Degradation by Particulate Ingestion

Erosive vs Corrosive Behavior

Effects of Erodent Material

- Define erosion and corrosion as dominant regimes within a set of conditions used for testing.
    - All 168 μm samples exhibited erosion-dominated behavior (i.e. consistent mass loss).
    - Flow through the burner at 1300°C was rapid enough to not produce fully molten particles at this particle size range.
- 43 μm particles became fully molten at 1300°C, resulting in deposition and reaction with 7YSZ
- Varying CMAS compositions will result in shift of regimes



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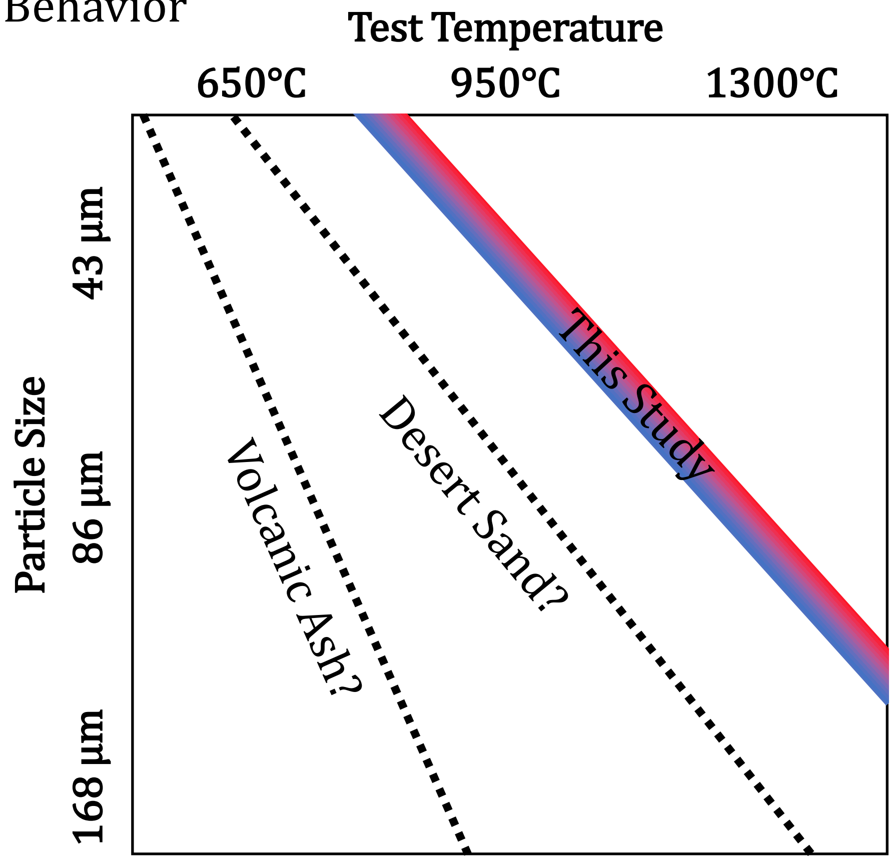

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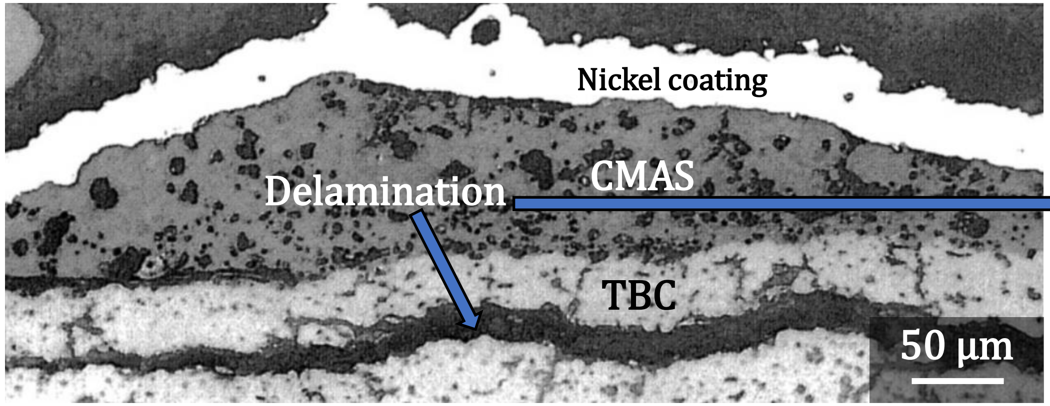
Degradation by Particulate Ingestion

Mechanisms of Degradation

Burner Rig Testing: Comparison to Furnace Tests and In-Service Components

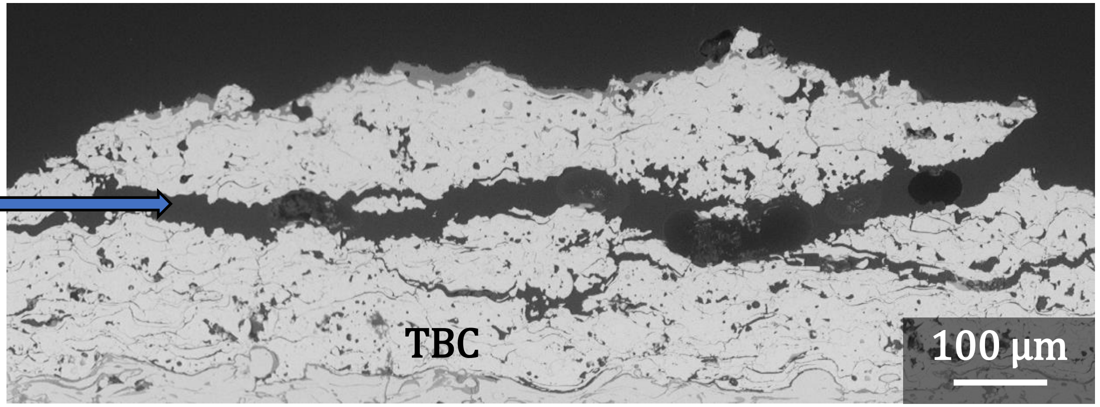
- In static furnace testing, CMAS is observed to completely infiltrate YSZ coatings
- Limited CMAS infiltration was observed in burner rig testing in remaining coating
- Thermal gradient and thermal cycling cause progressive exfoliation of layers of YSZ upon cooling

In Service Component



Borom et al., *Surface and Coatings Technology* **86-87** (1996)

Burner Rig



Conclusions

- Incorporation of new material systems such as ceramic matrix composites (CMCs) offer potential for higher efficiencies and reduced emissions but require environmental barrier coatings for use in next generation turbine engines.

- High temperature corrosion via the oxidation of the silicon bond coat or SiC substrate is a critical mechanism that needs to be slowed for long-life EBCs and will be of even more important at temperatures >2400°F (1316°C).

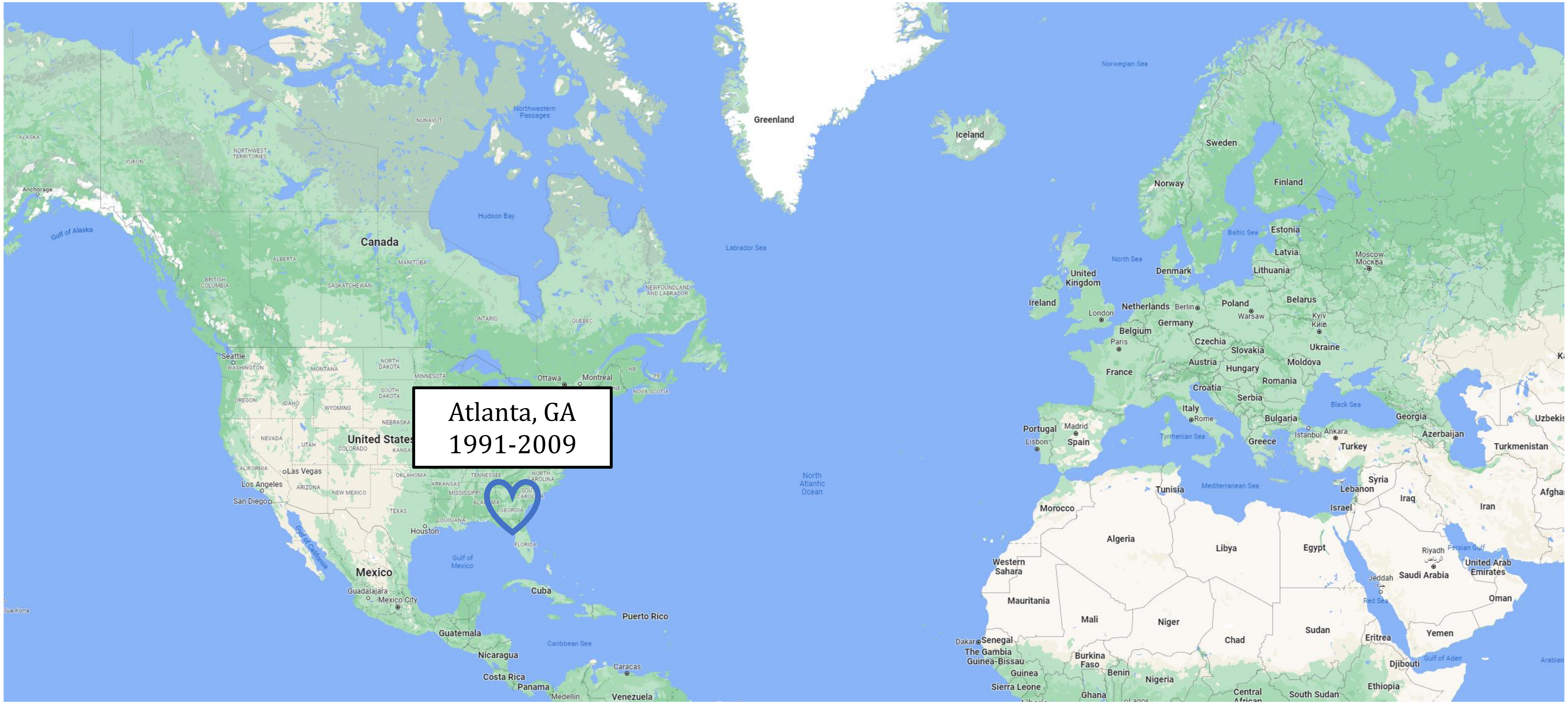
- Recession via the formation of $Si(OH)_4$ needs to be suppressed as much as possible for long-life / durability.

- CMAS may be the most challenging problem on the horizon, as it will require new materials and test methods to design coatings capable of withstanding the thermochemical and thermomechanical (physical) effects of glass corrosion.

- Overall, design of EBCs requires a knowledge of both chemistry and physics to design for long-life and durability in the extreme environment of a turbine engine.

intern.nasa.gov – Internships, fellowships and scholarship opportunities

About Me!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Cuba
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Nicaragua
Costa Rica
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Las Vegas
Los Angeles
San Diego
Houston
Ottawa
Montreal
Guadalajara
Mexico City
Sweden
Norway
Finland
Estonia
Latvia
Lithuania
Denmark
United Kingdom
Ireland
Netherlands
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Ukraine
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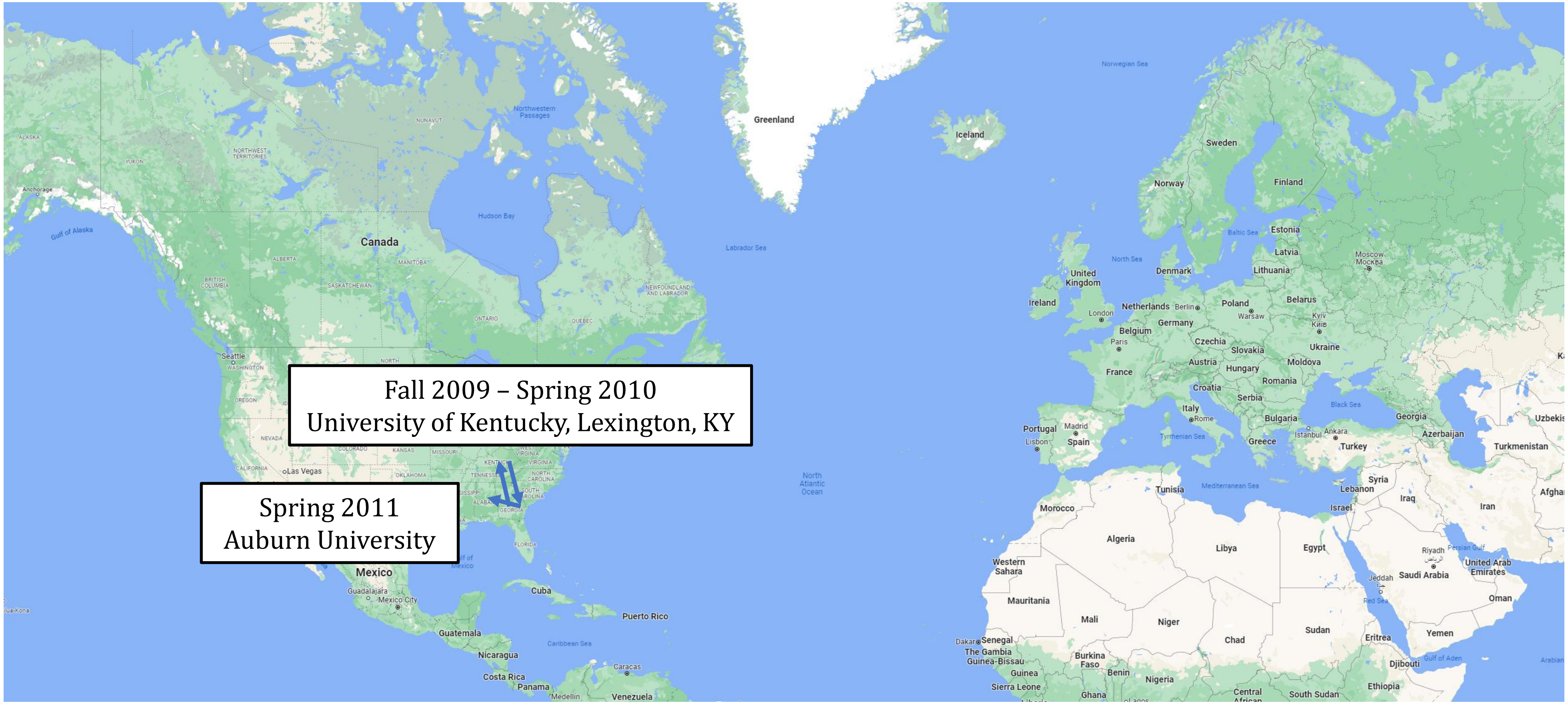
Mauritania
Mali
Niger
Chad
Sudan
Saudi Arabia
United Arab Emirates
Oman
Yemen
Eritrea
Djibouti
Ethiopia
South Sudan
Senegal
The Gambia
Guinea-Bissau
Guinea
Sierra Leone
Burkina Faso
Benin
Nigeria
Ghana
North Atlantic Ocean

About Me!


Fall 2009 – Spring 2010
University of Kentucky, Lexington, KY
Spring 2011
Auburn University
Greenland
Iceland
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Labrador Sea
Gulf of Alaska
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Seattle
Las Vegas
Mexico
Guadalajara
Mexico City
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Nicaragua
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Norwegian Sea
North Sea
Baltic Sea
Sweden
Norway
Finland
Estonia
Latvia
Lithuania
Denmark
United Kingdom
Ireland
London
Netherlands
Berlin
Poland
Warsaw
Belarus
Germany
Belgium
Paris
Czechia
Slovakia
Ukraine
Austria
Hungary
Moldova
France
Romania
Croatia
Serbia
Italy
Rome
Bulgaria
Portugal
Madrid
Spain
Lisbon
Greece
Istanbul
Ankara
Turkey
Black Sea
Georgia
Azerbaijan
Turkmenistan
Syria
Lebanon
Israel
Iraq
Iran
Tunisia
Mediterranean Sea
Morocco
Algeria
Libya
Egypt
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Saudi Arabia
Riyadh
Jeddah
United Arab Emirates
Oman
Yemen
Eritrea
Djibouti
Ethiopia
South Sudan
Senegal
The Gambia
Guinea-Bissau
Guinea
Sierra Leone
Burkina Faso
Benin
Nigeria
Ghana
Moscow

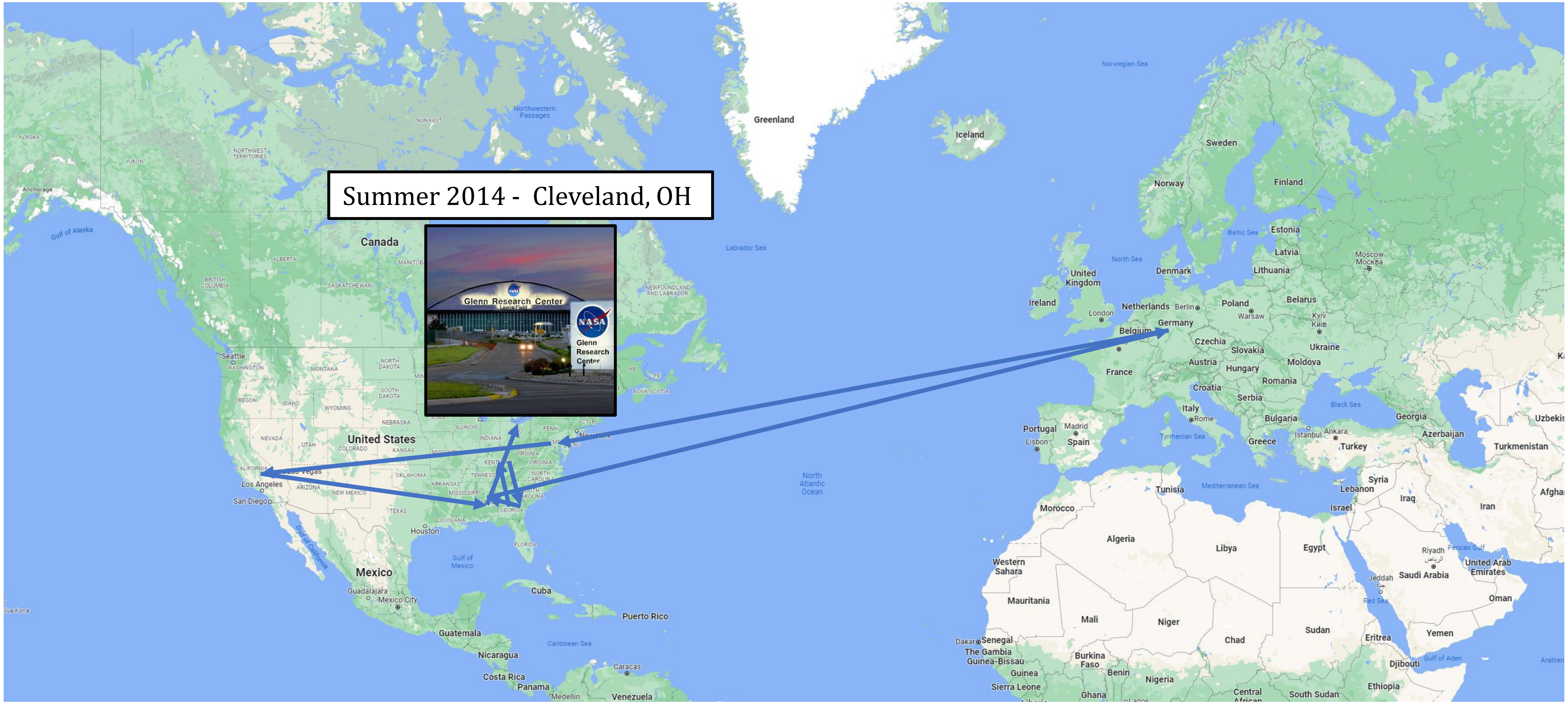
About Me!


Fall 2012 - Reutlingen, Germany
Hochschule Reutlingen
Reutlingen University
Canada
United States
Mexico
Greenland
Iceland
Germany
North Atlantic Ocean

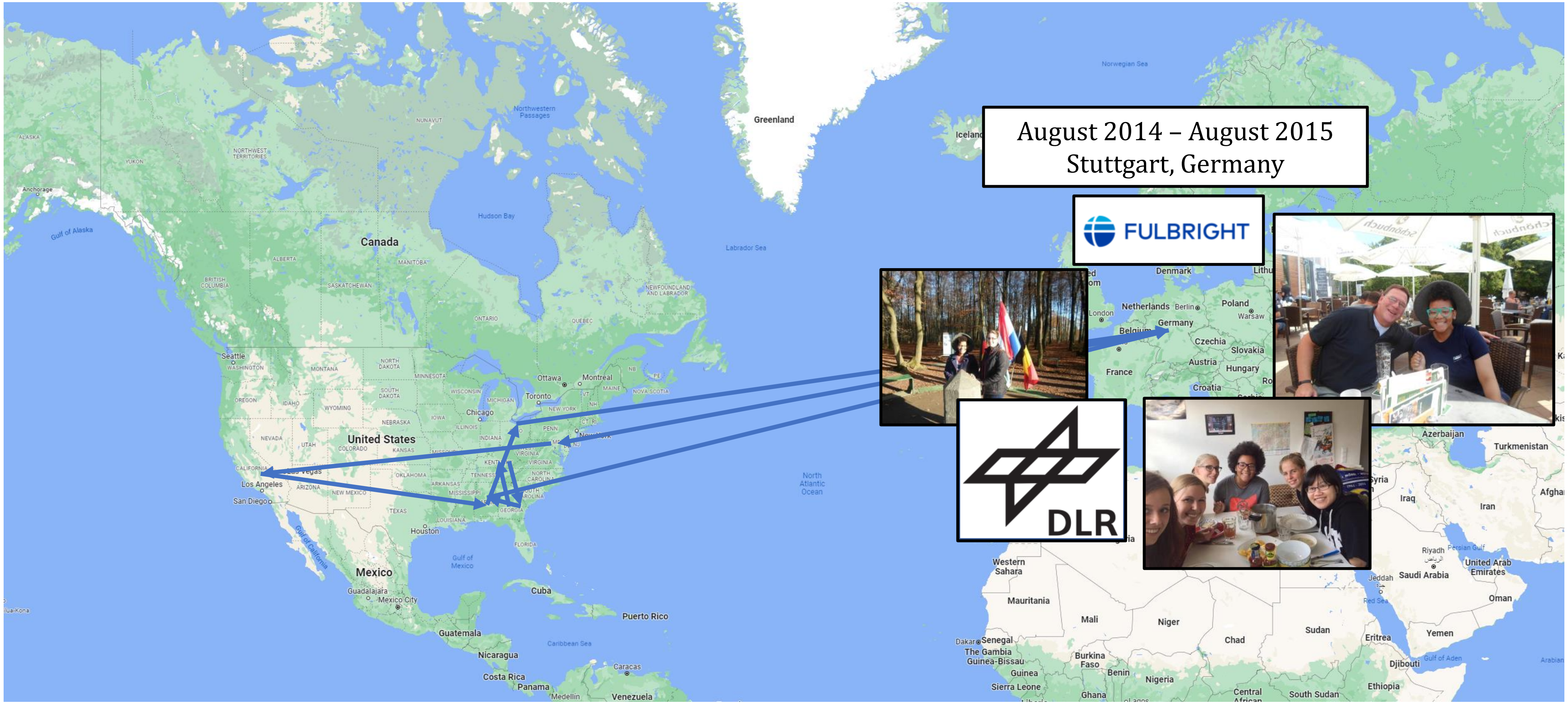
About Me!

Spring 2013 - Greenbelt, MD
NASA Goddard Space Flight Center
Summer 2013 - Pasadena, CA
NASA Jet Propulsion Laboratory
California Institute of Technology
Greenland
Iceland
Canada
United States
Mexico
Cuba
Puerto Rico
Norway
Sweden
Finland
United Kingdom
Ireland
Germany
France
Spain
Portugal
Italy
Poland
Ukraine
Turkey
Morocco
Algeria
Libya
Egypt
Saudi Arabia
Iran
North Atlantic Ocean

About Me!


Summer 2014 - Cleveland, OH
Glenn Research Center
NASA
Glenn Research Center
Canada
United States
Mexico
Greenland
Iceland
Norway
Sweden
Finland
United Kingdom
Ireland
Germany
France
Spain
Portugal
Italy
Poland
Ukraine
Turkey
Morocco
Algeria
Libya
Egypt
Saudi Arabia
Iran
North Atlantic Ocean
Seattle
Los Angeles
San Diego
Houston
Cuba
Puerto Rico
Guatemala
Nicaragua
Costa Rica
Panama
Venezuela

About Me!


August 2014 – August 2015
Stuttgart, Germany
FULBRIGHT
DLR
Greenland
Canada
Hudson Bay
Labrador Sea
United States
Mexico
Cuba
Puerto Rico
North Atlantic Ocean
Seattle
Los Angeles
San Diego
Houston
Chicago
Toronto
Ottawa
Montreal
Gulf of Mexico
Caribbean Sea
Guatemala
Nicaragua
Costa Rica
Panama
Venezuela
Denmark
Netherlands
Germany
Poland
Czechia
Slovakia
Austria
Hungary
France
Croatia
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Nigeria
Saudi Arabia
Iran
Iraq
Oman
Yemen
Ethiopia
Turkmenistan
Azerbaijan

About Me!


August 2015 – December 2019
State College, PA
Greenland
Iceland
Norwegian Sea
Sweden
Norway
Finland
Estonia
Latvia
Lithuania
Denmark
North Sea
United Kingdom
Ireland
Netherlands
Germany
Poland
Belarus
France
Czechia
Slovakia
Austria
Hungary
Ukraine
Moldova
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Serbia
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Bulgaria
Portugal
Spain
Greece
Turkey
Georgia
Azerbaijan
Turkmenistan
Black Sea
Mediterranean Sea
Tunisia
Morocco
Algeria
Libya
Egypt
Syria
Lebanon
Israel
Iraq
Iran
Saudi Arabia
United Arab Emirates
Oman
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Eritrea
Yemen
Djibouti
Senegal
The Gambia
Guinea-Bissau
Guinea
Sierra Leone
Burkina Faso
Benin
Nigeria
Ghana
South Sudan
Ethiopia
Venezuela
Caracas
Seattle
Toronto
Ottawa
Montreal
Anchorage
Gulf of Alaska
Penn
PennState

About Me!

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