

Evaluation of Particle Degradation of a Ytterbium Disilicate Gas Turbine Coating in a Combustion Environment

Technical Paper Presentation GT2026-174893

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NASA Glenn Research Center

Acknowledgments
Hybrid Thermally Efficient Core (HyTEC) Project
Transformational Tools and Technologies (TTT) Project

Introduction and Motivation – Coatings for Hot Section Engine Components

- TBCs protect nickel-based superalloy components against oxidation and reduce component temperature
- EBCs protect SiC-based CMCs against high temperature oxidation/corrosion from water vapor and other combustion specie

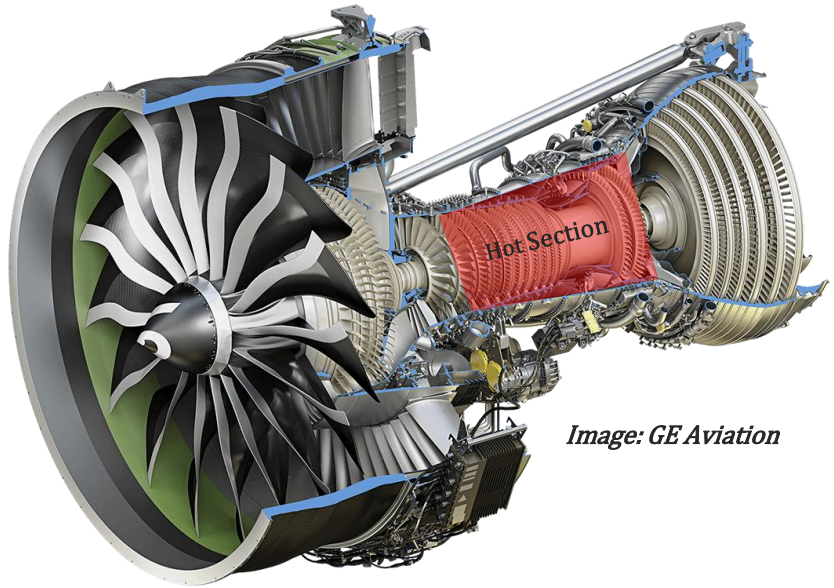
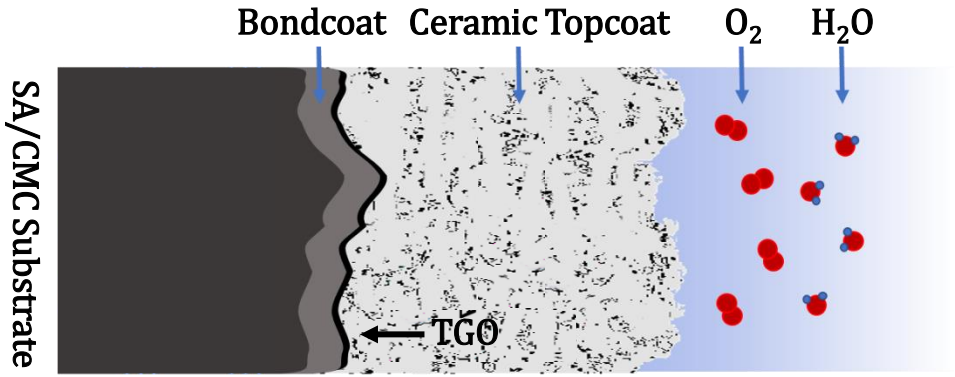
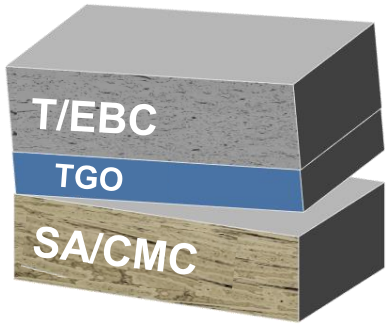


Image: GE Aviation

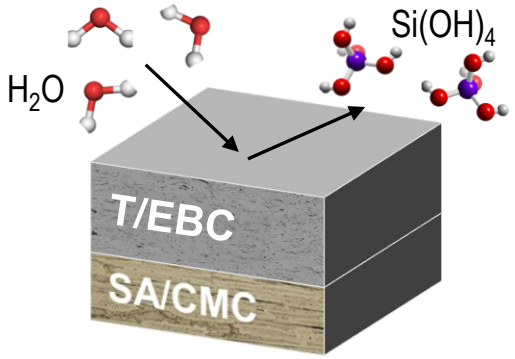
Thermal/Environmental Barrier Coatings (EBCs)



Introduction and Motivation – T/EBC Development and Testing



Oxidation

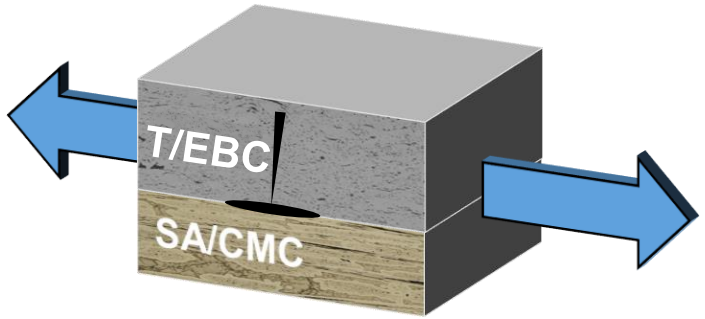


Volatilization

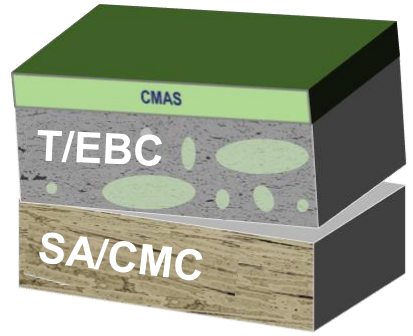
Testing of T/EBC systems is critical

Individual mechanisms must be well understood before evaluating combinatorial effects

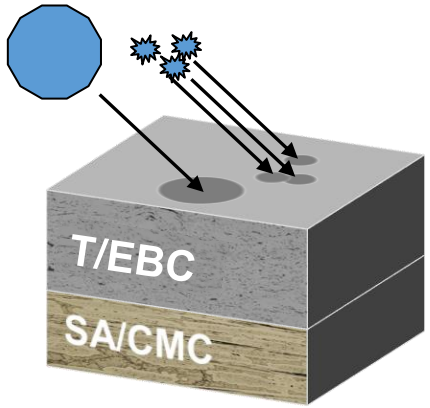
Synergies between extrinsic failure modes determine EBC lifetime and design requirements



Thermomechanical Durability



Molten Silicate Attack and Infiltration



Erosion and FOD

Lee, "Environmental Barrier Coatings for CMCs"; in Ceramic Matrix Composites, (2015)

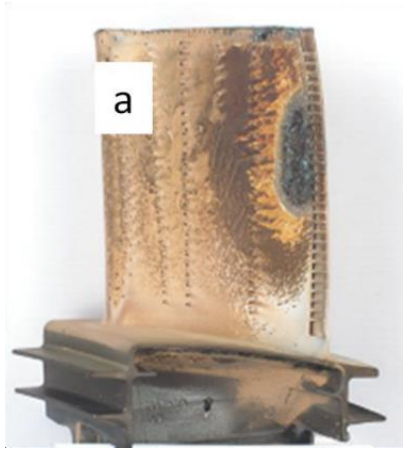
Introduction and Motivation – T/EBC Degradation by Particulate Ingestion

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



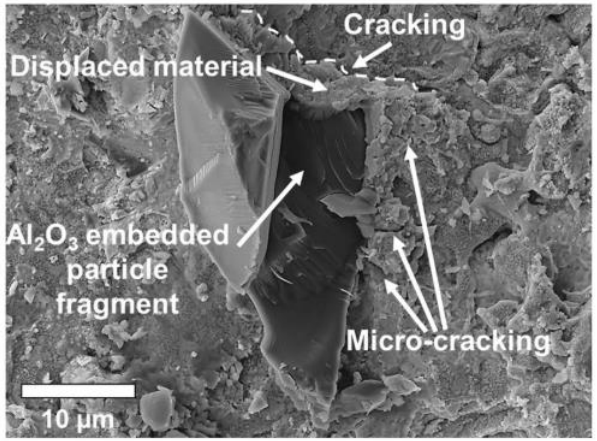
Eyjafjallajökull volcano eruption in Iceland (2010)

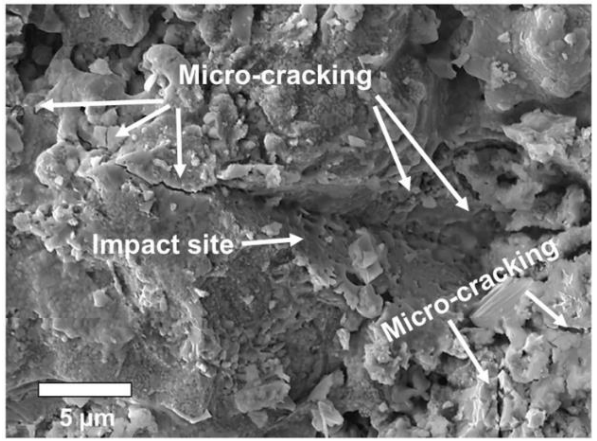


Damage on a turbine blade caused by CMAS >1200°C

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)

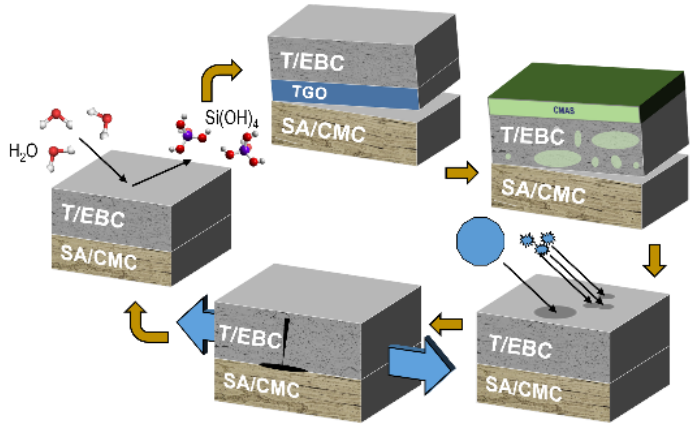
Presby et al., *Coatings* **13** (2023)

Introduction and Motivation – T/EBC Degradation by Particulate Ingestion

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- Particulates (i.e. sand, volcanic ash) ingested by engine melt into **C**alcium **M**agnesium **A**lumino **S**ilicate **(CMAS)** deposits
- Molten CMAS deg
  - CMAS infiltratio elevated temper
  - Thermochemica

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

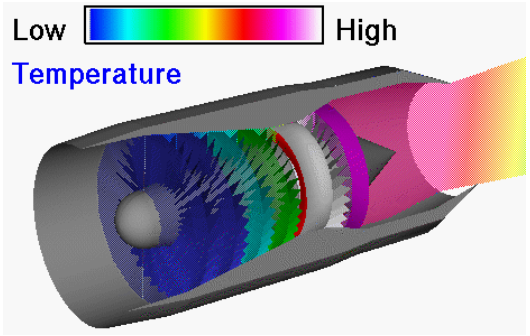


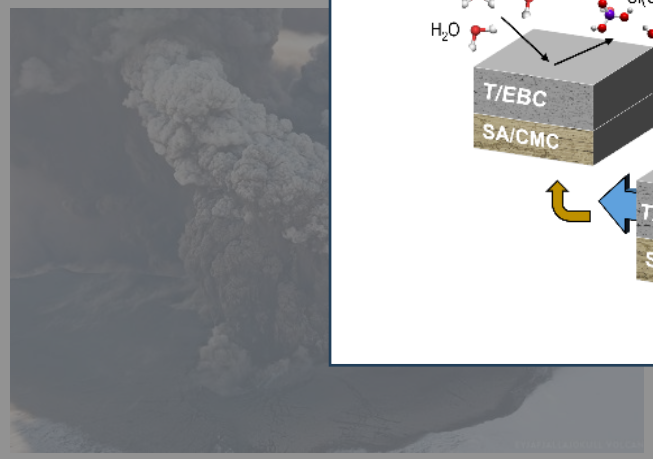
Solid Particle Erosion

ingested by engine
higher temperatures

esponse of T/EBCs at

Laboratory scale testing in relevant environments





Eyjafjallajökull volcano eruption in Iceland (2010)

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

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

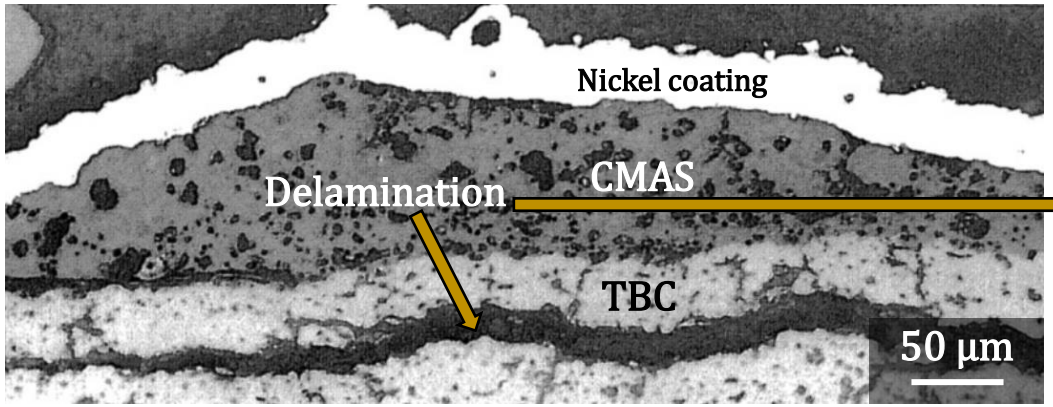
Presby et al., *Coatings* **13** (2023)

Mechanisms of Degradation

Burner Rig Testing of 7YSZ: Comparison to Furnace Tests and In-Service Components

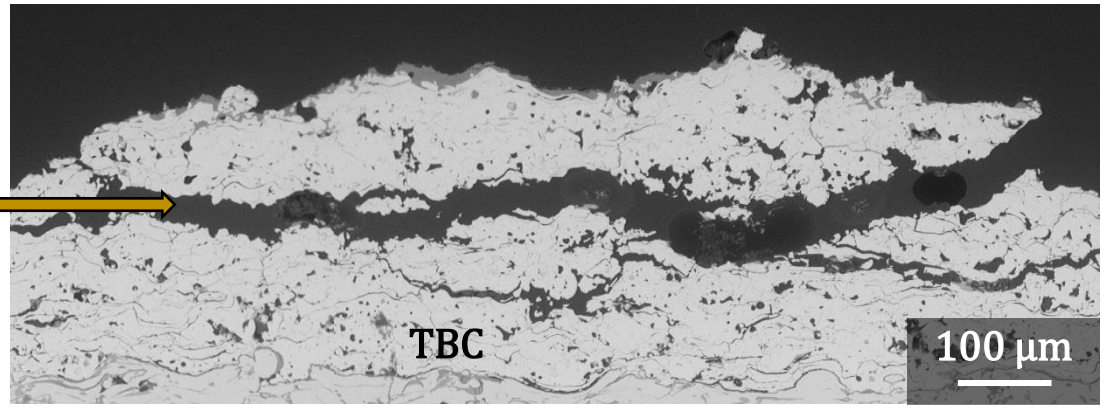
- In static furnace testing, CMAS is observed to completely infiltrate YSZ coatings
- Limited CMAS infiltration was observed in burner rig testing in remaining coating
- Thermal gradient and thermal cycling cause progressive exfoliation of layers of YSZ upon cooling

In Service Component



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

Burner Rig

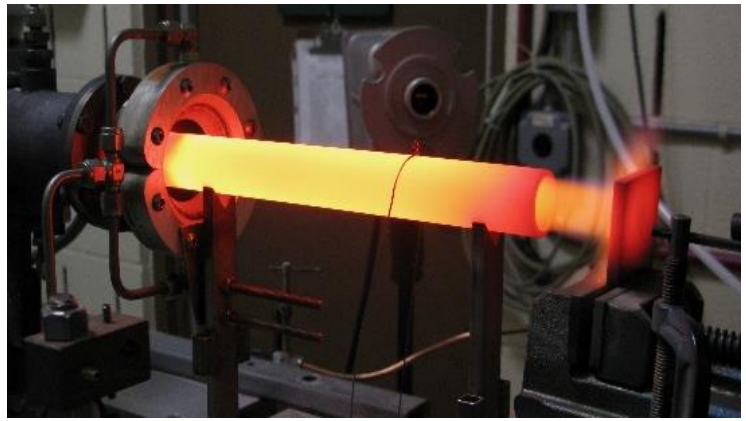


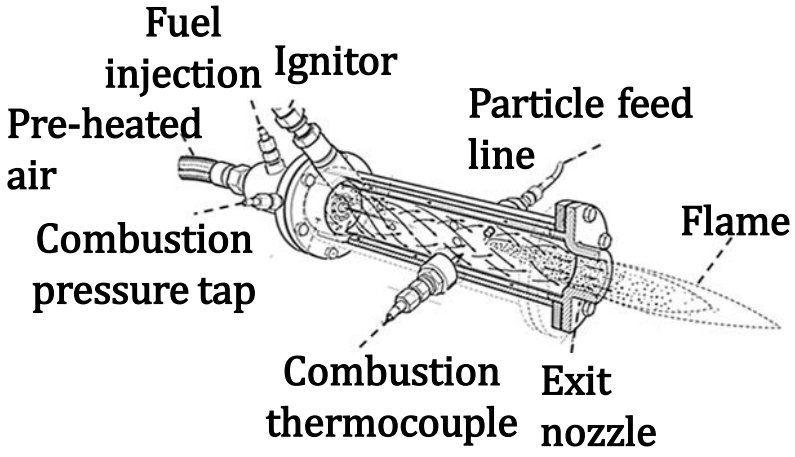
Stokes and Presby, *J. Eng. Gas Turbines and Power* **146** (11): 111006-1 (2024)

How do SOA EBCs degrade in a combustion environment?

Experimental Procedures

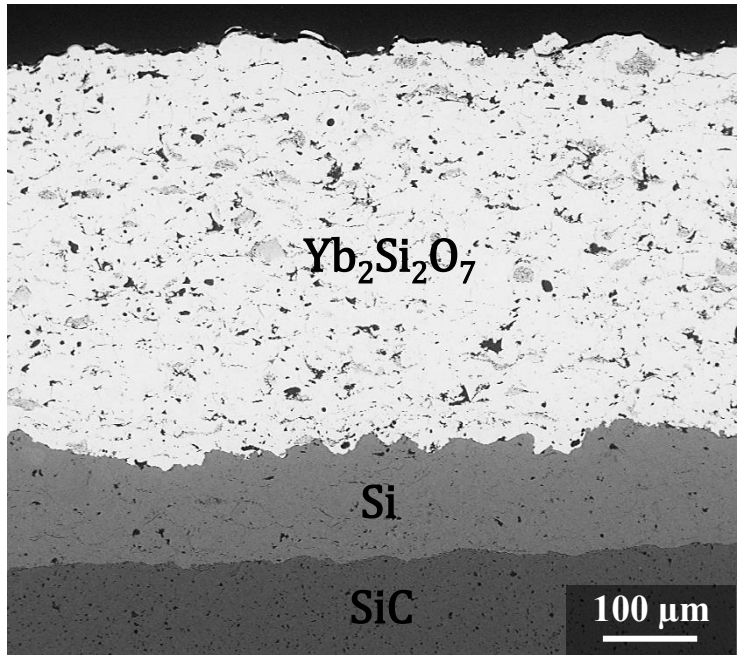
NASA Glenn Erosion Burner Rig Facility





D.S. Fox et al., NASA/TM- 2011216986 (2011)

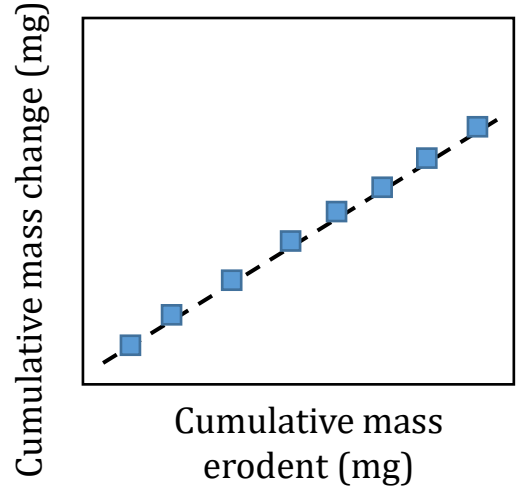
Ytterbium Disilicate $Yb_2Si_2O_7$ EBC



Particle Characteristics

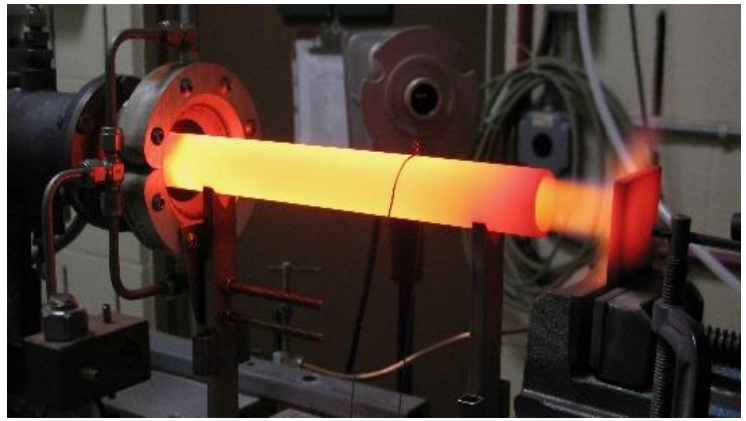
Avg. Particle Size (µm)	43	86	168
Flame Temperature (°C)	650	950	1300

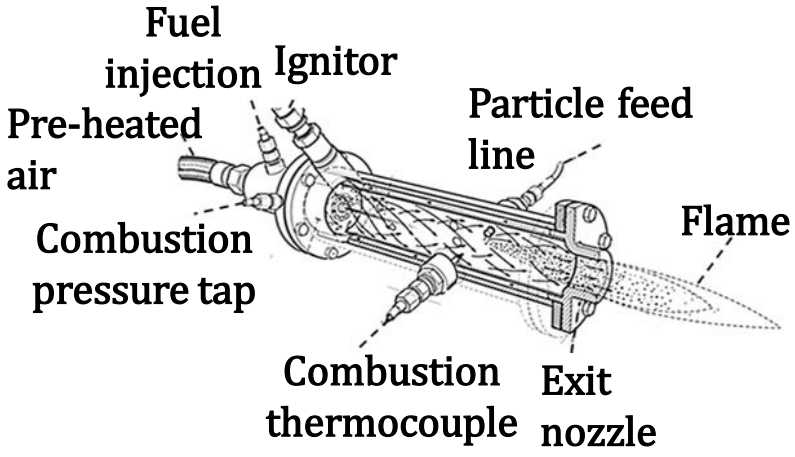
- 30.67CaO–8.25MgO–12.81$AlO_{1.5}$–48.27SiO_2 (mol.%) glass frit
  - ~1240°C congruent melting behavior
  - ~1 mg/cm^2 loading per increment
- Phase 1 Tests:
  - Effect of particle size, test temperature and deposition rate on erosion/corrosion mechanisms
  - 10 increments of deposition per test



Experimental Procedures

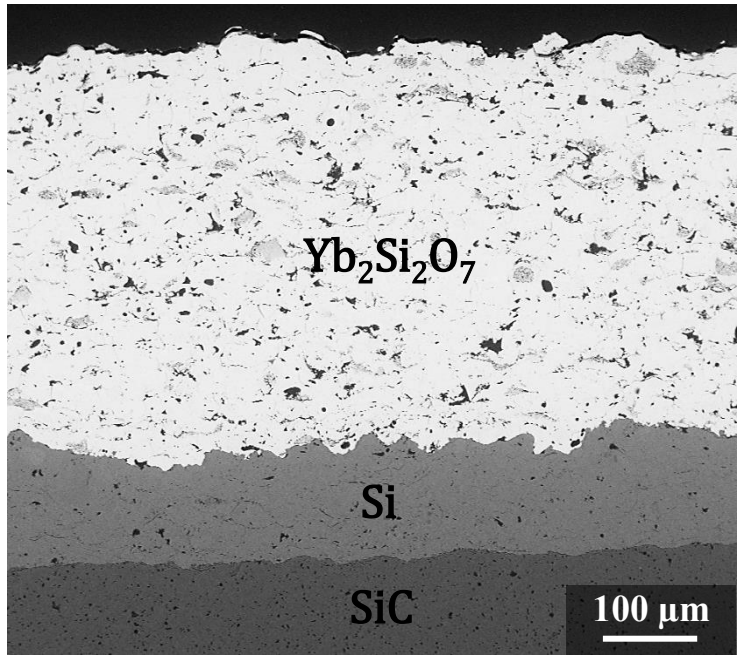
NASA Glenn Erosion Burner Rig Facility





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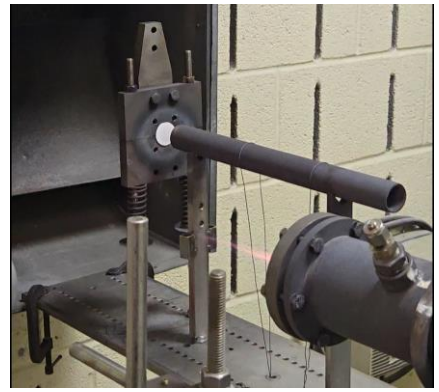
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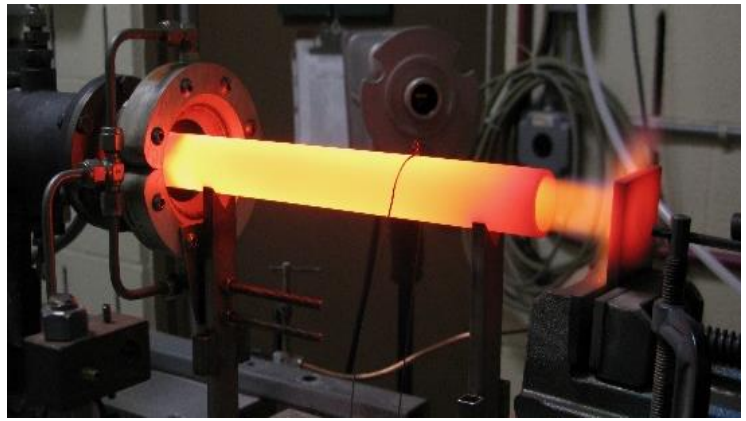
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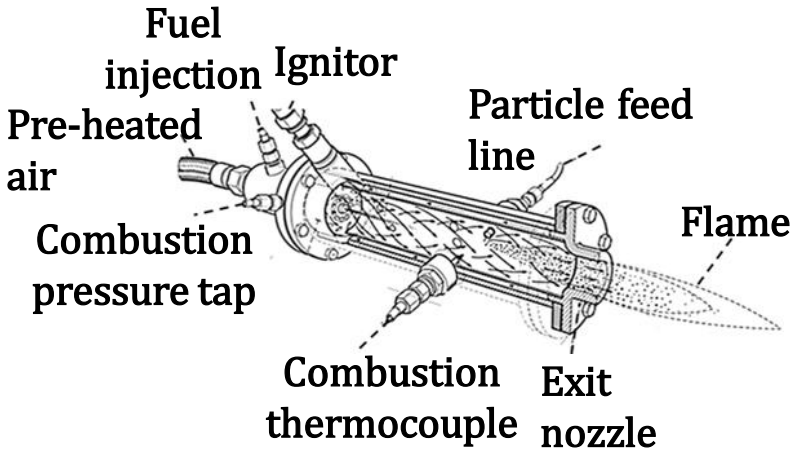
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  - ~1240°C congruent melting behavior
  - ~1 mg/cm^2 loading per increment
- Phase 2 Tests:
  - Effect of thermal cycling on coating durability under 43 µm CMAS deposition at 1300°C
  - First reported study on the evaluation of a YbDS EBC under CMAS degradation in a combustion environment



Experimental Procedures

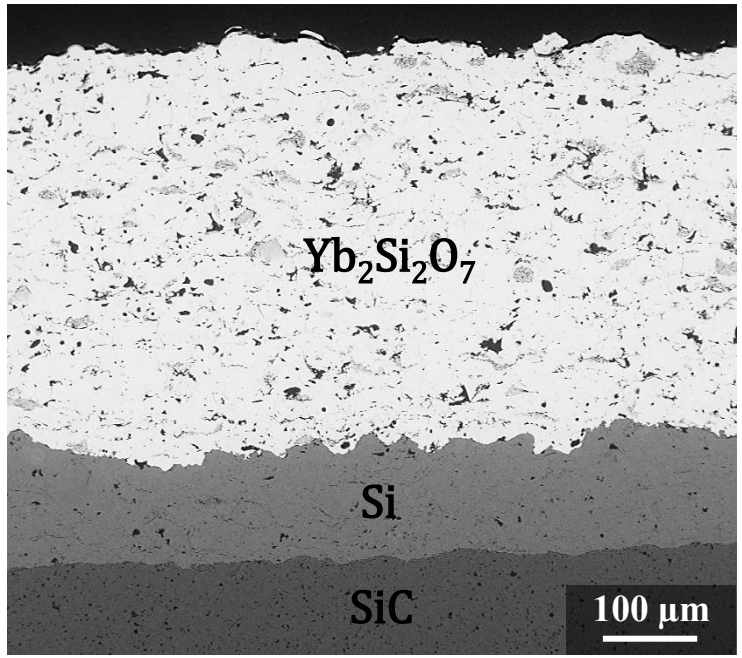
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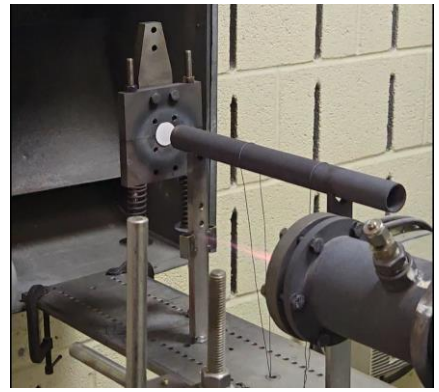
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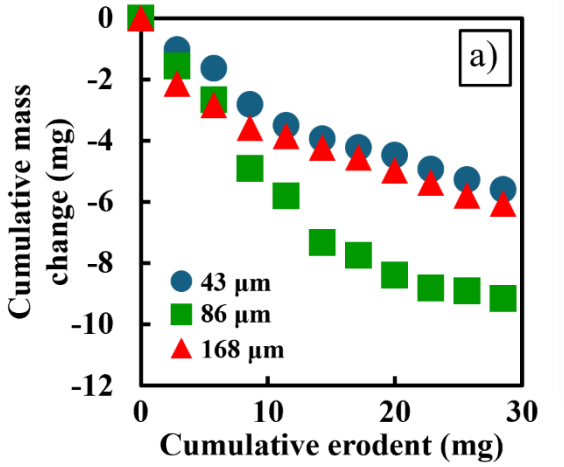
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  - ~1240°C congruent melting behavior
  - ~1 mg/cm^2 loading per increment
- Phase 3:
  - Assessment of literature studies on CMAS testing of YbDS and comparison of dynamic to static results.
  - Framed within previous estimations of proposed damage and engine failure for dust concentrations in flight.



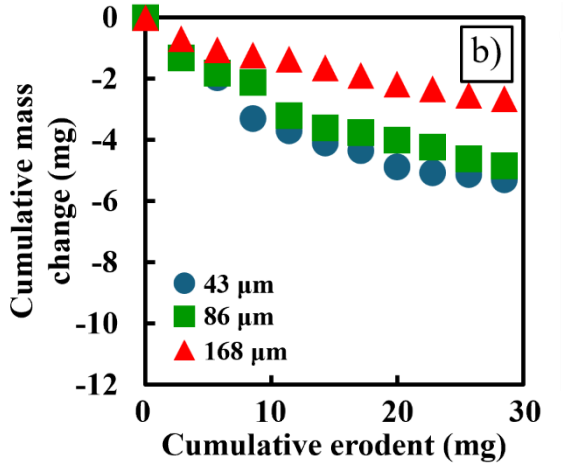
Phase 1: Effects of Temperature, Particle Size, and Deposition Rate

Mass Change Analysis

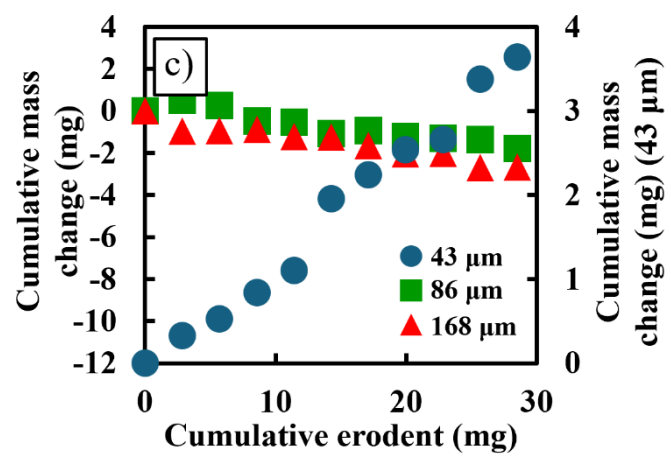
Erosion-dominated
650°C



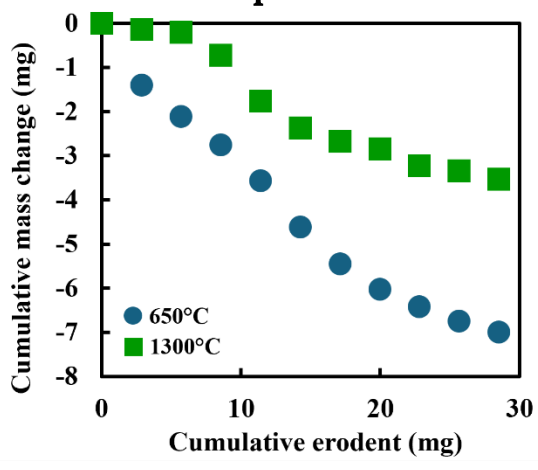
Erosion-dominated
950°C



Erosion+Corrosion
1300°C



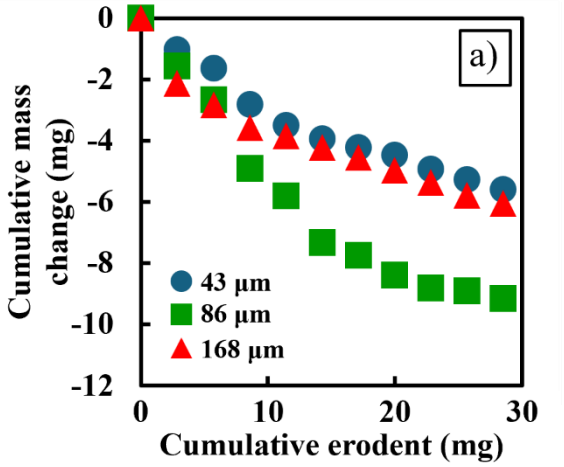
Erosion-dominated
Al_2O_3 60 µm Deposition



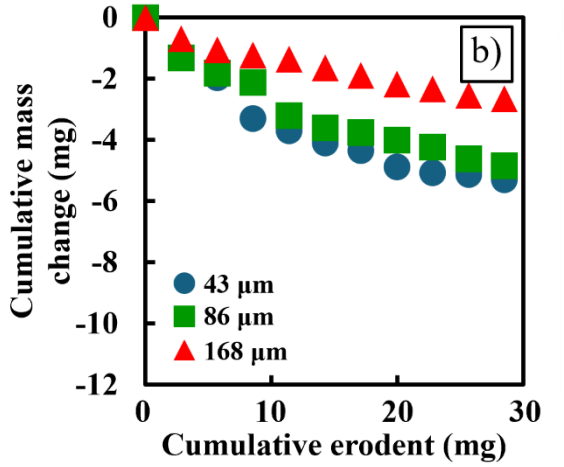
- At both 650 and 950°C, mass loss was observed during CMAS deposition, indicating that erosion of the coating was occurring.
- Mass loss did not trend with particle size, although a slight effect of temperature was observed

Mass Change Analysis

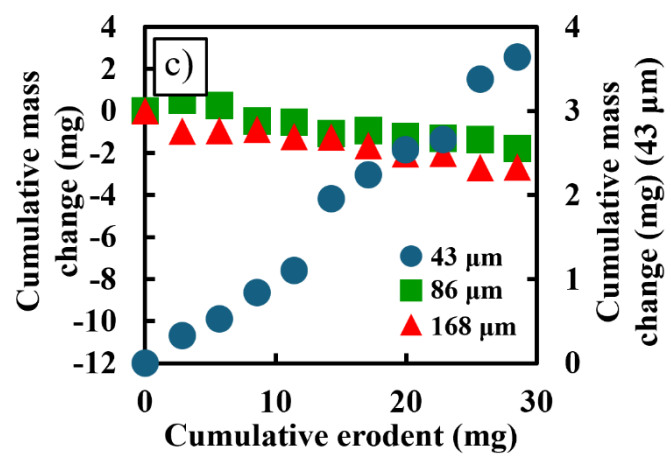
Erosion-dominated
650°C



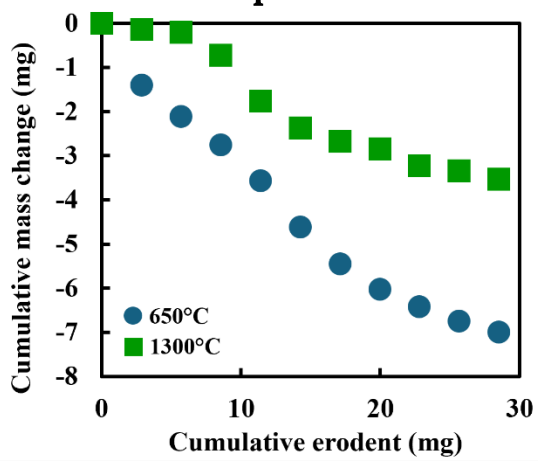
Erosion-dominated
950°C



Erosion+Corrosion
1300°C



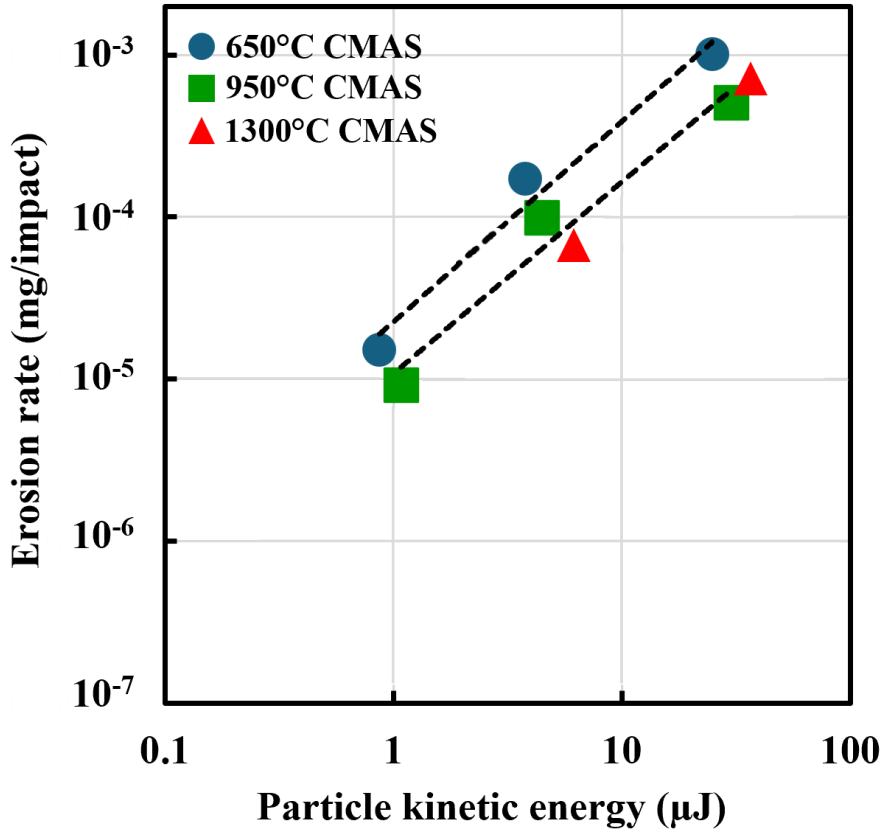
Erosion-dominated
Al_2O_3 60 µm Deposition



$$E\left[\frac{mg}{mg}\right] = \frac{m_L}{m_E} \Rightarrow E\left[\frac{mg}{impact}\right] = \frac{m_L}{m_E} m_p \Rightarrow E\left[\frac{mg}{impact}\right] = \gamma U_k^b$$

Erosion Rate vs Particle Kinetic Energy

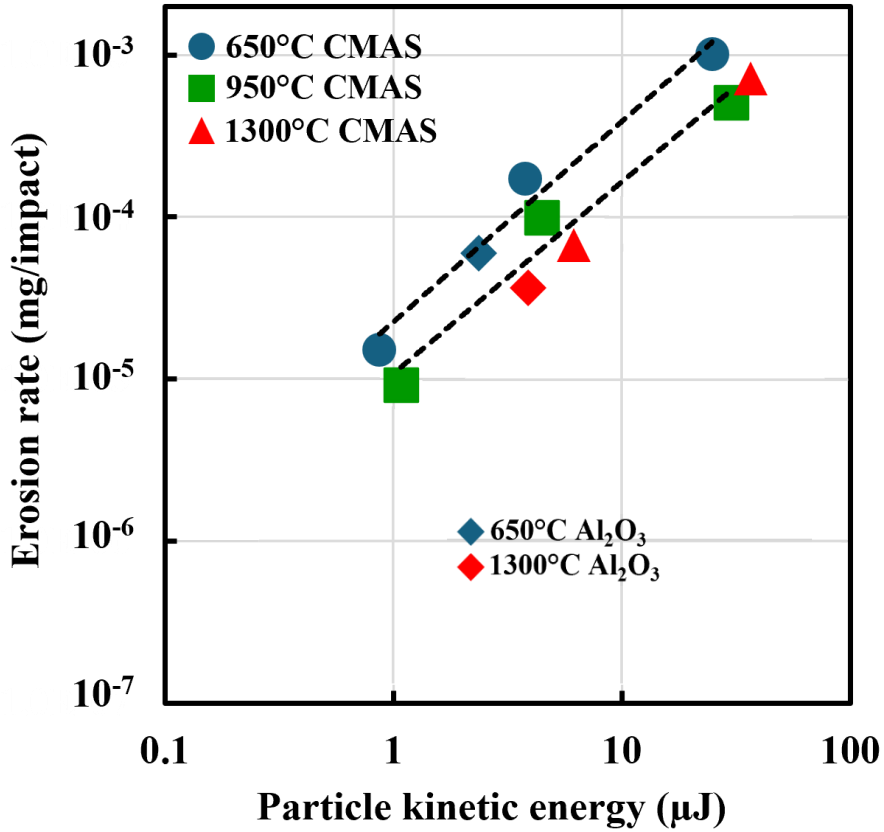
- CMAS erosion results at 650°C and 950°C show very good agreement with kinetic energy model
- CMAS-based erosion behavior has strong temperature dependence



$$E\left[\frac{mg}{impact}\right] = \gamma U_k^b$$

Erosion Rate vs Particle Kinetic Energy

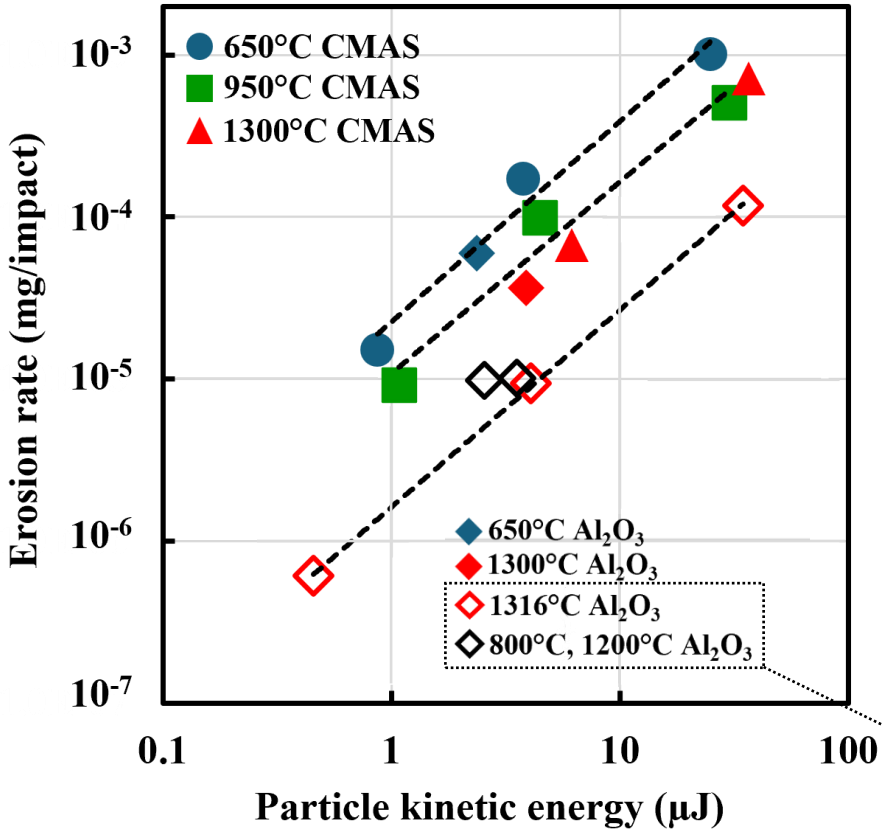
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  - Al_2O_3 at same deposition rate displayed similar temperature dependence



$$E\left[\frac{mg}{impact}\right] = \gamma U_k^b$$

Erosion Rate vs Particle Kinetic Energy

- CMAS erosion results at 650°C and 950°C show very good agreement with kinetic energy model
- CMAS-based erosion behavior has strong temperature dependence
  - Al_2O_3 at same deposition rate displayed similar temperature dependence
- Previous data on APS YbDS roughly an order of magnitude lower
  - Influence of particle flux should be considered when evaluating coating materials.



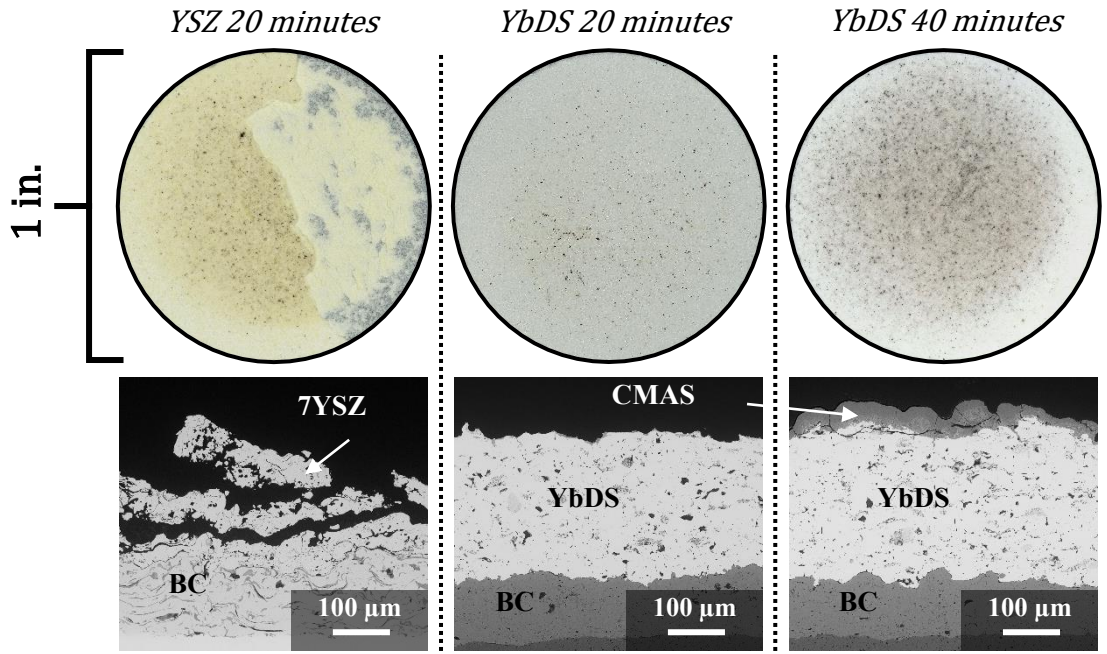
$$E\left[\frac{mg}{impact}\right] = \gamma U_k^b$$

Presby et al. *Coatings*, **13**(5), p. 902. doi:10.3390/coatings13050902

Phase 2: Effects of Cycling Deposition and Thermal Gradient on Degradation

Scanning Electron Microscopy of Cross-Sectional Morphology

- Initial samples were cycled for 20 minutes (10 minutes of total hot time); an additional YbDS sample was cycled for 40 minutes (20 minutes of total hot time)
- SOA 7YSZ was also tested for comparison

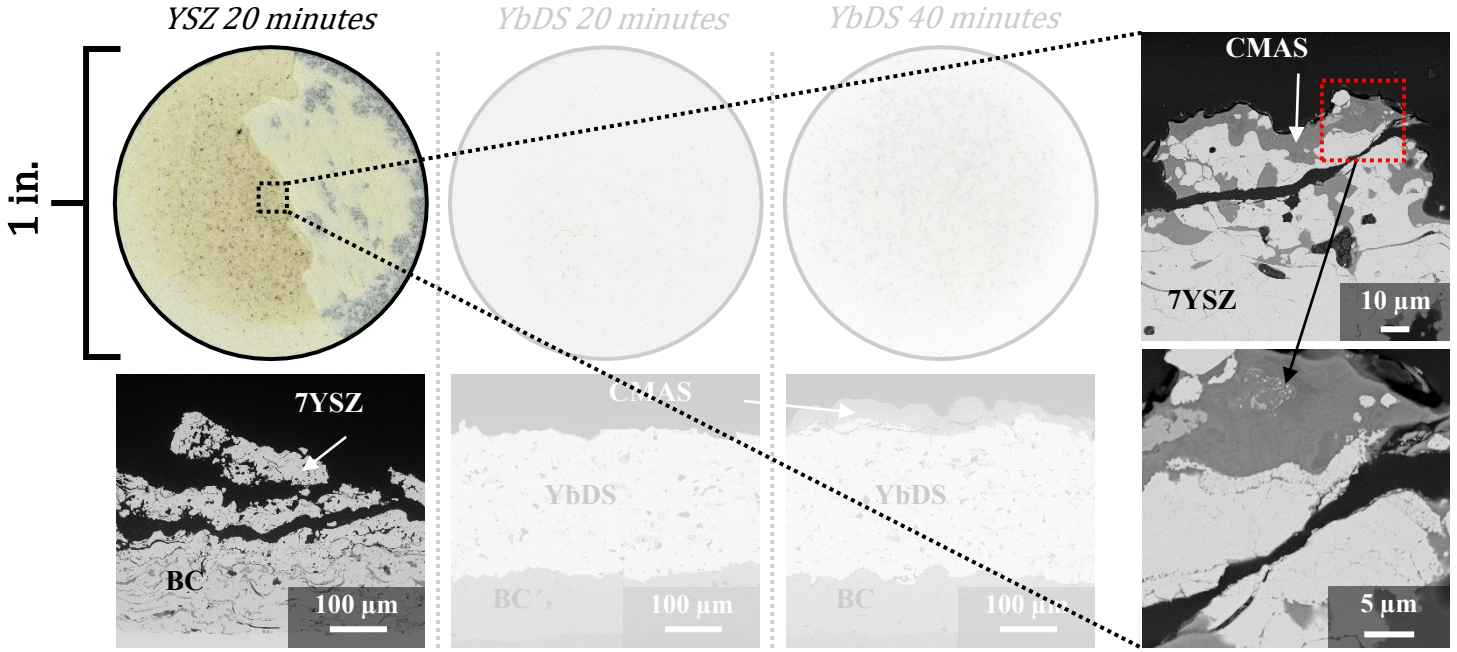


- Large portions of the 7YSZ coating spalled off during the 20-minute test.
- YbDS sample remained intact and no large changes in the coating were readily observed
- The YbDS sample cycled for 40 minutes also remained intact, and the largest change observed was the presence of a distinct CMAS layer adhered to the surface.

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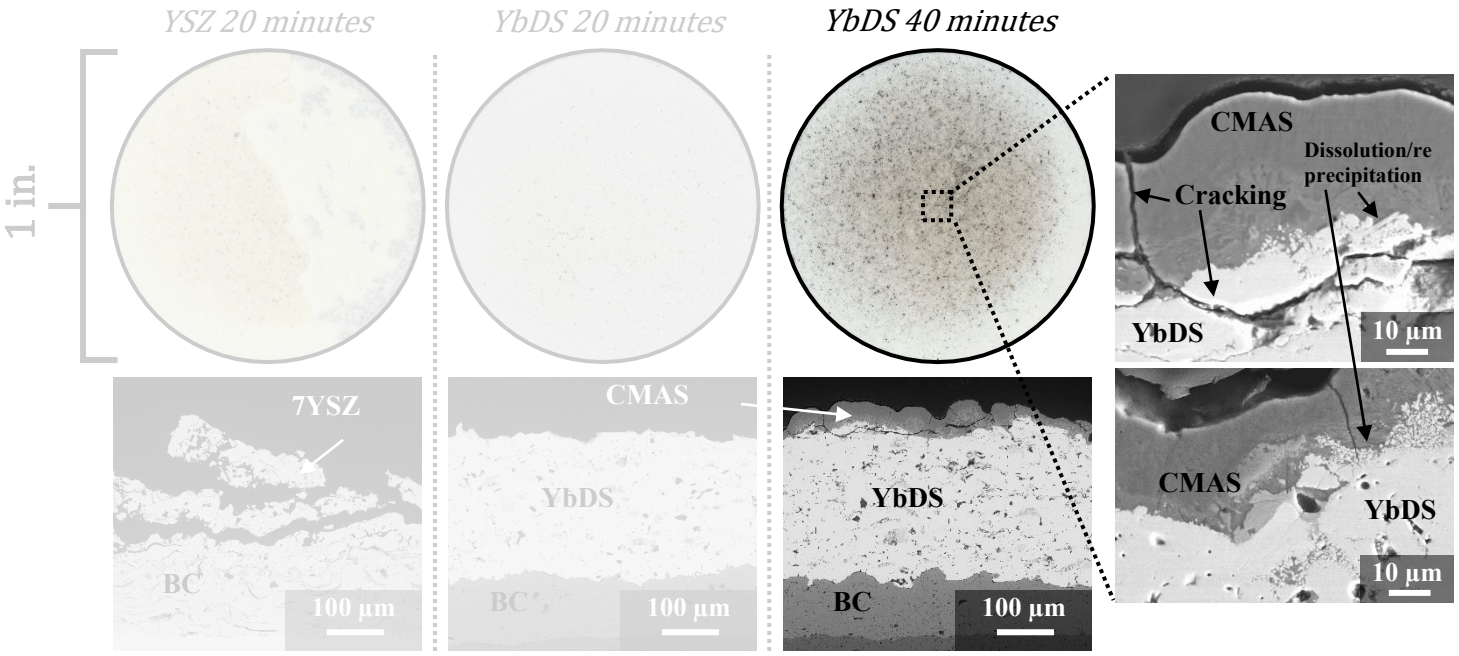


- Additional cracks were observed at the surface with several pockets of residual CMAS
- CMAS infiltration between the lamellar splats, as well as presence of globular precipitates and CMAS films between grain boundaries

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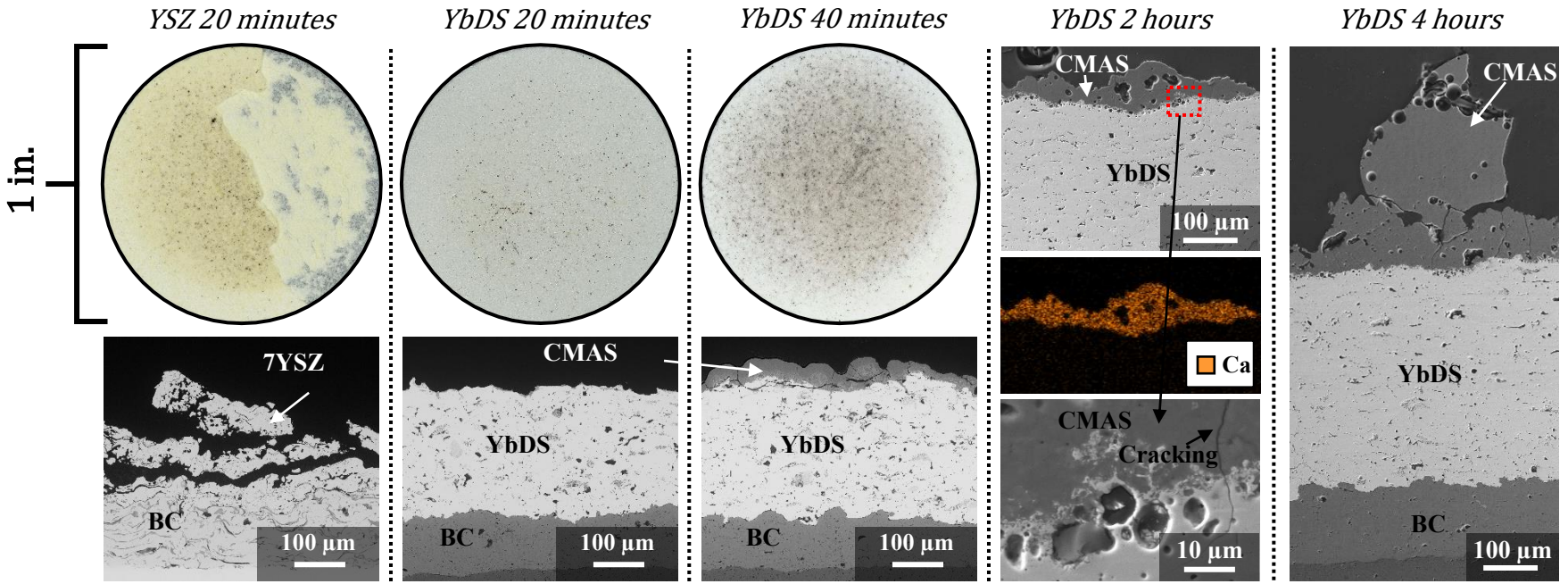


- Large cracks formed within the CMAS layer, extending partially into coating in contact with molten deposit
- Corrosion was primarily limited to the surface and only extended ~10 µm into the coating

Phase 2: Effects of Cycling Deposition and Thermal Gradient on Degradation

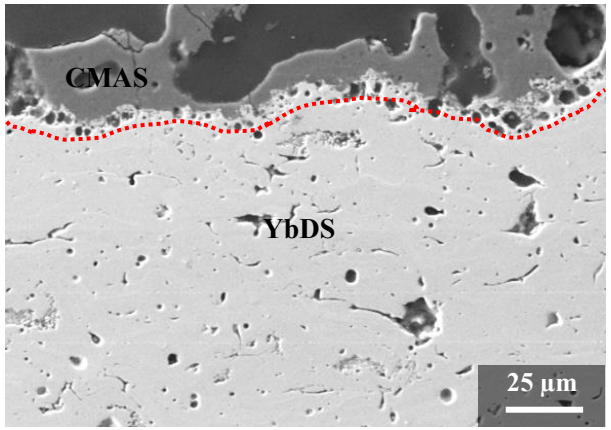
Scanning Electron Microscopy of Cross-Sectional Morphology

- Initial samples were cycled for 20 minutes (10 minutes of total hot time); an additional YbDS sample was cycled for 40 minutes (20 minutes of total hot time)
- SOA 7YSZ was also tested for comparison

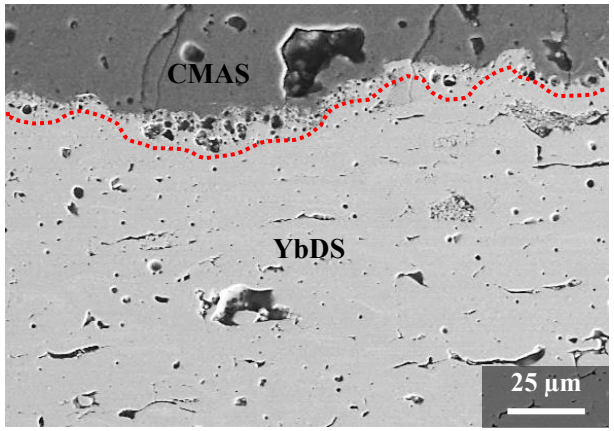


Scanning Electron Microscopy of Cross-Sectional Morphology

YbDS 2 hours



YbDS 4 hours

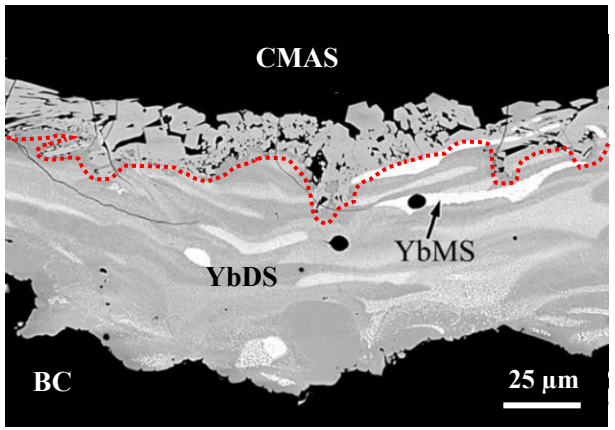


- Limited degradation of the YbDS coating from CMAS deposition was observed in this study

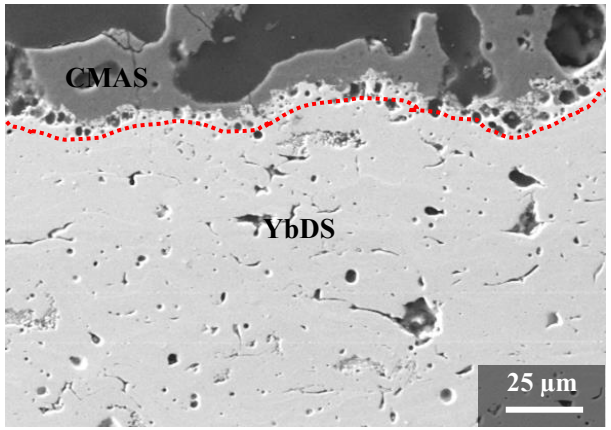
Phase 3: Comparisons to Static Tests and Damage Regimes for Flight Hardware

Scanning Electron Microscopy of Cross-Sectional Morphology

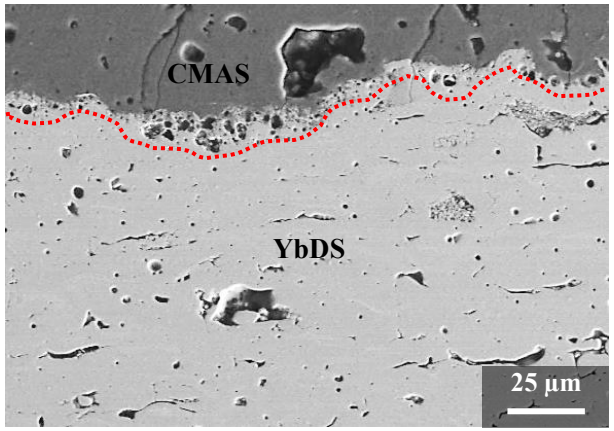
YbDS, static hold, ~10 mg/cm², 1 hour (Zhao et al.)



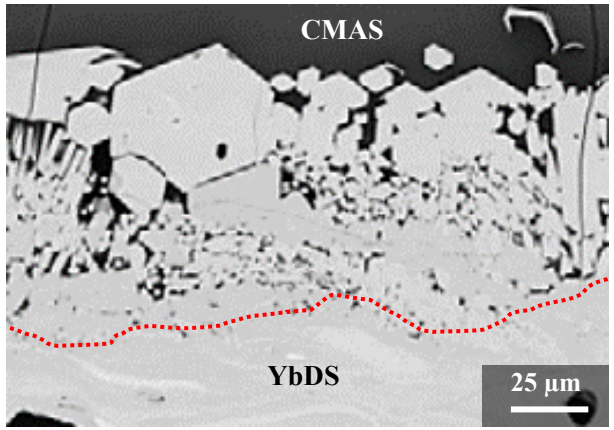
YbDS 2 hours



YbDS 4 hours



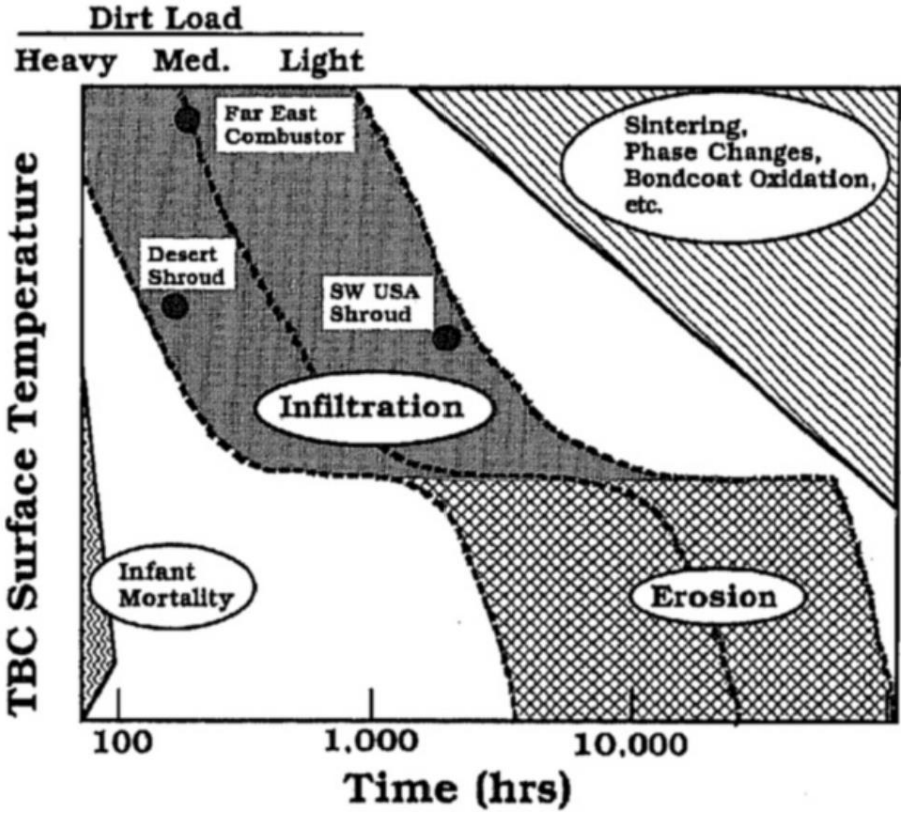
YbDS, static hold, ~10 mg/cm², 100 hours (Zhao et al.)



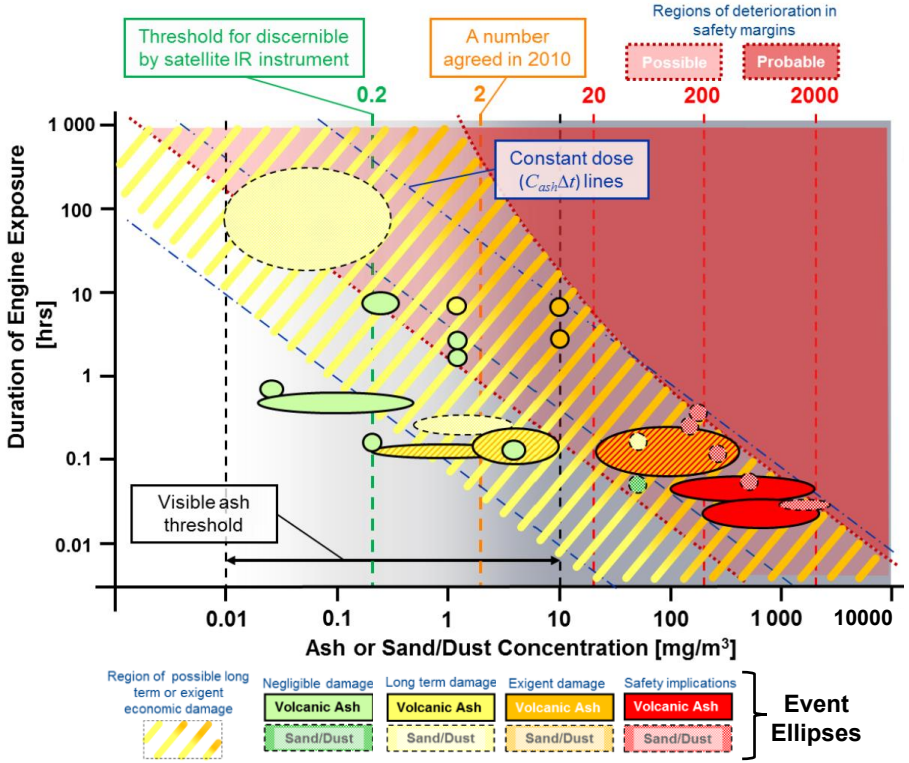
- In study from *Zhao et al.* on APS YbDS coatings, immense phase formation, infiltration, and cracking was observed in static testing (furnace heat treatment) with a similar CMAS composition
  - At 1 hour, there was a ~25 µm thick reaction layer in a 100 µm coating

Zhao et al. , *Surface and Coatings Technology* **288** pp 151-162(2016)

Hypothetical Damage Regimes for Flight Hardware



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



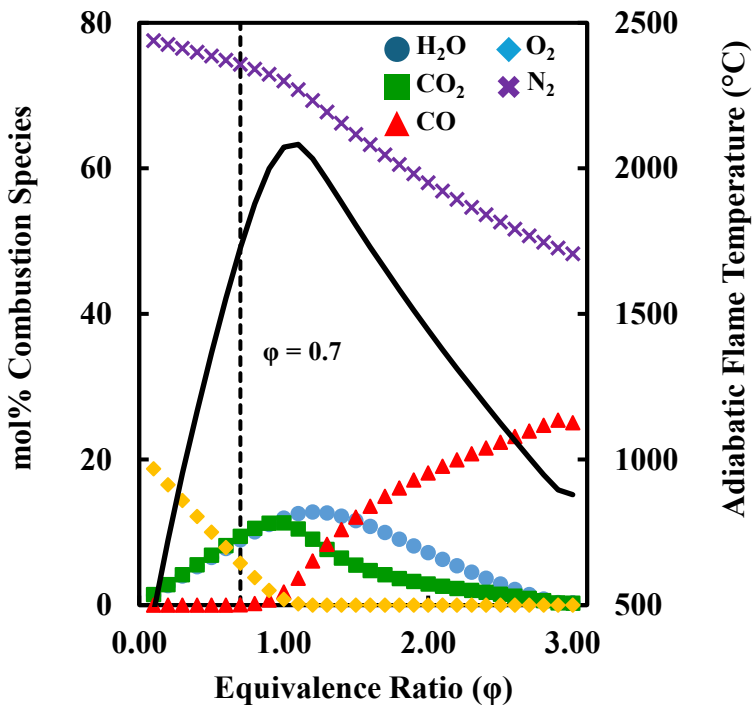
Clarkson et al., *NATO STO-MP-AVT-272-20* (2017)

Combustion Analysis and Estimation of Dust Concentration

- NASA Chemical Equilibrium with Applications (CEA) to determine equivalence ratio (φ) ratio of specific heats (γ), and sonic velocity to calculate Mach number of gas

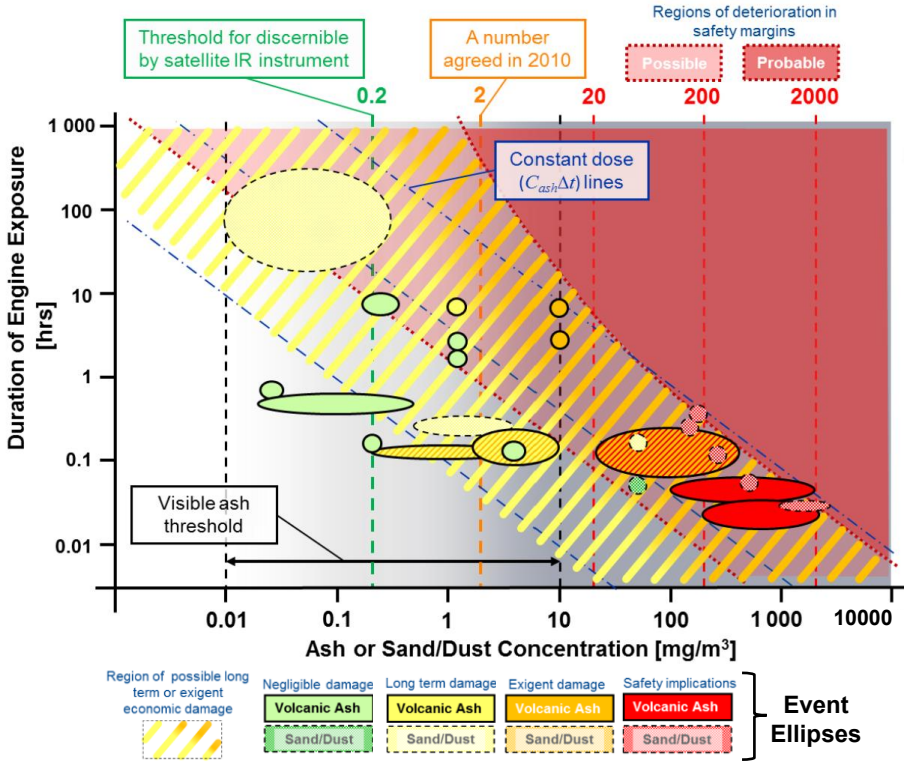
$$M = \sqrt{\left(\frac{2}{\gamma - 1}\right)\left[\left(\frac{P_b}{p_e}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

- Good agreement with higher fidelity CFD modeling (Kuczmarski et al. 2011)
- Volumetric gas flow ~0.11 m^3/s
- Particle concentration ~0.55 mg/m^3



Phase 3: Comparisons to Static Tests and Damage Regimes for Flight Hardware

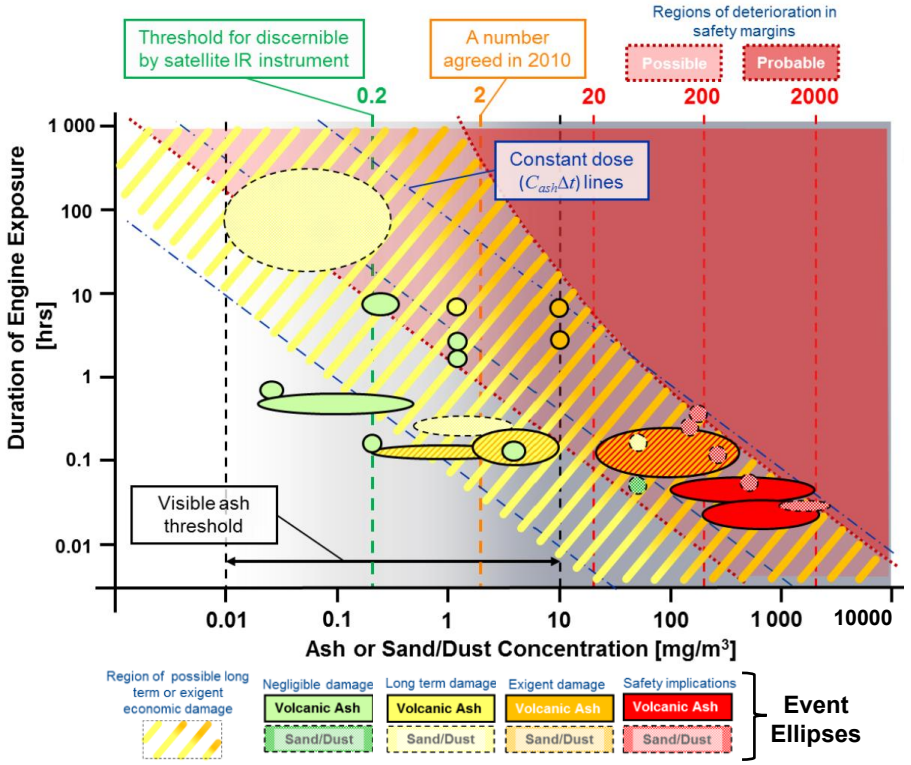
Graphing within DEvAC Chart

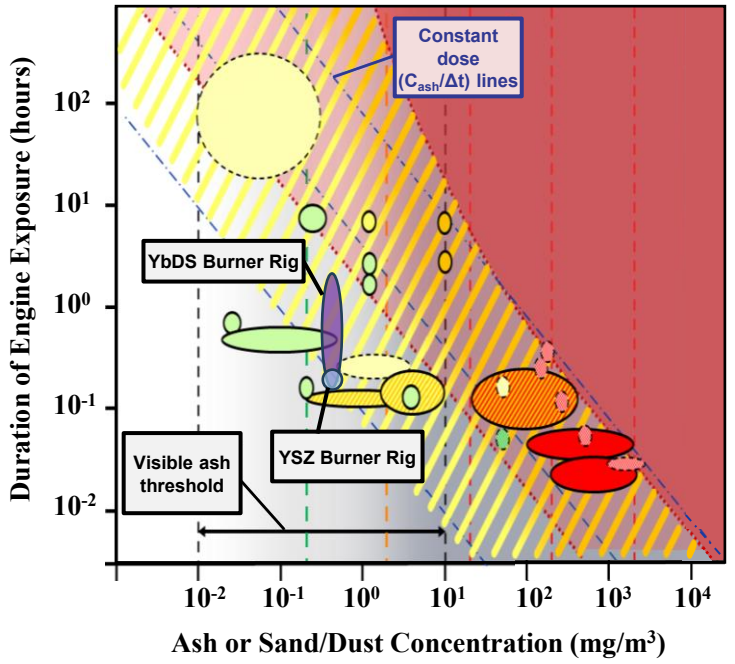


Clarkson et al., *NATO STO-MP-AVT-272-20* (2017)

Phase 3: Comparisons to Static Tests and Damage Regimes for Flight Hardware

Graphing within DEvAC Chart



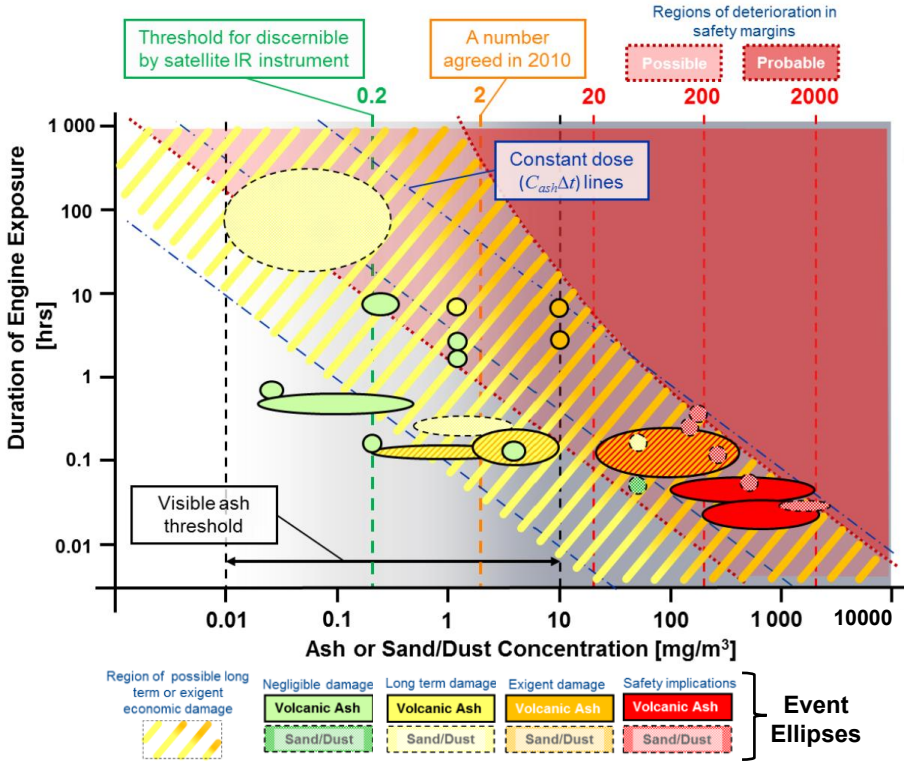


- Overall, implication of "long-term damage" agrees well with observations of coating behavior during burner rig testing.

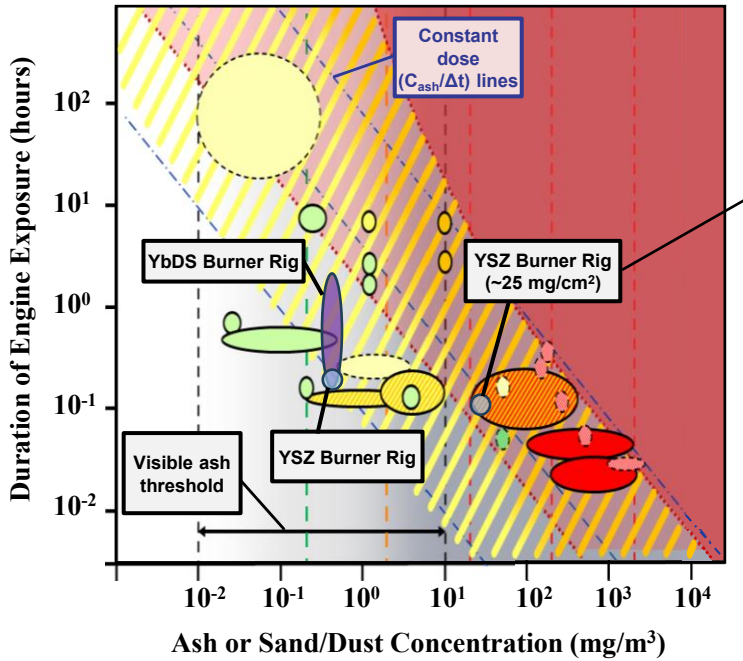
Clarkson et al., *NATO STO-MP-AVT-272-20* (2017)

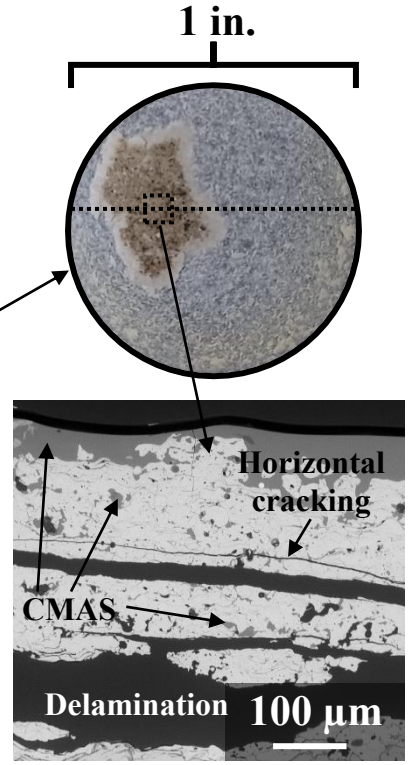
Phase 3: Comparisons to Static Tests and Damage Regimes for Flight Hardware

Graphing within DEvAC Chart



Clarkson et al., *NATO STO-MP-AVT-272-20* (2017)

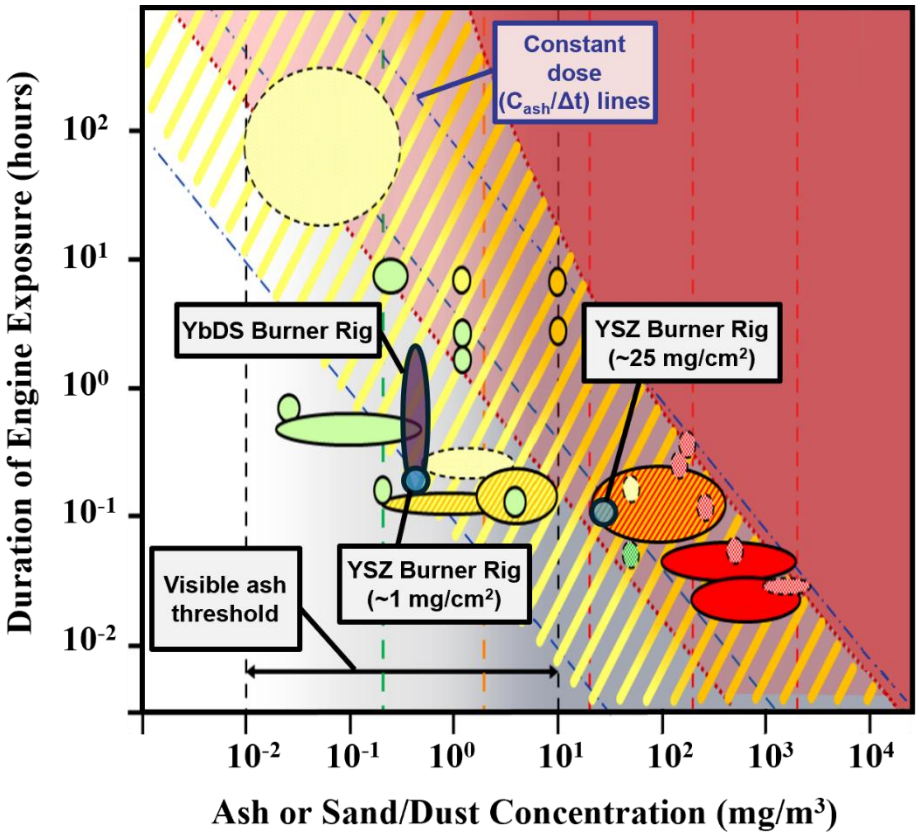


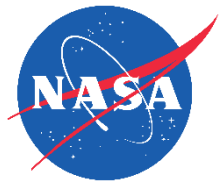


- Additional 7YSZ sample tested at ~19 mg/m^3 exhibited catastrophic failure and agreed well with "exigent" damage regime

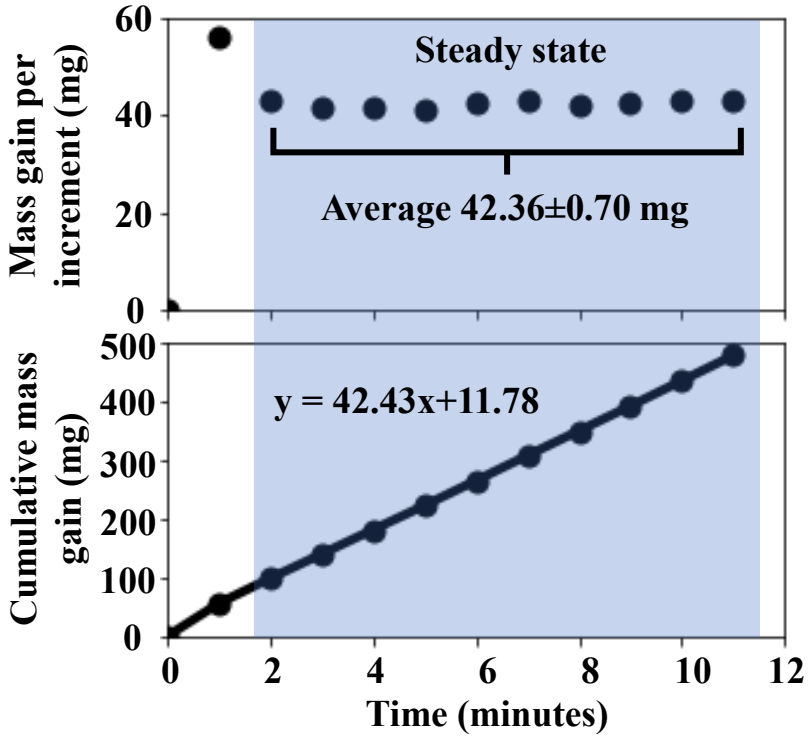
Summary

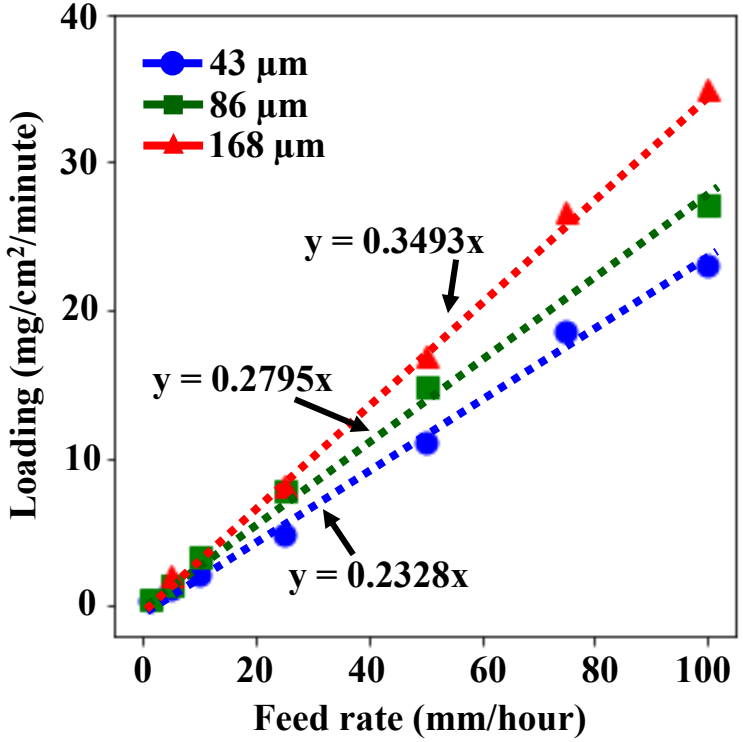
- A SOA ytterbium disilicate (YbDS) EBC was tested to determine the relationship between particle erosion and corrosion, as well as the effects of thermal cycling and gradient on damage propagation.
- Regarding erosion mechanisms, the influence of test temperature was exacerbated when testing with lower particle fluxes.
- YbDS does undergo dissolution and reprecipitation, albeit at much slower rates than previously expected from static exposures in literature.
- YbDS was more robust against particle corrosion compared to a SOA 7YSZ TBC, and the presented results were compared to hypothetical service regimes.
- Overall, this study contributes to ongoing understanding on improving future coating systems against particle degradation and improving testing methods.





Thank You!





Particle Size	Feed rate (mm/hr)	Loading (mg/cm²/min)	Time per increment (sec) to equal 1 mg/cm² deposition
43 µm	5	1.185	~51
86 µm	5	1.534	~39
168 µm	5	2.414	~25