Advanced Ceramics for NASA's Current and Future Needs

Ceramic composites and monolithics are widely recognized by NASA as enabling materials for a variety of aerospace applications. Compared to traditional materials, ceramic materials offer higher specific strength which can enable lighter weight vehicle and engine concepts, increased payloads, and increased operational margins. Additionally, the higher temperature capabilities of these materials allows for increased operating temperatures within the engine and on the vehicle surfaces which can lead to improved engine efficiency and vehicle performance. To meet the requirements of the next generation of both rocket and air-breathing engines, NASA is actively pursuing the development and maturation of a variety of ceramic materials. Anticipated applications for carbide, nitride and oxide-based ceramics will be presented. The current status of these materials and needs for future goals will be outlined. NASA also understands the importance of teaming with other government agencies and industry to optimize these materials and advance them to the level of maturation needed for eventual vehicle and engine demonstrations. A number of successful partnering efforts with NASA and industry will be highlighted.

Advanced Ceramics for NASA's Current and Future Needs

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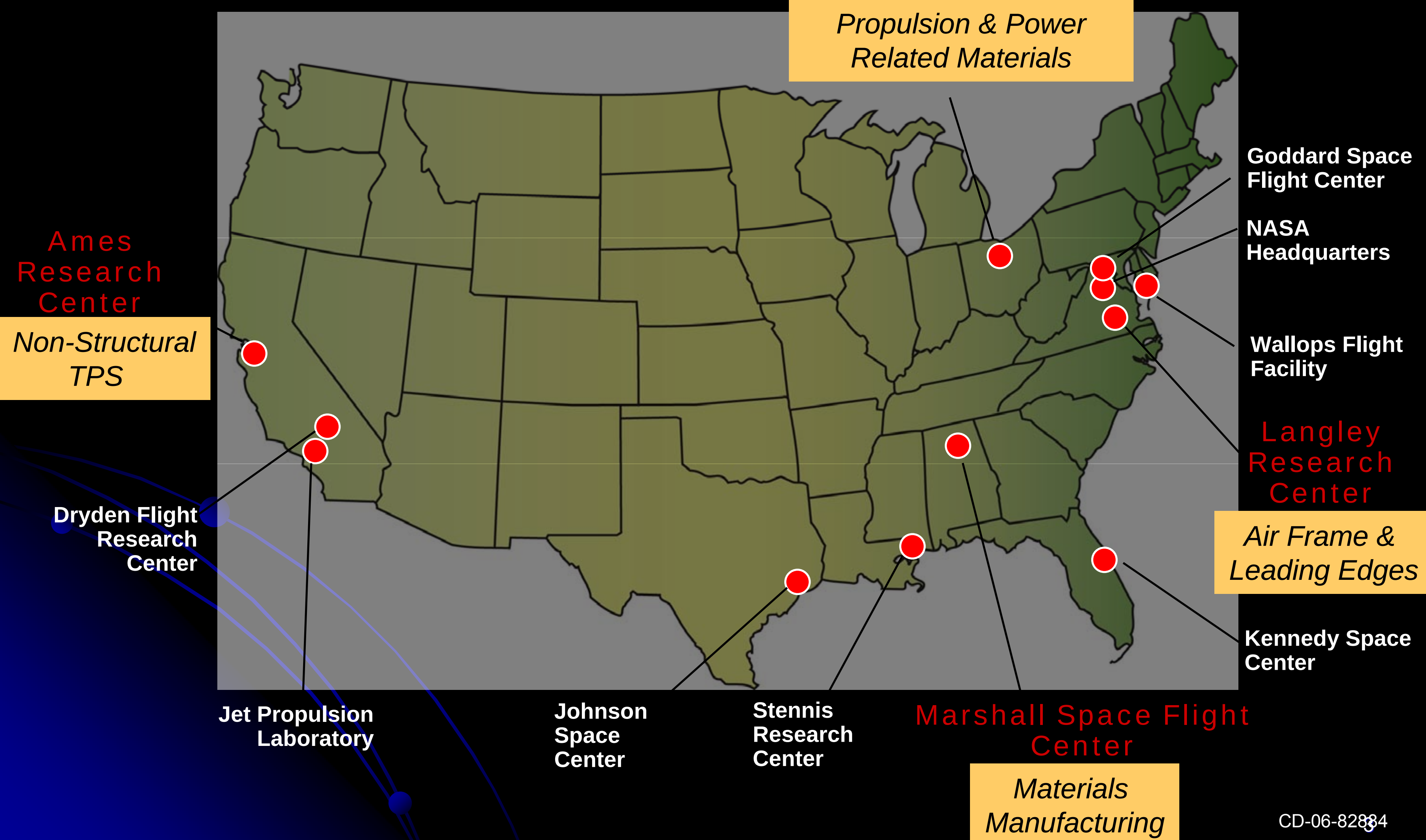
Tecnargilla 2006
Rimini, Italy

Outline

- NASA Centers and their Core Materials Technologies
- NASA Missions and Materials Research Focus Areas
- Materials Applications in Aeronautics and Space
- Current Status of NASA's Ceramics Efforts
  Structural, Non-structural, Functional, Fuel Cells
- Where we are headed
  -Improvements needed to reach goals
  -Testing programs
- How do we get there?
  -Partnering/Teaming with Industry, Academia
  and other Government Agencies

NASA Installations



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Materials Research at NASA Glenn

- Research applies to Propulsion, Power, Nuclear, Hot Airframe composites

- Fundamental understanding of processing – nano to microstructure property relationships

- Broad spectrum of expertise
  - polymers, metals/alloys, ceramics
  - all of their composites, joining
  - long term durability, coatings
  - “built-in” reliability

- Integrated approach of materials compatibility and interactions

- Testing capabilities ranging from comprehensive materials properties evaluation to subscale component testing in representative thermal and chemical environments in engine tests

NASA Aeronautics Missions

Fundamental Aeronautics Program (FAP)

- NASA will conduct long-term, cutting-edge research in the core competencies of aeronautics in all flight regimes, producing knowledge/data/capabilities design tools that are applicable across a broad range of air vehicles.

- Four thrust areas
  - Hypersonics
  - Supersonics
  - Subsonics: Fixed Wing
  - Subsonics: Rotary Wing

Materials Research focused in Fundamental Aero

- **Materials needs recognized as common technical issues across all flight regimes**
- **Materials research will be approached in an integrated and coordinated manner.**

Aviation Safety Program (AvSP)

- NASA will build upon unique safety-related research capabilites

Airspace Systems Program (ASP)

- NASA will directly address the Air Traffic Management R&D needs of NGAT

Aeronautics Test Program

- NASA will protect and maintain our key research and test facilities

NASA Space Exploration Missions

Overall objectives:
- -Implement a sustained and affordable human and robotic program
- -Extend human presence across the solar system and beyond
- -Develop supporting innovative technologies, knowledge and infrastructures
- -Promote international and commercial participation

Advanced Capabilities
- - **Technology Development**
- - **Prometheus**
- - Robotic Lunar Exploration
- - Human Research

Constellation
- - **Crew Exploration Vehicle (CEV)**
- - **Crew / Cargo**
- - Launch Systems
- - Launch / Mission Systems
- - EVA
- - Exploration Comm & Nav
- - Advanced Systems

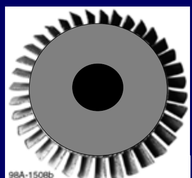
- Opportunities for Ceramics development within both key elements
- Aggressive schedule for space missions does not allow for time for basic materials research
- First unmanned CEV flight planned for early next decade
- Aggressive schedule demands rapid development and application of state-of-the-art technology

Ceramic Applications in Aero and Space Missions

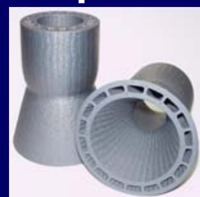
Structural Ceramics

Ceramic Matrix Composite Development

CMCs For Aero and Space Propulsion



CMC blade on metal disk



Cooled CMC structures

Hot Surface CMC/foams structures

Monolithic Ceramics

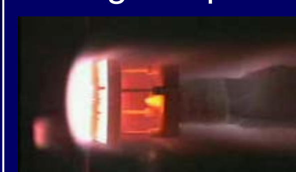
Cooled Si_3N_4 Vane

UHTCs

Ultra High Temperature CMCs for Leading Edges

Joining & Repair

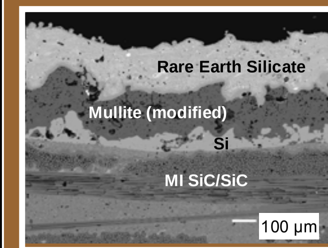
Shuttle Leading Edge Repair



Non-Structural Ceramics

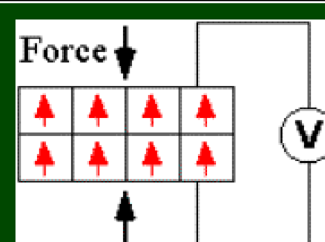
Ablatives

Coatings

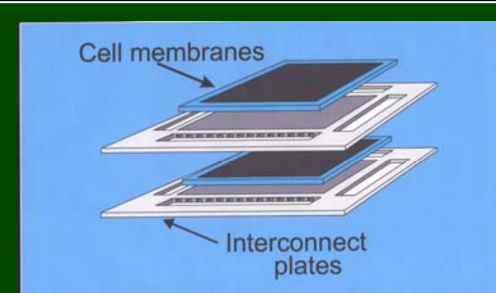


Functional Ceramics

Oxide Ceramics

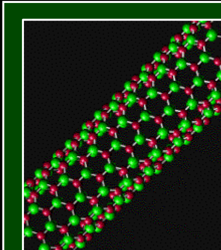


Piezoelectric Ceramics for Smart Components



Solid Oxide Fuel Cell

Nanotechnology



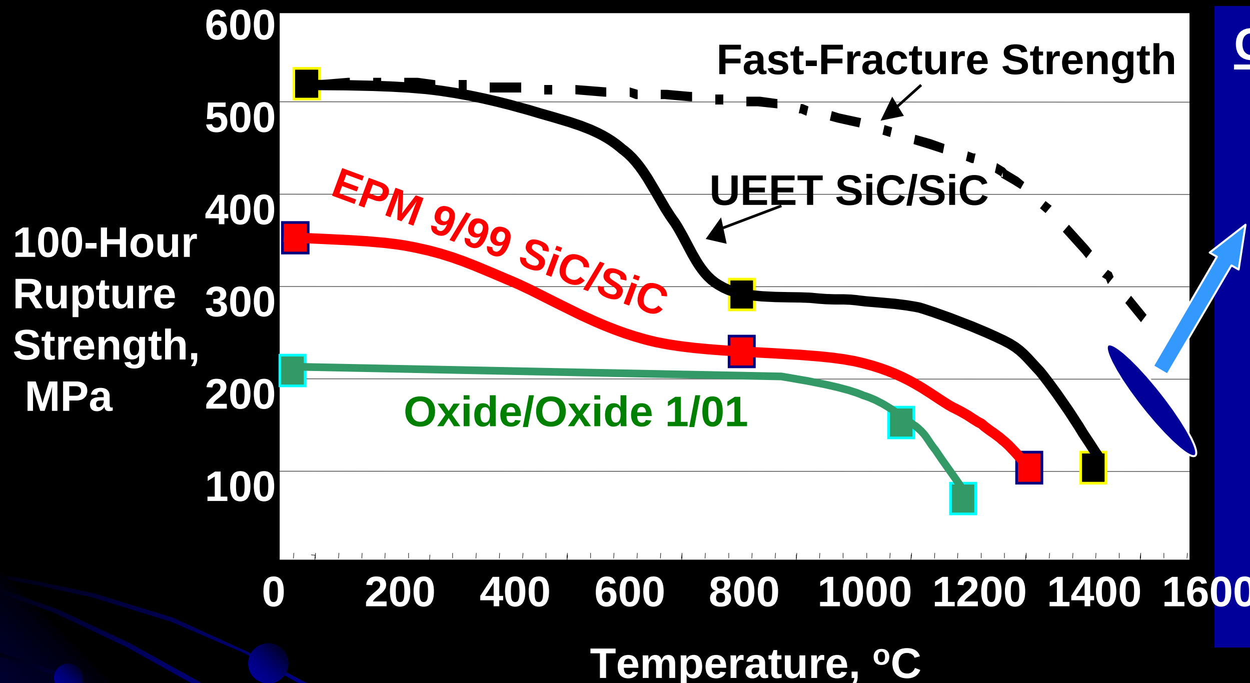
Nanotubes For H_2 Storage & Composite Reinforcement

Key Ceramic Properties for NASA Applications

- High Strength to Weight
- High Temperature / High Heat Flux Capabilities
- Durability
- Controlled Thermal Conductivity
- Reusability for Multi mission cycles
- Maintainability / Repairability
- Thermal Shock Resistance
- Reliability
- Manufacturability / Scalability
- High Emissivity
- Tailorable Electrical Properties

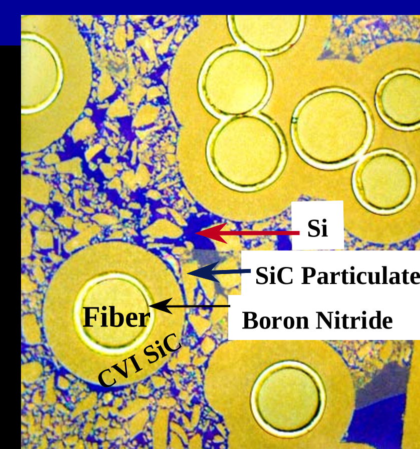
Advanced Materials and Processes Developed for High Temperature SiC/SiC Components

Properties of SiC/SiC CMC Improved Significantly in Various NASA Programs



Goals:

- Increasing temperature capability
- Increasing thermal conductivity for cooled structures
- Increasing matrix cracking stress for rotating components
- Increasing lifetime and durability



Melt Infiltrated (MI) SiC/SiC CMC

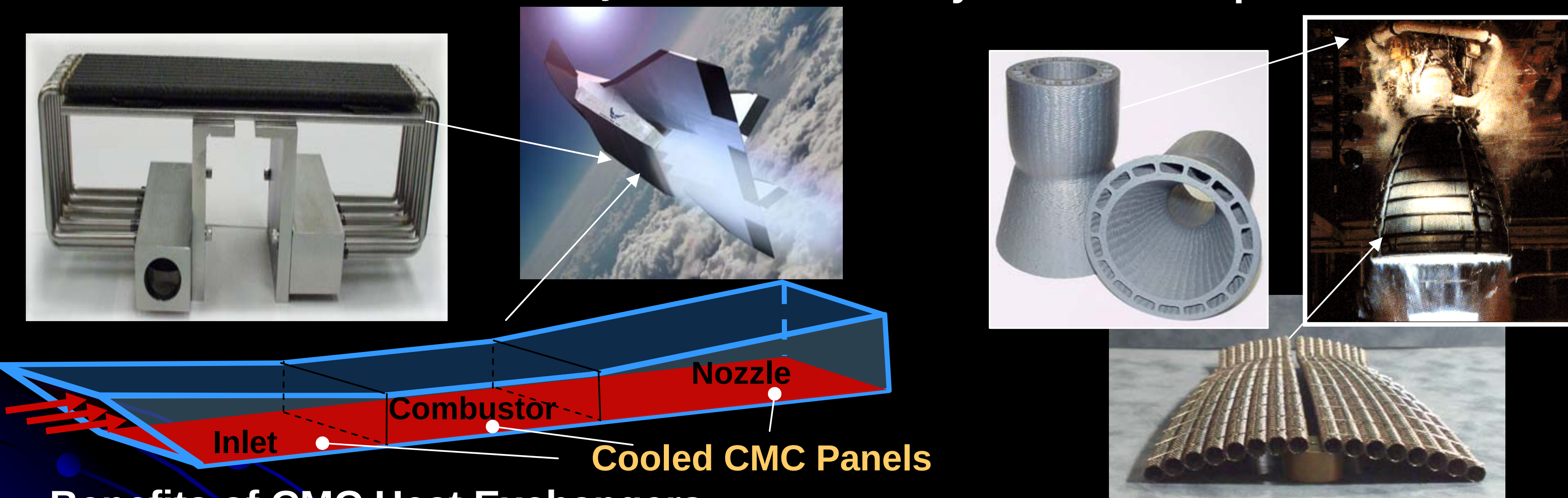
Improvements in Melt Infiltrated (MI) SiC/SiC CMC Due To:

- Stoichiometric SiC Fiber (Sylramic fiber)
- In-situ BN heat treatment process
- Outside debonding (debonding at coating/matrix interface)

Cooled CMC Development at NASA

Actively cooled Ceramic Matrix Composites are structures with built in coolant channels for flowing coolant / fuel, does not include film or backside cooling

Flat Panels for Scramjets | **Axisymmetric Components for Rockets**

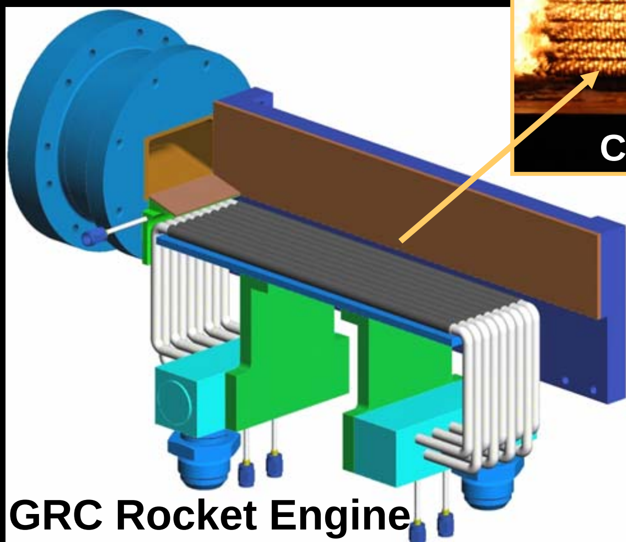


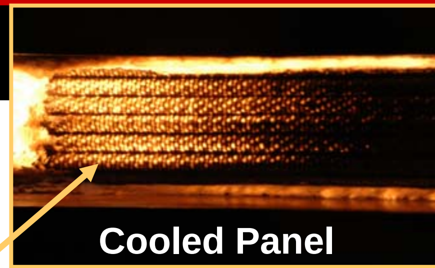
Benefits of CMC Heat Exchangers:

- Lighter weight than metallic designs – up to 50% weight reduction calculated
- Lower coolant flow requirements
- May eliminate re-entry cooling requirements
- Can provide higher fuel injection temperatures
- Enable vehicle and engine designs/cycles
- Increased operational margin -- translates to enhanced range and/or payload

Cooled Ceramic Matrix Composite Panels Successfully Tested in Rocket and Scramjet Engines

Rocket Engine Tests





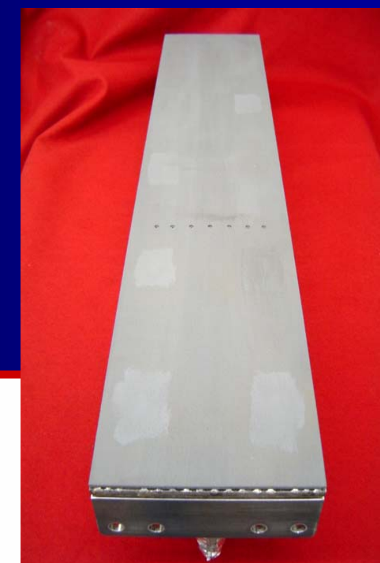
Hydrogen Cooled CMC Panel in Rocket Engine Test

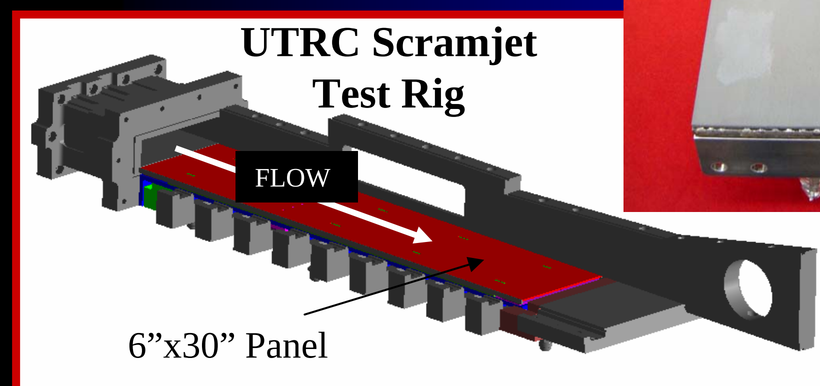
- Tested 5 cooled CMC panel concepts under representative rocket engine conditions
- Measured heat flux up to ~ 16 W/m^2 (~10 BTU/in^2·sec)

Need for: - increased thermal conductivity
- improved durability in both coatings and CMC

Scramjet Engine Tests

- 6 ”x30” Cooled CMC Panel
- Largest cooled CMC panel ever fabricated
- First cooled CMC panel to be tested in a scramjet engine



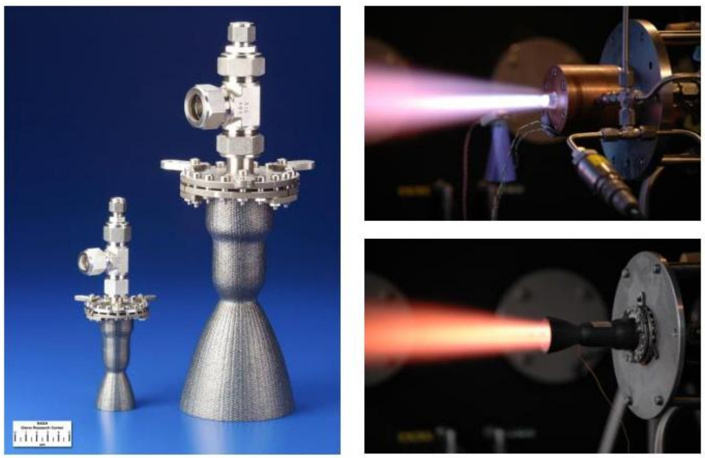


- Panel successfully tested at Mach 6.5 conditions with hydrocarbon coolant
- CMC exposed to 2200ºC combustion gases

Engine and Burner Rig Testing Supporting Industry and Government Labs

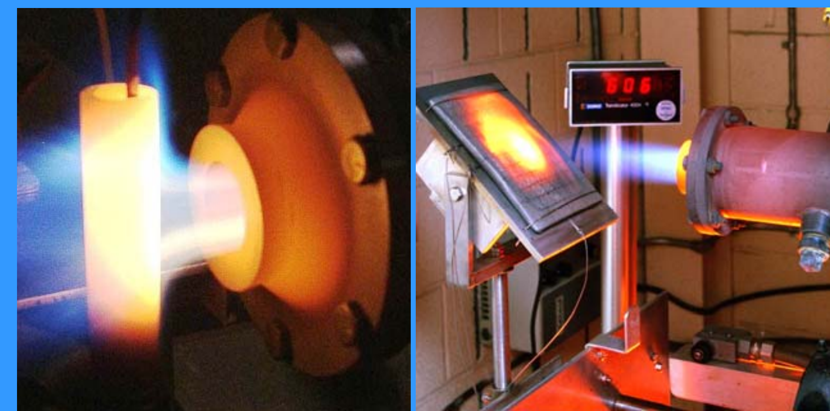
Rocket Engine - Cell 22 Testing

Small Ceramic Engines
- Ceramic foam injectors
- CMC thrustcell



Radiation Cooled Nozzles
- CMC Materials Screening
- Use temperature to ~1920ºC

Burner Rigs – Mach 0.3 to 1.0



Quick Access Rocket Exhaust Rig

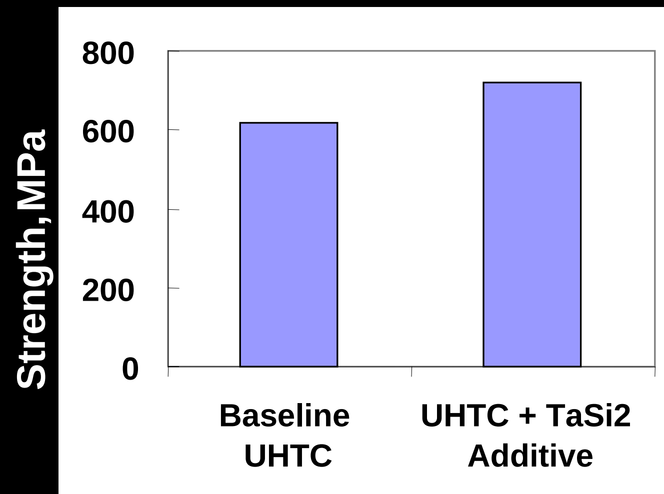
Ultra-High Temperature Ceramics for Re-entry Vehicle Leading Edge Applications

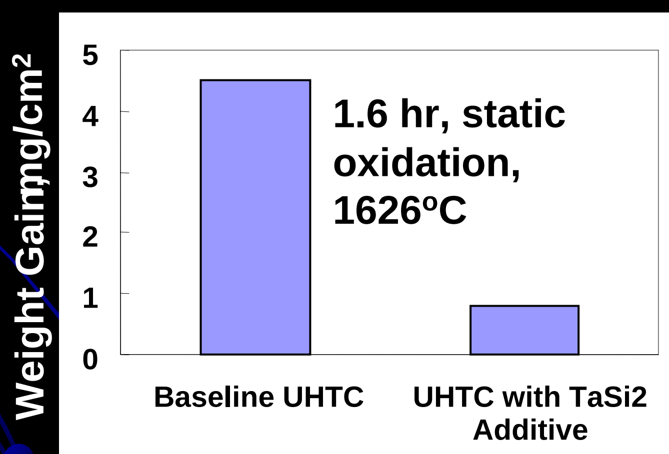
Tantalum additions show promise for improving oxidation properties of UHTCs up to temperatures of 1800°C (3272°F)

Baseline UHTC

Baseline UHTC + $TaSi_2$

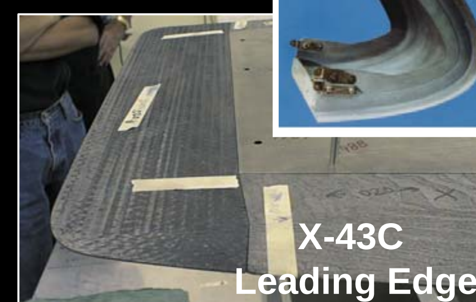
10 min 50 min 100 min





Leading Edge Requirements

- Temps >2000°C
- Multi-use
- Light weight
- High heat flux/temperature
- Sharp or blunt

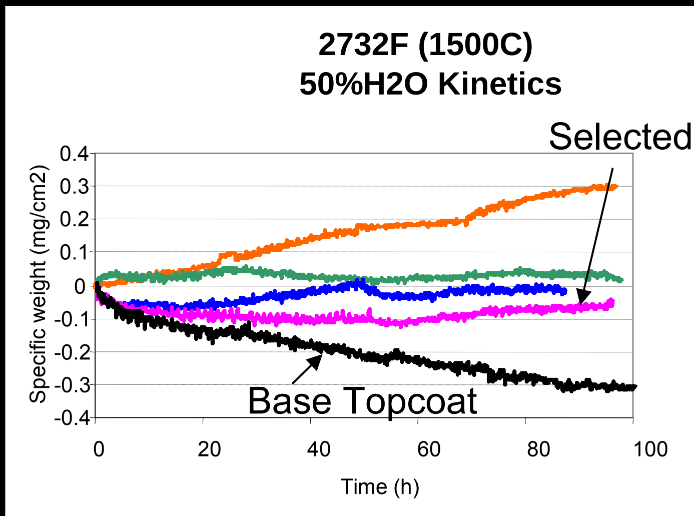


Technical challenges

- Environmental durability
- Life
- Manufacturing

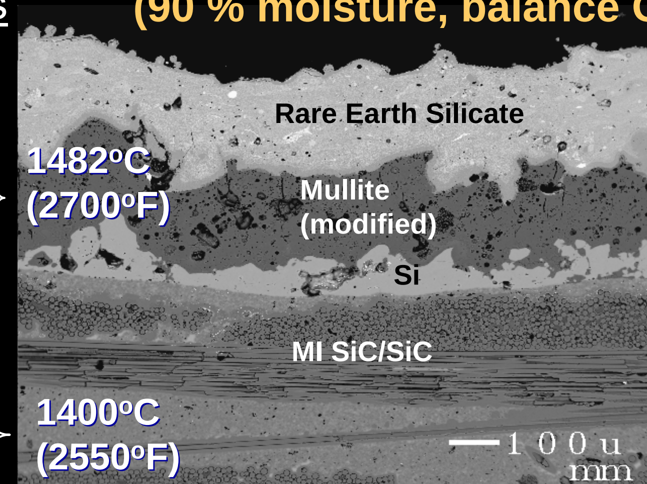
Environmental Barrier Coating Development

Volatility of Rare Earth Silicate Topcoats



Met program goals
- Topcoat stable in water vapor
- Chemical compatibility, top coat/mullite
- Ox resistance & Adherence
- Composite stable to therma cycling

1400°C (2550°F), 600 hr, 1 hr cycle (90 % moisture, balance O_2)



As Fabricated

EBC Coated SiC/SiC Vane

After 110 Cycles in High Pressure Burner Rig

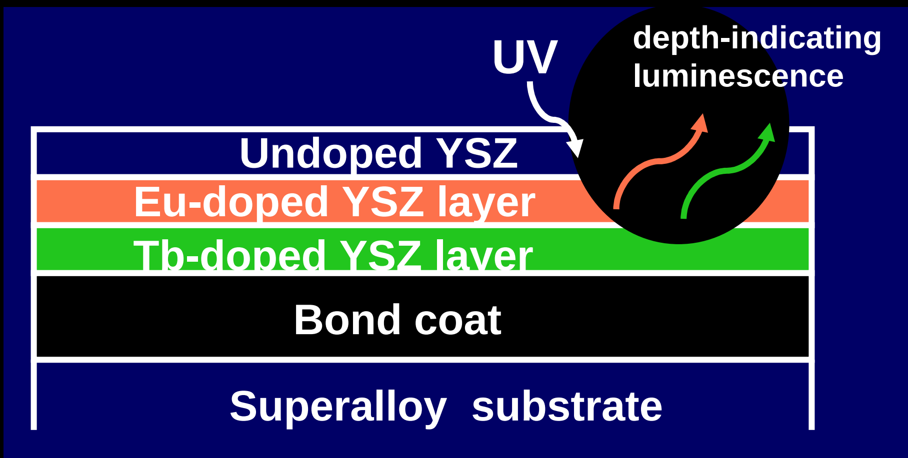
Superalloy Vane

Severe Erosion on trailing edge of superalloy vane

- No obvious degradation of SiC/SiC vane with EBC coating after 110 cycles
- Superalloy vanes and holder sustain heavy damage.

Erosion Self-Indicating Thermal Barrier Coatings

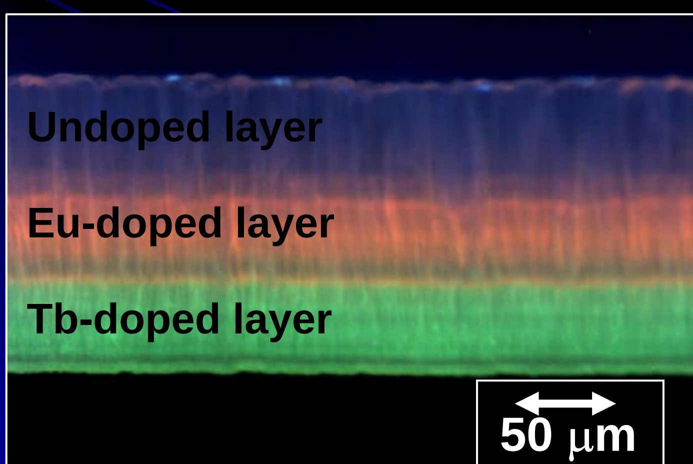
Coating Design



Benefit

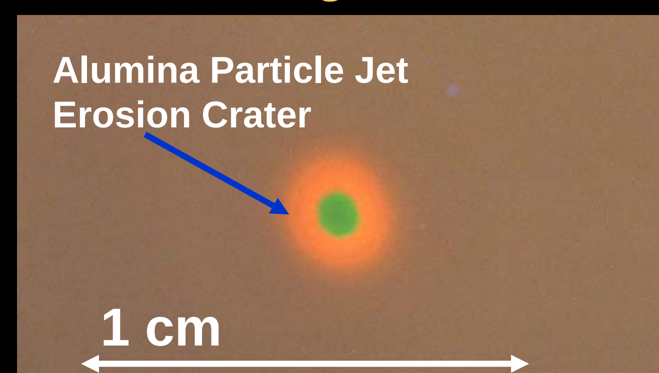
UV illumination excites visible luminescence in sublayers exposed by erosion or cracking providing immediate identification of location and severity of erosion and cracking.

Ultraviolet Illuminated Cross-Section



Successful sublayer deposition

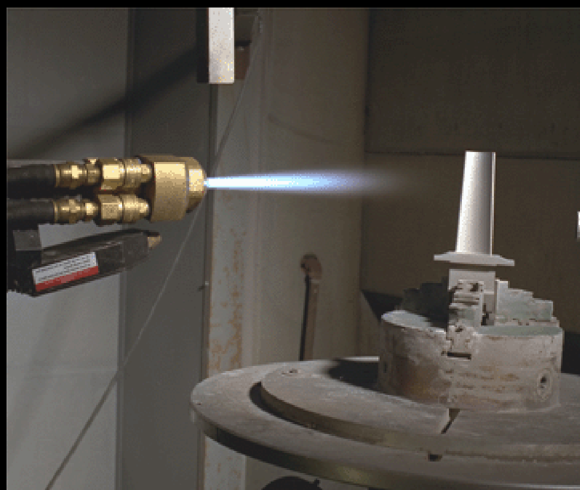
Ultraviolet Illuminated Coating Surface

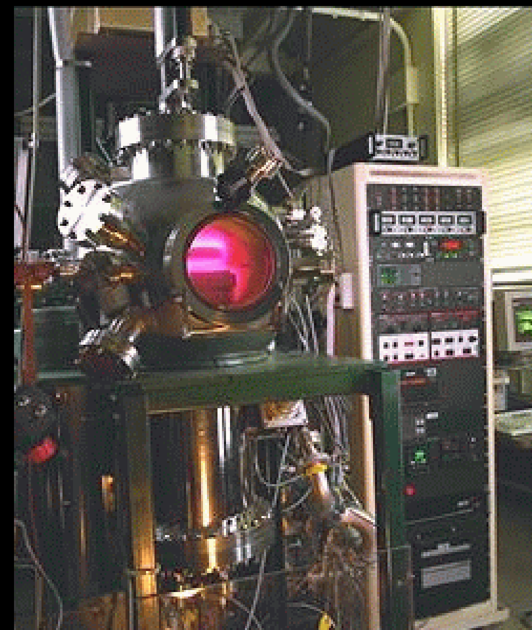


Erosion Indication

Protective Coating Development

Ambient Plasma Spray Processing

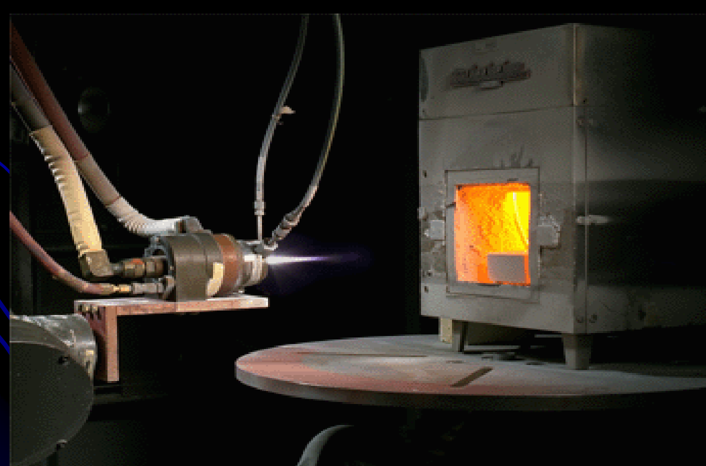


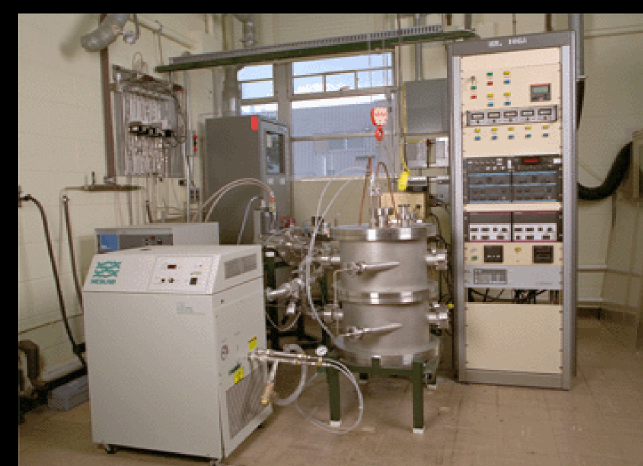


Plasma Enhanced CVD

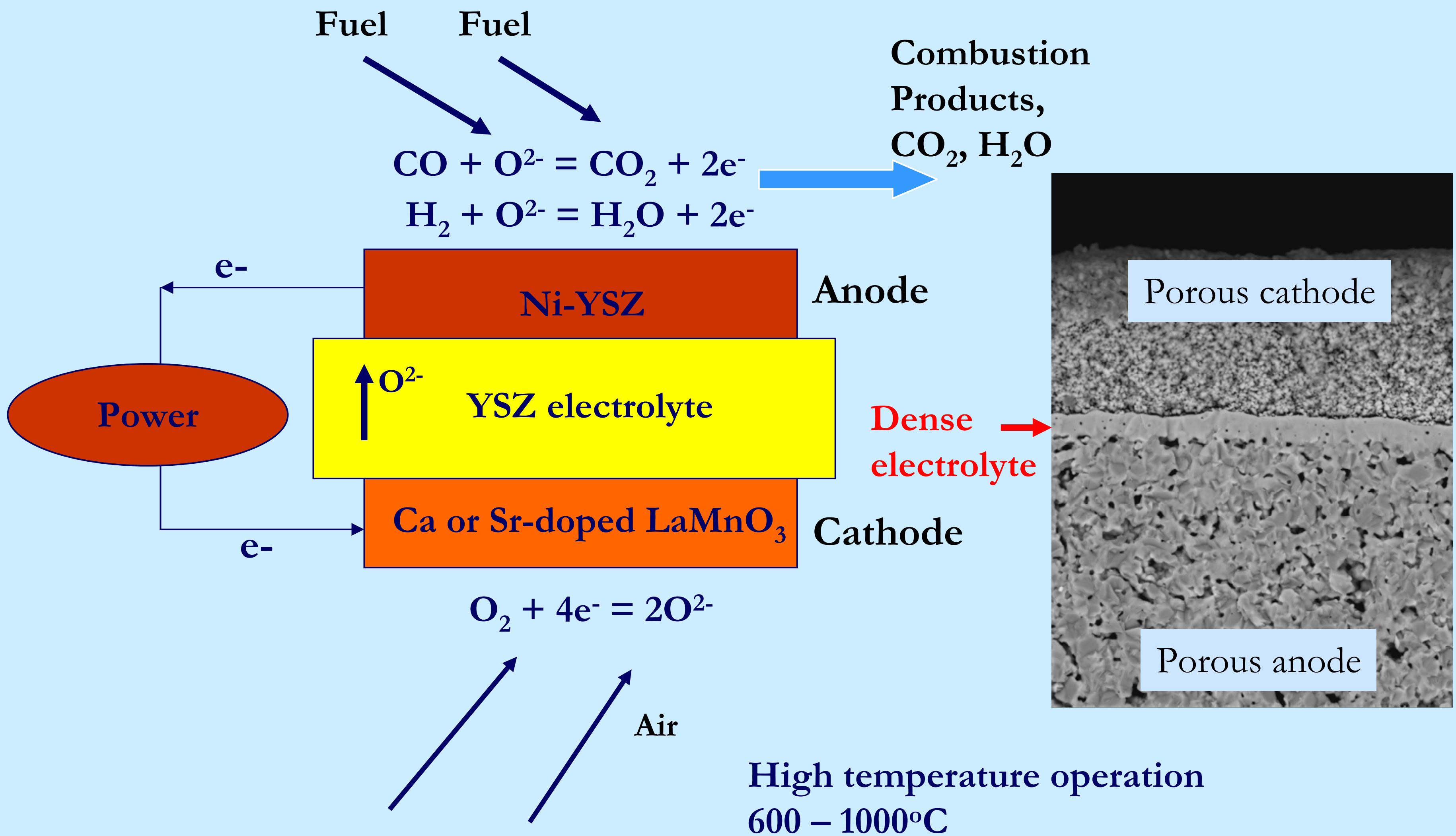
Physical Vapor Deposition

Adapting deposition approach to achieve desired coating properties





Principle of Solid Oxide Fuel Cell



NASA Fuel Cell Requirements

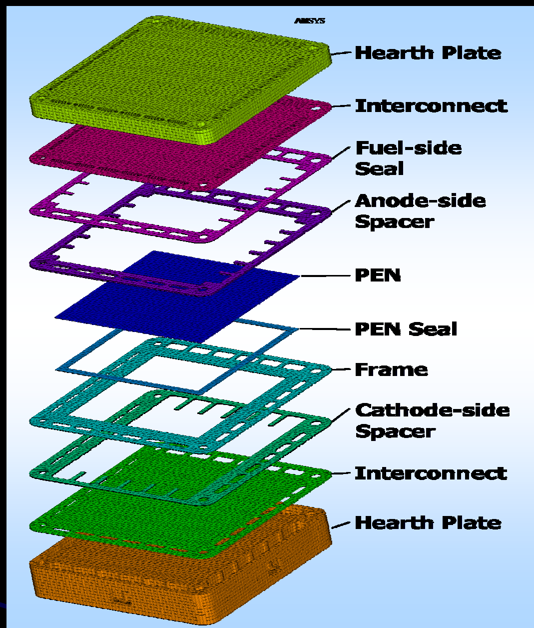
Aerospace Fuel Cell Power

- High Efficiency
- High Specific Power Density
  - Lightweight
  - Low Ohmic Losses
  - High Temperature
- Mechanically Robust
- Reliable Hermetic Seals
- Compatibility with existing fuel architectures

Stack Description	Specific Power Density (kW/kg)
SECA 5 kW Unit	0.1
2006 – NASA Phase I Target	0.5
2008 – NASA Phase II Target	1.0

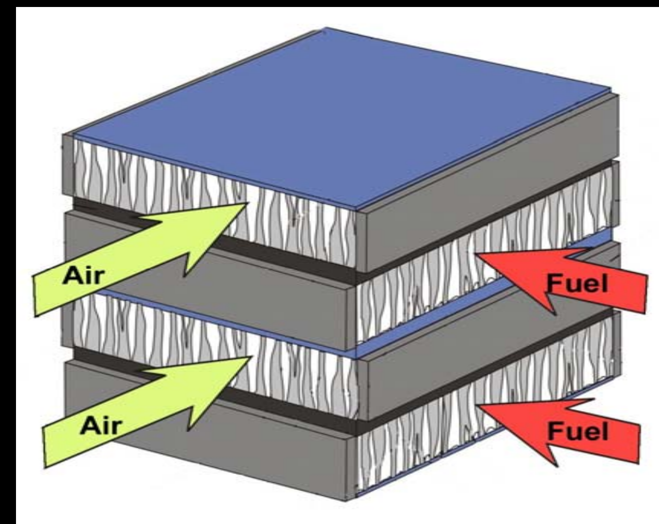
State- of-Art SOFC Technology

Industry Standard SOFC Design



- Individual cells and interconnects, manually assembled with multiple coatings, leads to high internal contact resistance. **Loss of up to 70% Power.**
- Ceramic cell to metal interconnect bonding results in some **leakage** of fuel due to expansion mismatch with thermal cycling.
- Temperature has been reduced from 850 to 700-750°C due to Cr-poisoning from metal. **40% Power Loss.**

NASA SOFC Design Solution



- All ceramic cells and interconnects, preassembled into stack and then sintered at high temperature into a unitized block. **Reduces internal resistance.**
- Ceramic edge seals, made of zirconia, are fabricated with the stack and are **hermetic**.
- Operating temperature is **850-900°C** due to all ceramic technology.

Functional Ceramics for Sensors and Devices

Piezoelectrics – Pushing the temperature limit for high temperature devices:

Sensors/switches – motion, vibration, strain, MEMS
Power – transformer, high voltage generator, energy storage
Intelligent Control – shape morphing, vibration damping, noise suppression, combustion control, structural health monitoring
Medicine – imaging, drug delivery, tissue ablation
Processing – welding, sono-chemistry, fluid pumps, atomizer
Motors – high power to weight ratio

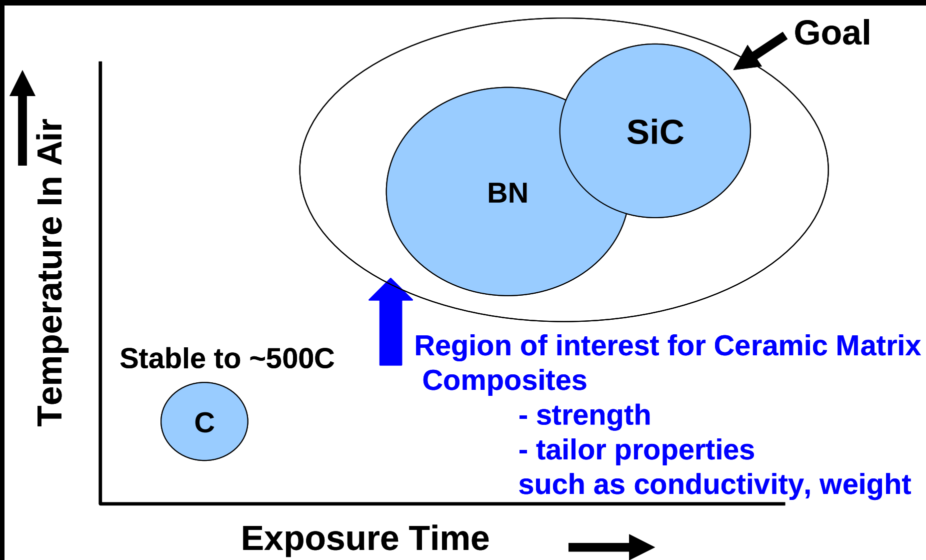
Thermoelectrics – Long life, high performance devices from novel chemistries

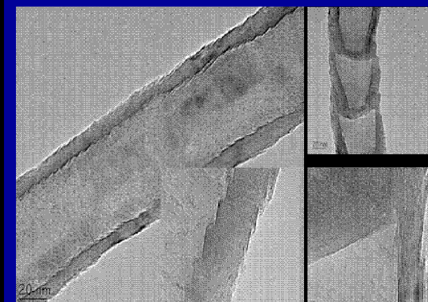
Oxide Thermoelectrics offer the potential for:

- Increased temperature capability, low λ
- Increased Thot/Tcold ratio
- Environmentally stable in air
- High structural stability at high T

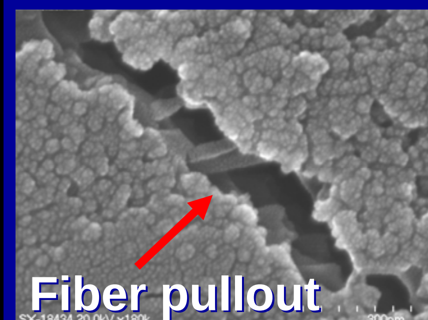
Development of High Temperature Nanotubes

Structural Applications





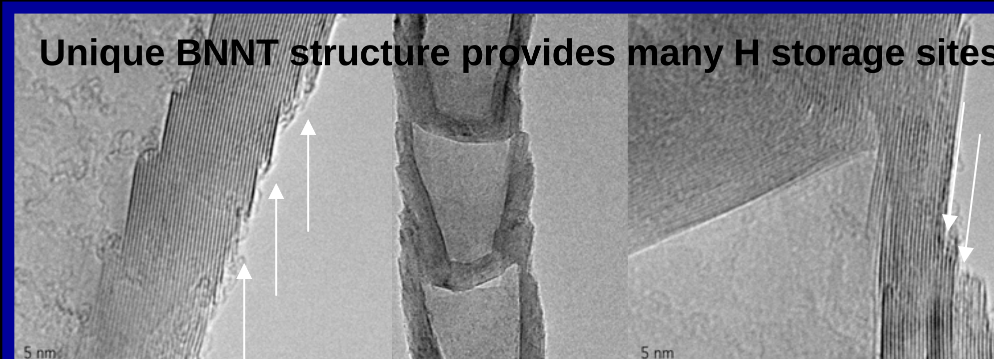
BN nanotube successfully synthesized with capability of producing > 1 gm/day



Composite Behavior Demonstrated in Nanotube Reinforced Composites

Hydrogen Storage

Theoretically BN nanotubes can store up to 18 wt % hydrogen, far in excess of the DOE goal of 6.5 wt %.
BNNT is more robust than CNT, with a much higher use temperature (1000C in air vs 500 C in air), also more oxidation resistant
- CNT is pyrophoric.



- In preliminary testing **~3 weight % hydrogen adsorption** measured for as-processed BNNT, better than CNT
- Improvements are expected from purified BNNT

Status of Advanced Ceramics at NASA

Structural Ceramics

Improved SiC/SiC composites – increased temperature capability 1480^{o}F

-Rupture time >500 hrs at stress ~60% of elastic limit

Cooled Composites –tested 6”x30” C/C panel in scramjet rig, M6.5, gas temp=2200^{o}C, material temperature 1370 – 1530^{o}C

- C/C, C/SiC and SiC/SiC tested in rocket engine, heat flux ~16 W/m, material temperatures 1370 - 1650 (in localized areas)

UHTCs – $TaSi_2$ additions improve oxidation properties up to ~ 1800^{o}C

Coatings

Environmental Barrier Coatings – Rare earth top coats proven for 600hr at 1400^{o}C

Thermal Barrier Coatings – Developed novel non-destructive method of evaluating coating continuity and quality with luminescent sublayers

Functional Ceramics

Nanotechnology – Demonstrated composite behavior with nanotube composites

Measured ~3 wt % absorption for hydrogen with boron nitride nanotubes

Fuel Cells – Achieved specific power density of 1.0 kW/kg

Operating temperature slightly increased to 900^{o}C with all ceramic cells

Concluding Remarks

Advanced Ceramics Research at NASA:

Aeronautics – Long term basic research: Structural, and Functional

Space –Applying state-of-the-art materials and technology to meet specific needs

Materials Needs:

For structural application - Increased temperature capability – 1920^{o}C for uncooled components, high specific strength, improved durability, longer life

For functional applications – Increased temperature capability – 950^{o}C for SOFCs, tailorable electrical and thermal properties for smart materials, Increased H2 absorption for nanotubes

Emerging Growth Opportunities:

Emphasis on Functional Materials: Nanotechnology, Piezoelectrics, Thermoelectrics, Fuel Cells

Partnering – International opportunities exist in both Space and Aero arenas

NASA offers: capabilities in modeling, design, analysis, evaluation and testing – from laboratory scale up to representative engine environments, vehicle systems knowledge