Ceramic Matrix Composites: The Next Material Revolution?

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Applied Materials for Space and Hypersonics

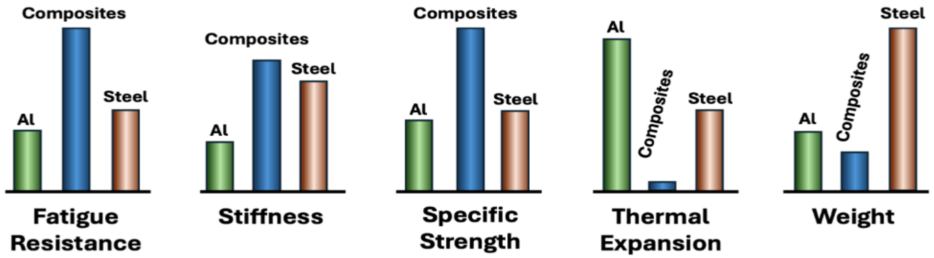
Outline

- Introduction
- Highlighted ceramic matrix composite (CMC) sectors
- Challenges & opportunities
- Concluding remarks

What are Composites?

- **Two or more constituents combined on macro scale**
  - Often comprised of a matrix (binder) and reinforcement
- **Types of reinforcement**
  - Continuous or long fibers
    - Unidirectional, woven, braided, or random architecture
  - Random or short fibers
  - Particulate, flakes, or fillers
- **Benefits**
  - Light-weight
  - Tailorable to different applications
    - Strength / stiffness
    - Coefficient of thermal expansion (CTE)
    - Hardness, fatigue life, damage tolerance

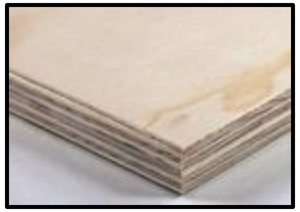
PMC versus metallic properties



- **Common composite examples**
  - Reinforced concrete and masonry
  - Composite wood such as plywood
  - Polymer matrix composites (PMC)
  - Ceramic matrix composites (CMC)

B787 PMC Fuselage

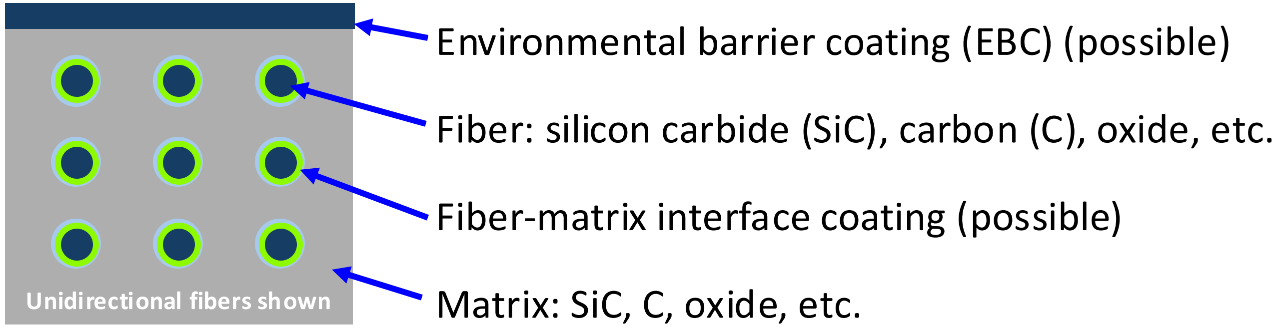
PMC Composite Bicycle



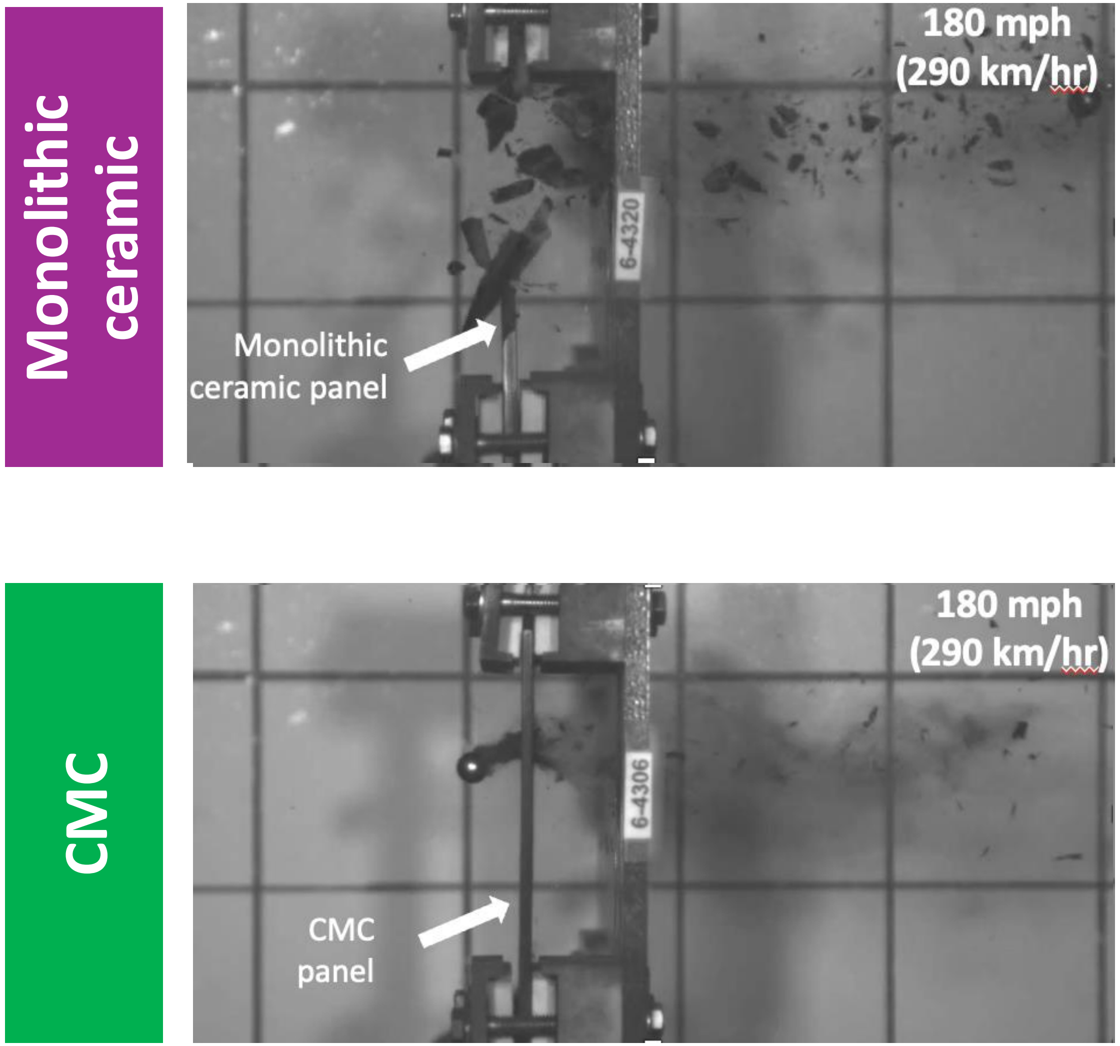
Composite plywood

Ceramic Matrix Composites (CMCs)

- **CMC = Ceramic (or carbon) fiber in a ceramic matrix**
  - Material nomenclature is "fiber/matrix"



- **Common examples**
  - Oxides: Oxide/alumina-silicate, oxide/alumina-mullite
  - Carbides: SiC/SiC, C/SiC, C/C-SiC
  - Carbon/carbon: C/C
- **Characteristics**
  - Moderate density
  - High use temperature
  - Chemical resilience
  - Excellent mechanical capability
- **"Game changer" for high-temperature applications**



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Perception of CMCs

- **Analogous to that of PMCs in the mid-1980s**
- **Commonly viewed as promising, but…**
  - Too many problems, unknowns, and risks
  - Immature manufacturing techniques and supply chain
  - Immature supply chain
  - Exotic
  - Complex to analyze and implement
  - Too expensive and therefore unrealistic for "real-world structures"
- **Is this perception valid?**

CMC brake discs, calipers, and pads are NOT complex, immature, or risky

Credit: J. Chenenko, used with permission

Reality of CMCs

- **Offer increased efficiency and *decreased* complexity for elevated-temperature applications**

- **Have reached an inflection point in maturation**
  - Viable predictive and design capabilities
  - Proof of profitability in multiple industries
  - Actively developing supply chain
  - Technological advances/improvements in manufacturing
    - Can be tailored to application
    - Decreased costs with increased quality and throughput

- **Analogous to CFRP composites in the mid-80s – CMCs are poised for explosive growth…**

Passport engine oxide/oxide mixer and nozzle

Credit: " EBACE 2019, Le Grand-Saconnex (EB190671)" by Matti Blume licensed under CCA 4.0.

Cost Perceptions and Cost Realities of CMCs

- **CMCs have a reputation as too expensive**
  - Acquisition costs can cause hesitation in adoption of CMCs, even if life-cycle costs are reasonable
  - Costs must be balanced against drivers for CMC technology

Demand / Pull for CMC Technology
- Performance
- Efficiency
- Emissions
- Environmental
- Safety

Sector Level of Industrialization / Capitalization

Demand / Pull	Low	High
High	Business case for industrialization	Cost often competitive
Low	Cost prohibitive	Cost can be competitive

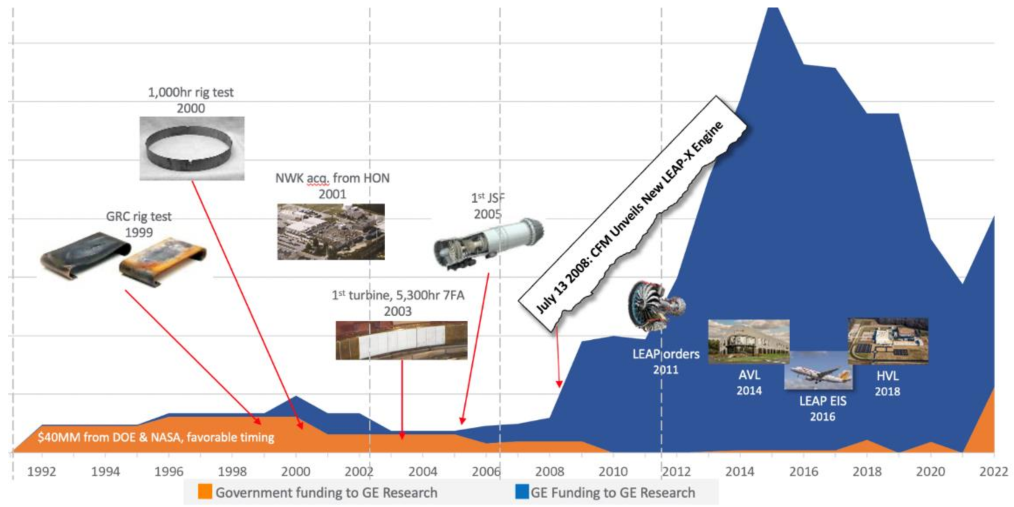
- **Investment in industrialization for high-pull business cases improves future business cases**

Credit: "British Aerospace EAP at the Farnborough Air Show, 1986" by Mean as custard licensed under CCA 3.0.

PMC Business Case Evolution 1980's to present

Credit: "Tennis Racket and Balls" by Vladsinger licensed under CCA 3.0.

Business case for CMCs in aviation drove GE investment



Used by permission of GE Aerospace: Approved for external publication (July 2024)

S.J. Lewis, "The use of carbon fibre composites on military aircraft," Composites Manufacturing, Vol. 5 No. 2, 1994.

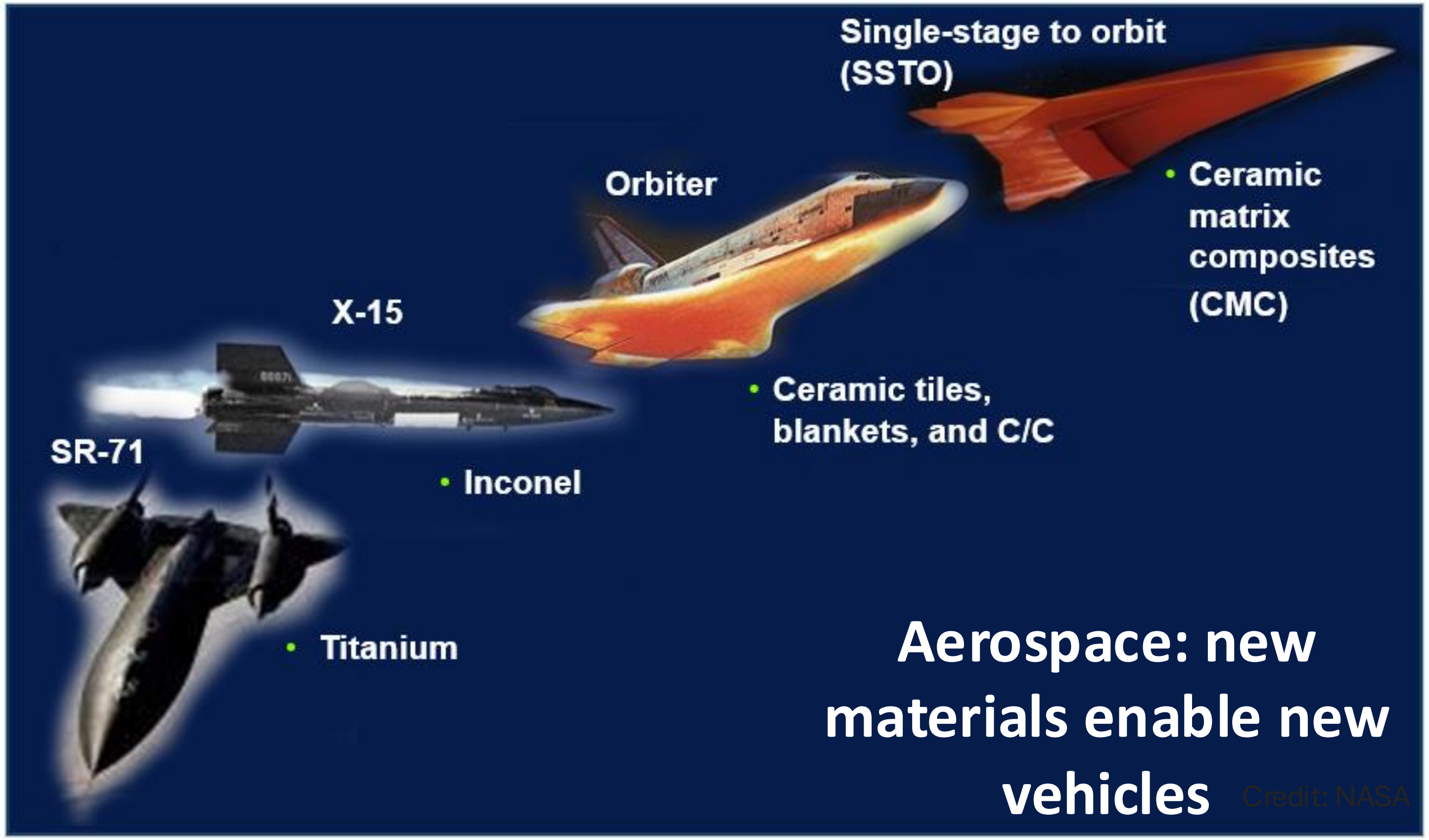
CMCs are Both Enablers and Benefit-Multipliers

CMCs enable new technologies and products

- Spacecraft, aircraft, defense, and nuclear and other power generation components are some currently identified examples

CMC implementation results in system benefits

- CMC components enable a system with lower weight, higher performance, higher efficiency and improved safety while decreasing overall complexity – a benefit multiplier



Credit: NASA

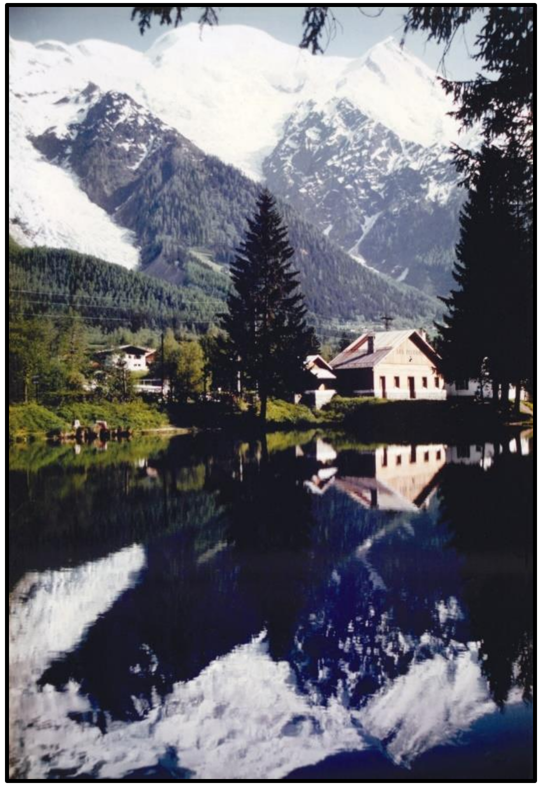
Example: Environmental Benefit-Multiplier

CMCs can be crucial to meeting environmental challenges

- Pollution, dwindling resources, and increasing population

CMCs can play essential roles in implementation of environmentally-friendly technologies

- Environmental impact of CMC production must be balanced with system benefits
- Many energy-generation supporting subprocesses require thermal conversion; higher efficiency processes drive demand for higher temperature materials
  - Examples: high temperature syngas synthesis for hydrogen production and carbon capture, fuel cell parts such as bipolar plates and end plates
- Decreased emissions
  - Improved efficiency in aircraft, ships and existing powerplants
    - *Light weight vehicle structures capitalize on the above, further improving fuel efficiency and extending range*
- High fatigue and corrosion resistance: Fewer replacements, fewer emissions with manufacturing and transport, less waste in all applications
- Turbines and all high-temperature processes in current and future power generation; CMCs can facilitate efficiency, longevity, lower cooling power, fewer replacements and overall value chain increases



Credit: D. Glass

Outline

- **Introduction**
- **Highlighted CMC sectors**
  - Automotive
  - Energy
  - Defense
  - Aviation
  - Space and hypersonics
- **Challenges & opportunities**
- **Concluding remarks**

Highlighted CMC Sectors

CMCs are currently making in-roads in multiple key industrial sectors

Automotive

Brakes

Credit: "PCCB Brake Carrera GT" by Nrbelex licensed under CCA 3.0.

Energy

Nuclear fuel rods

Credit: General Atomics Electromagnetic Systems (GA-EMS), used with permission

Defense

Rocket control vanes

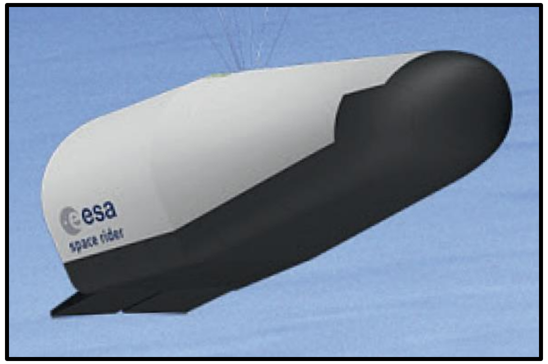
Credit: "IRIS-T air-to-air-missile" by Owly K licensed under CCA 3.0.

Aviation

Aircraft engine shrouds

Credit: “ORNL History (44684257470)" by ORNL History licensed under CCA 2.0.

Space and Hypersonics



ESA Space Rider

Credit: “Space Rider mission” by ESA©ESA, ESA Standard License

Automotive CMC Applications

Objectives

- Reduced exhaust gas emissions
- Lower fuel consumption
- Decreased vehicle weight

… to enhance vehicle safety and performance

Applications

- Motorsport headers, manifolds, and exhaust pipes
- Clutch discs
- Brake discs (also applicable to aviation)

Key benefit is thermal performance

- Dimensional stability
- Durability, wear resistance, and strength
- Frictional consistency
- Resistance to thermal shock

Plus, reduced weight

Automotive brake disc

Credit: "Toyota TF103 Front Brake Disc 01" by Hatsukari715, no license required.

Automotive exhaust manifold (metallic shown; CMCs in use)

Credit: “Exhaust manifold" by http://www.zircotec.com, no license required.

Example: Automotive Brakes

In the early 1980s, CMC brake adoption began in aircraft and high-performance automobiles

- C/C brakes introduced to Formula 1 by Brabham, used by all manufacturers by end of decade
- Now common in Formula 1, Le Mans, and other racing classes

In the early 2000s, use extended to advanced C/SiC and C/C-SiC brakes to first motorcycles and then automobiles

- Excellent wear resistance
- Low vibration/noise
- Oxidation resistance
- Low dust (environmental)
- 2002 Ferrari Enzo: One of the first production road cars to use CMC brake discs
- Commonly used in high-performance sportscars such as Porsche, Ferrari, etc.
- Increasing usage in commercial luxury cars such as Mercedes and Audi and in high-performance motorcycles
- “At last, ceramic brake disks are designed to last the entire lifetime of a car.” – Krenkel 2008

Ferrari FXX Using CMC Brakes

Credit: "Ferrari FXX (8925990630)" by emperornie licensed under CCA 2.0.

Increasingly popular in high-end consumer cars

Credit: "PCCB Brake Carrera GT" by Nrbelex licensed under CCA 3.0.

W. Krenkel, R. Renz, “CMCs for Friction Applications,” Ceramic Matrix Composites: Fiber Reinforced Ceramics and their Applications, May 2008, https://doi.org/10.1002/9783527622412.ch16.

Energy CMC Applications

- **Objectives**
  - Improve energy-generation reliability and performance, thereby…
    - Reducing emissions
    - Decreasing maintenance downtime
    - Increasing output
    - Improving safety
- **Applications**
  - High-efficiency turbines and generators (potential)
  - Concentrated solar power
  - Nuclear reactors
    - Plasma-facing components
    - Cladding
    - Control rods

- **Drivers of CMCs in nuclear applications**
  - Limited temperature degradation
    - Improved safety during loss of coolant
  - Low material corrosion
    - Impurity corrosion from water/oxygen
    - Mass-transfer induced corrosion
    - Transmutational products (HF/F_2) corrosion
  - Low irradiation degradation
    - Radiation hardening and embrittlement
    - Radiation induced phase instabilities
    - Irradiation creep
    - Volumetric swelling from void formation
    - High-temperature He embrittlement

Nuclear applications require utmost safety and reliability

Credit: General Atomics Electromagnetic Systems (GA-EMS), used with permission

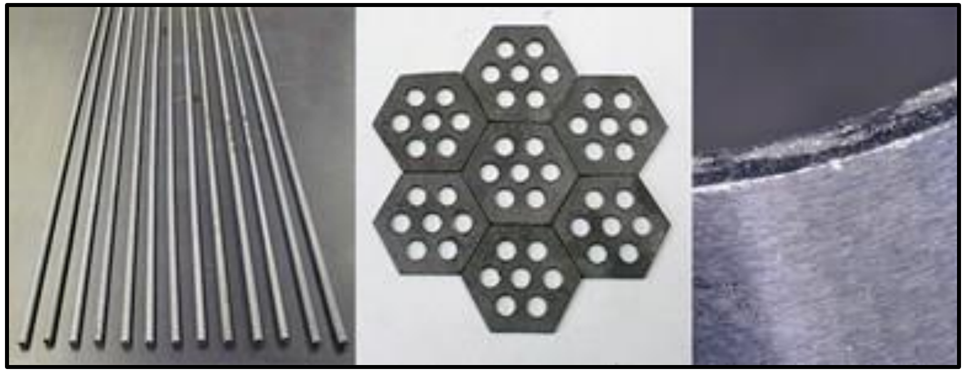
Example: General Atomics EMS Fast Modular Reactor (FMR)

FMR reactor uses SiC/SiC CMC to enable reactor operation at higher temperatures for greater efficiency

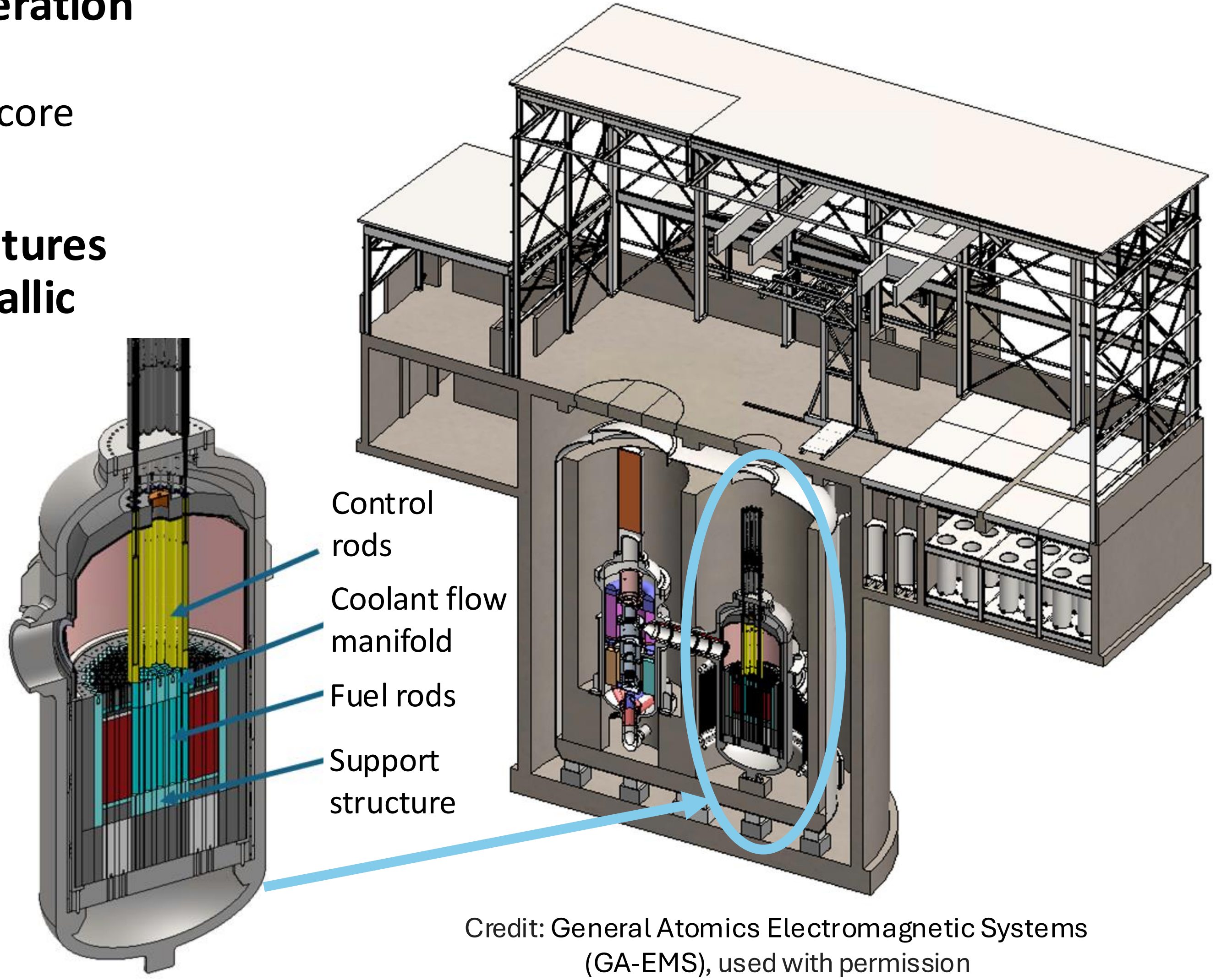
- Used in control rods, reactor cladding, and reactor core structure

SiC/SiC CMC material can withstand higher temperatures and resist oxidation and irradiation better than metallic alloy solutions

- Higher fuel burn-up
- Increased fuel cycle length
- Less dry cask storage
- Increased thermal margin



Credit: General Atomics Electromagnetic Systems (GA-EMS), used with permission



Credit: General Atomics Electromagnetic Systems (GA-EMS), used with permission

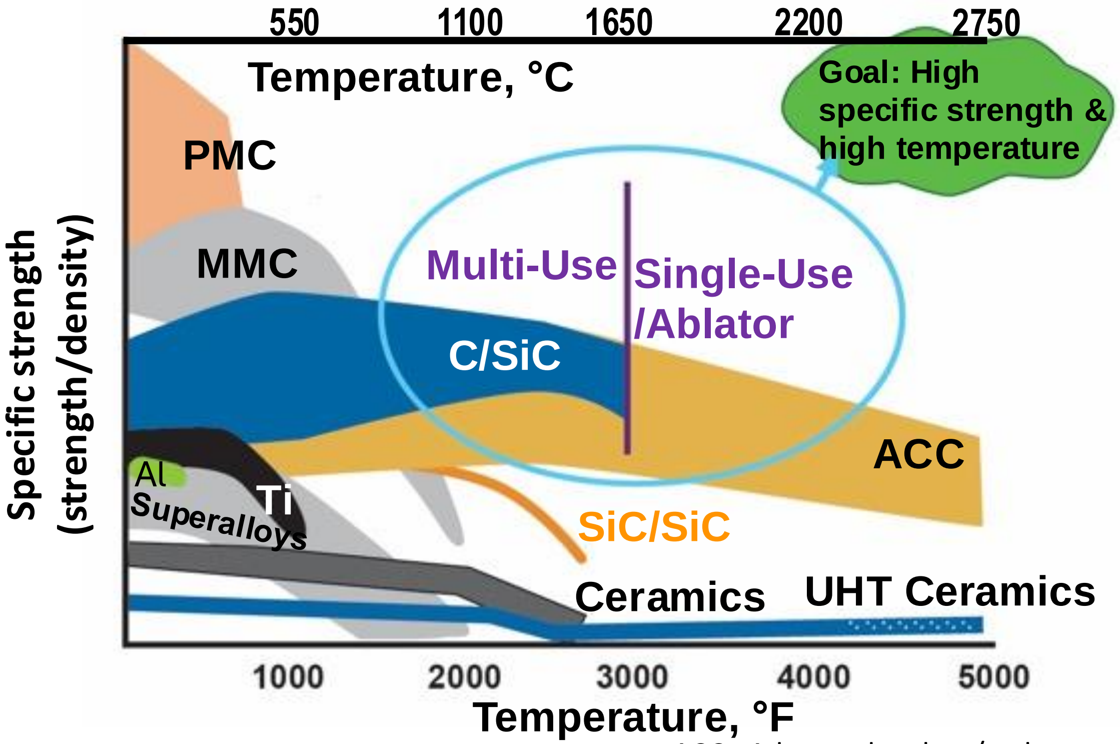
Defense CMC Applications

Objectives

- Low-weight systems
- High speed
- High temperature
- Better maneuverability
- More navigable/communicable
- Able to transport increased payloads
- More durable

Applications

- Transparent sensor windows
- Thermal protection systems (TPS) and hot structures
- Propulsion components
- Armor (potential)



ACC: Advanced carbon/carbon
UHT: Ultra high temperature
MMC: Metal matrix composite

CMCs enable performance under extreme environments

Credit: "AGM-88E AARGM" by Boevaya mashina licensed under CCA 4.0.

J.J. Swab and E.J. Sandoz-Rosado, "Identifying Opportunities in the Development of Ceramic Matrix Composite (CMC) Materials for Armor Applications" Army Research Lab Technical Report, 2017.

Example: Thrust Vector Control Vanes

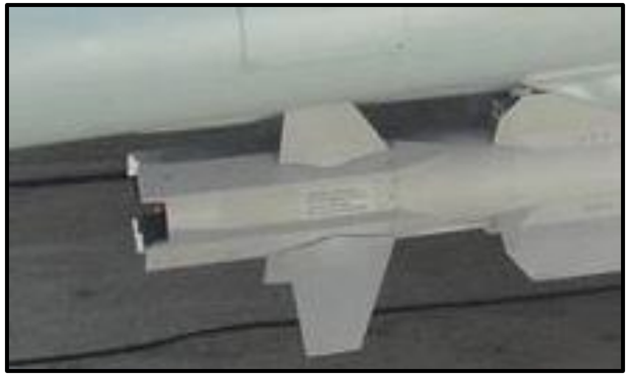
- **NAMMO (Norway) is flying C/C-SiC jet vanes for thrust vector control on European Iris-T, Iris-T SL, and Exocet missiles**
- **Rocket motor, 5 in. (127 mm)**
- **C/C-SiC vane**
  - Licensed from DLR (German Aerospace Center) and modified in-house
  - Lighter weight and higher abrasion resistance than refractory metal
  - Near net shape
  - Stagnation point 4400°F - 4940°F (2400°C – 2700°C) at Mach 5
  - Lasts as long as motors (seconds)

Exocet under wing

Credit: “Exocet AM39 P1220892" by David Monniaux licensed under CCA 3.0.

Iris-T under wing

Credit: "IRIS-T air-to-air-missile" by Owly K licensed under CCA 3.0.



Iris-T control vanes

Credit: “Luftwaffe Eurofighter Typhoon - Iris-T" by Georgios Pazios, no license required.

B. Heidenreich, et al., “C/C-SiC Materials for Highly Abrasive Resistant Structures”, Proceedings of 31st International Conference on Advanced Ceramics & Composites, Daytona Beach, FL, Jan 22-27, 2007.
E. Orbekk, “Novel TVC System Utilizing Guide Vanes with Jet Flap’s Into a High efficiency Compact Nozzle”, 41st AIAA Joint Propulsion Conference, July 10-13, 2005, Tucson, AZ, AIAA-2005-4499.

Aviation CMC Applications

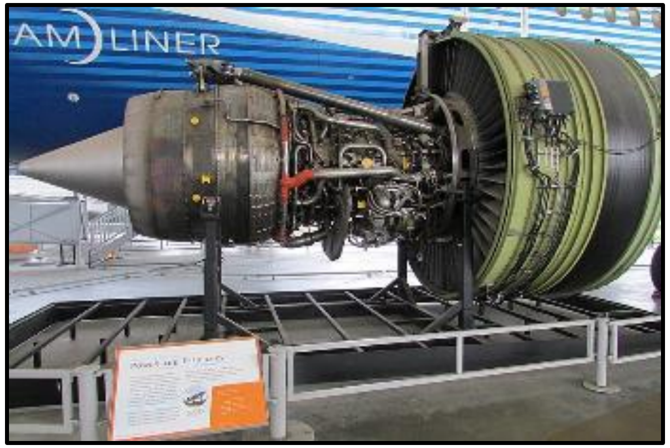
Objectives

- Improve efficiency of air transportation: increase fuel savings and reduce emissions
  - Decrease vehicle weight
  - Increase engine efficiency – higher temperature operation for more complete combustion

- **Applications**
  - Combustor shrouds, flaps, and seals
    - C/SiC, oxide/oxide, and SiC/SiC
  - Turbine engine blades
    - SiC/SiC
    - ~200 lb (90 kg) weight savings per mid-size turbine engine
  - Aircraft brakes
    - C/C and C/SiC
    - 500-1000 lbs (225-450 kg) per plane weight savings
  - Acoustic exhaust nozzles and mixers
    - Oxide/oxide
    - Potential of 1.0% fuel savings

737 C/SiC brake disc

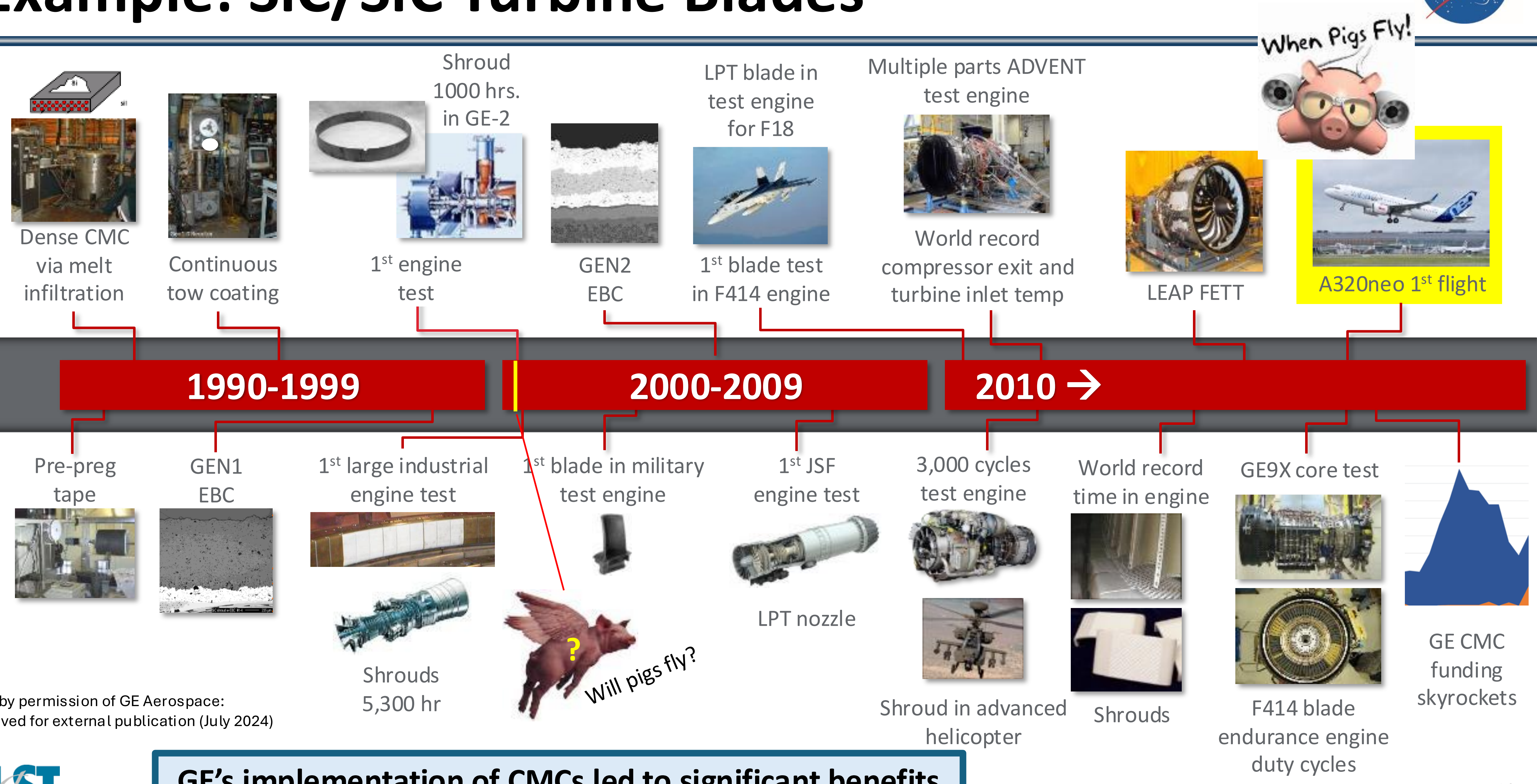
Credit: "Boeing 737 Next-Generation Carbon Brake PAS 2013 " by Julian Herzog licensed under CCA 4.0.



GE90-115B Turbofan (CMC blades and shrouds)

Credit: " GE90-115B Turbofan 9397" by Chris Light licensed under CCA 4.0.

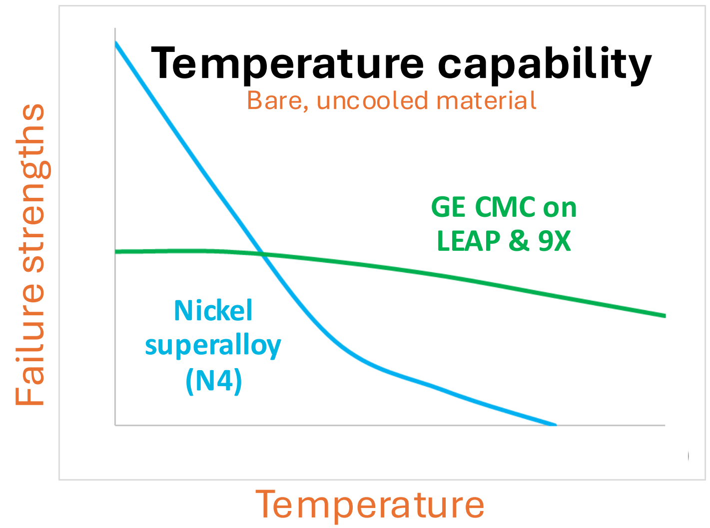
Example: SiC/SiC Turbine Blades

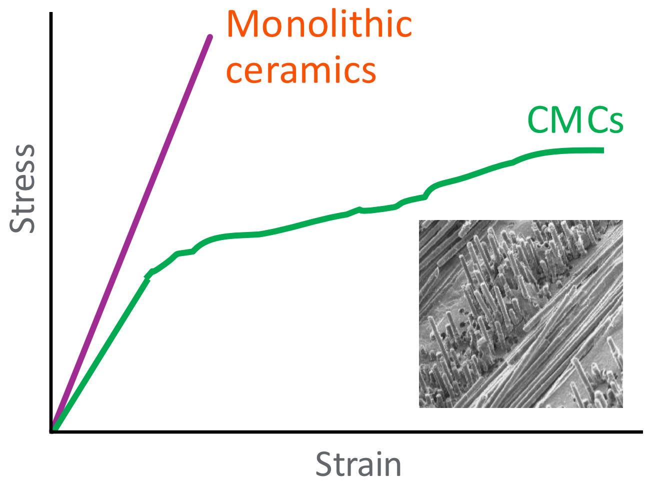


GE's implementation of CMCs led to significant benefits

Impact of CMCs in Jet Engines

High-temp endurance + Lightweight & durable => Up to 2% fuel savings per aircraft





	CFM LEAP	GE9X
	Part of up to 20% less fuel burn	*Part of 10% less fuel burn*
USING CMCs	**18 parts**	**107 parts**

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Approved for external publication (July 2024)

CMCs increase efficiency for customer fuel savings

Space and Hypersonics CMC Applications

Objectives

- Develop viable single-use and reusable space and hypersonic flight technologies
  - High-temperature survivability – well over 3000°F (1650°C)
  - Low weight – extremely critical for flight vehicles
    - Hot structures provide ~ 25% weight savings over insulated cold structure

Applications

- Re-entry vehicle heat shields and TPS
- Hypersonic hot structures
  - Wings, leading edges, and control surfaces
  - Fuselage (future)
- OEMs have identified a potential business case for intercontinental and trans-oceanic hypersonic flight capabilities, e.g., HYPLANE (Hypersonic Aerospaceplane)

NASA space shuttle with C/C nose cap and leading edges

Credit: NASA

CMC X-38 body flaps

Credit: “CMC-X38-Bodyflaps” by MT Aerospace AG, Augsburg, Germany licensed under CCA 3.0.

Need for a strong, light-weight, high-temperature material points to CMCs

Examples: ESA IXV and Space Rider

Successful IXV flight test in 2015

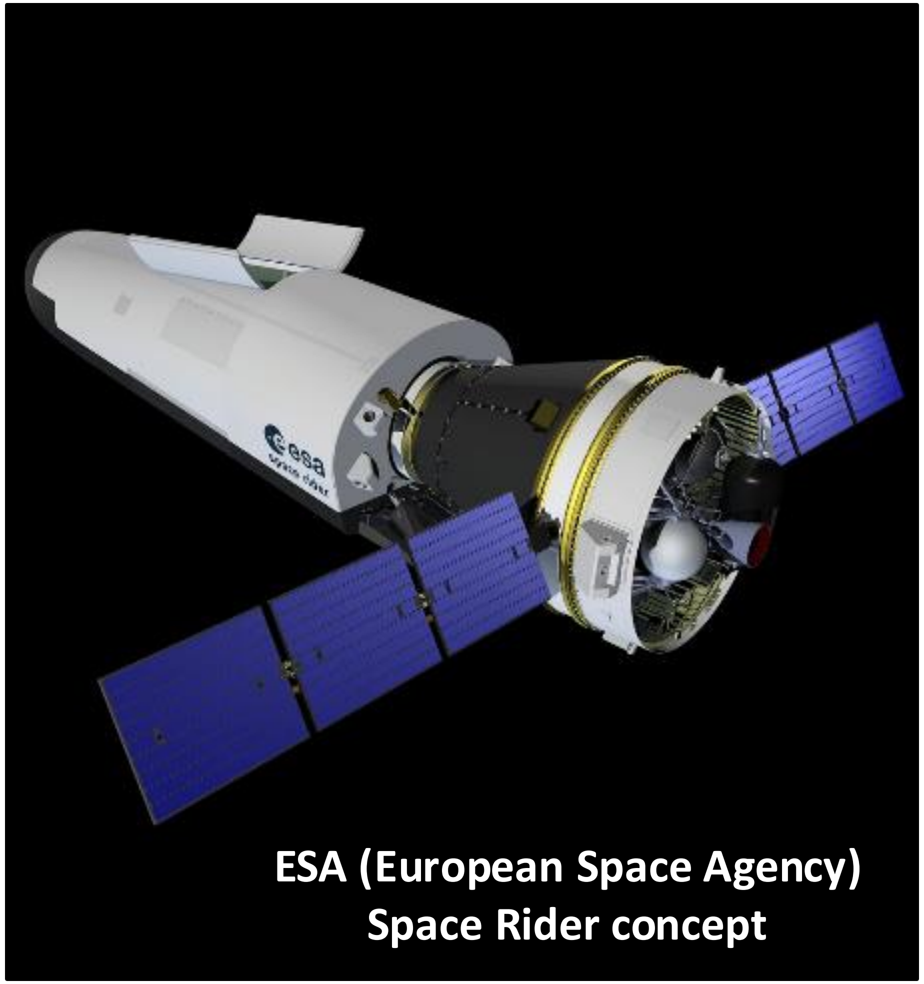
- 100-minute mission duration
- Approached Mach 25 during reentry

Petroceramics (Italy) providing C/C-SiC parts for Space Rider

- Body-flap assembly
- Hinge TPS
- Hinge
- Nose cap
- Shingle TPS

C/C-SiC hot structure

Credit: “IXV is being prepared for launch” by M. Pedoussaut, ©ESA, ESA Standard License



Credit: “Space Rider” by ESA-Jacky Huart ©ESA, ESA Standard License

“IXV mission recap” ESA, https://www.esa.int/Enabling_Support/Space_Transportation/IXV/IXV_mission_recap

Example: CMC Rocket-Nozzle Extensions

Composite nozzle extensions provide significant advantages for a variety of upper stage, in-space, and lander propulsion systems

- Weight reduction – ~50% savings versus metallic extensions
- Improved thermal design margins – 500°F to 2000°F (260°C to 1100°C)
- Less complex designs and/or manufacturing processes possible
- Substantial reduction in overall costs versus metallic design

Numerous potential applications

- NASA: Space Launch System (SLS), in-space, and lander systems for crewed and robotic exploration.
- USAF Evolved Expendable Launch Vehicles: Atlas, Delta, Falcon, Vulcan, etc.
- Commercial space industry: Both engines and vehicles

RL10B-2 C/C nozzle extension

Credit: NASA

Valentine, P.P, and Gradl, P.R., "Extreme-Temperature Carbon- and Ceramic-Matrix Composite Nozzle Extensions for Liquid Rocket Engines," 7th International Astronautical Congress (IAC), Washington DC, USA, October 2019.

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Challenges to Widespread Implementation

- **High cost of CMC products**
  - Highly dependent upon application
- **Manufacturing**
  - Most sectors are not sufficiently industrialized for high CMC production rates or quality requirements
    - Lack of automation, machining, furnaces, and other processing equipment
- **Limited data sets**
  - Expensive test coupons and unrefined test methods
  - Proprietary data sets
  - Inconsistent manufacturing processes
- **Availability of large quantities of continuous ceramic fibers, particularly SiC**

PMC industry overcame significant implementation challenges

Credit: “Largest Autoclave in the World" by ASC Process Systems, no license required.

Business cases are developing that help address these challenges

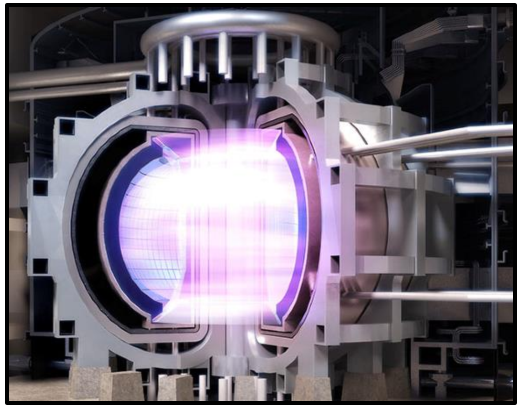
Opportunities

- **CMCs are poised to be the next material revolution**
  - Evolving advanced manufacturing capabilities
  - Efficiency-improving, cost-lowering, high-value, enabling technology
  - Demonstrated predictive and design capabilities
- **Potential for disruptive change**
  - Environmentally-friendly energy and mobility sectors
  - Emerging applications across a variety of sectors
  - Increasing awareness and acceptance
- **Major worldwide benefits**
- **Significant economic returns for leading countries and companies**
- **Collaboration and cooperation between researchers, manufacturers, and end-users can enable key advances to facilitate rapid adoption of CMCs**

Power-station turbogenerator

Opportunity for revolutionary changes in the energy sector

Credit: "Turbogenerator01" by Siemens licensed under CCA 3.0.

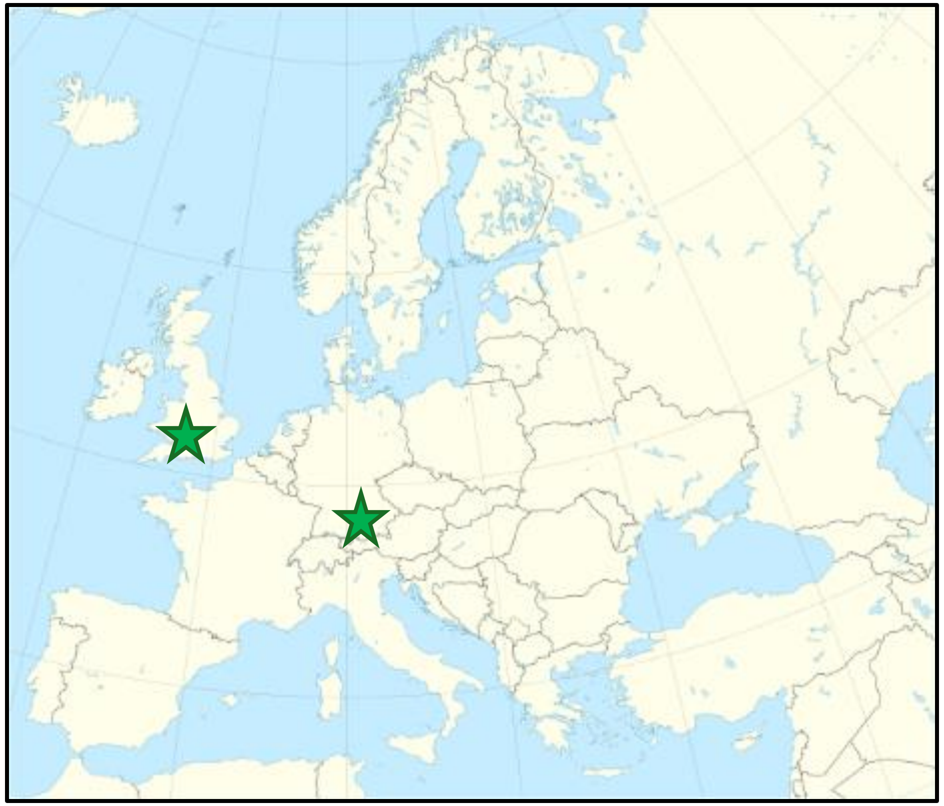


General Atomics EMS concept for cost-effective self-sustaining fusion system

Credit: General Atomics Electromagnetic Systems (GA-EMS), used with permission

National Institutes

- **National institutes play a key role in facilitating adoption of CMCs**
- **National Composites Centre (UK)**
  - Centre of excellence for composites research and development
  - Centre goals
    - World leader in composite technology
    - Accelerate the development and uptake of digital technologies for sustainable composites
    - Grow the market for composites by driving innovation through collaboration and partnerships
- **Ceramic Composites Network (Germany)**
  - Intensify the development and dissemination of CMCs for the benefit of German society and industry
  - More than 60 institutional members from leading companies and institutes throughout Germany



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Concluding Remarks

- **CMCs can be the next material revolution**
  - Rapidly maturing class of materials with potential to cause disruptive change across a wide variety of sectors
- **Enabling technology *and* benefit-multiplier**
- **Strongly contributing to implementation of environmentally-friendly technologies**
- **Providing significant economic benefits to countries and companies adopting CMCs**
- **Pace of advancement currently hampered by lack of awareness, lack of acceptance, and manufacturing challenges**
  - Advancements in manufacturing technology will strengthen business opportunities
- **Tremendous opportunity to assume a leadership role and provide wide-reaching benefits**