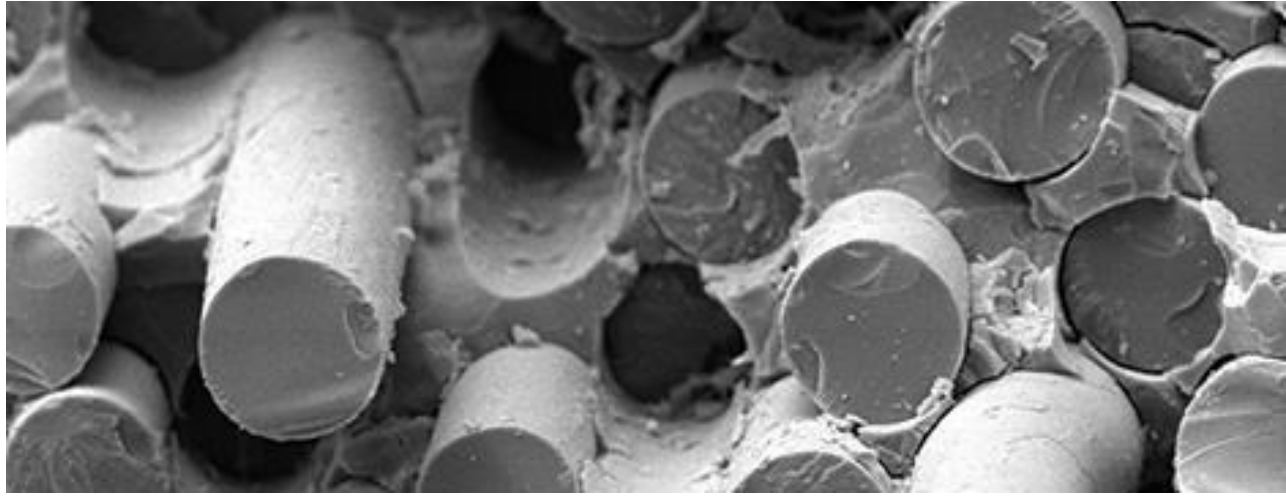
Research and Development Opportunities for Thermal/Environmental Barrier Coatings and Ceramic Matrix Composites for Hydrogen Gas Turbines



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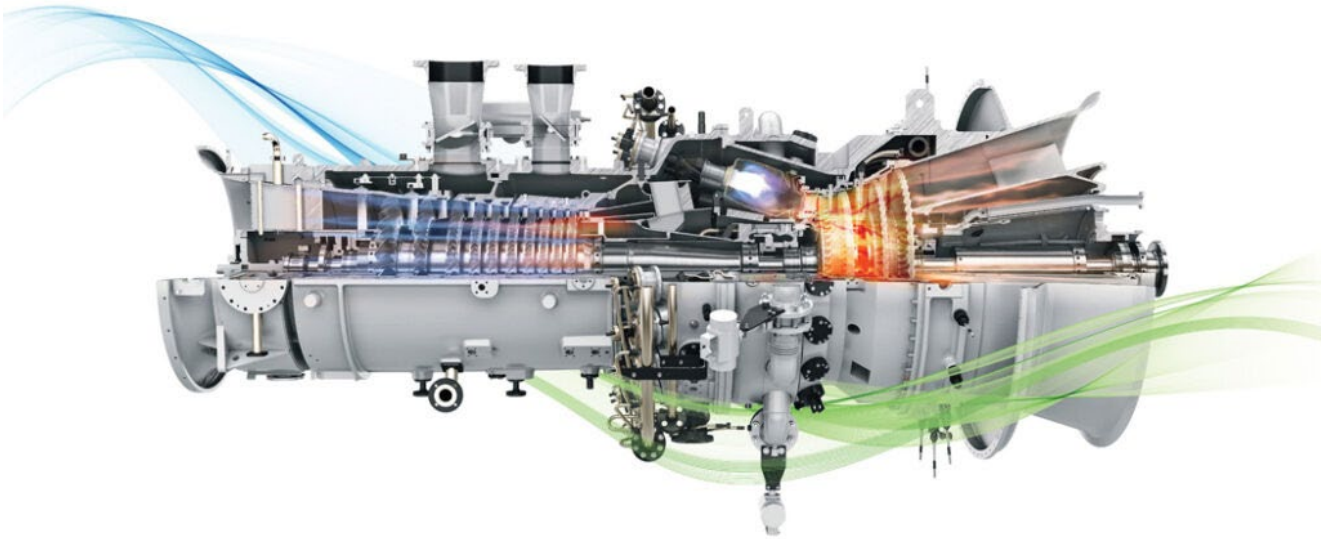


NATIONAL ENERGY TECHNOLOGY LABORATORY

2024 FECM/NETL Spring R&D Project Review Meeting

April 24, 2024

Pittsburgh, PA

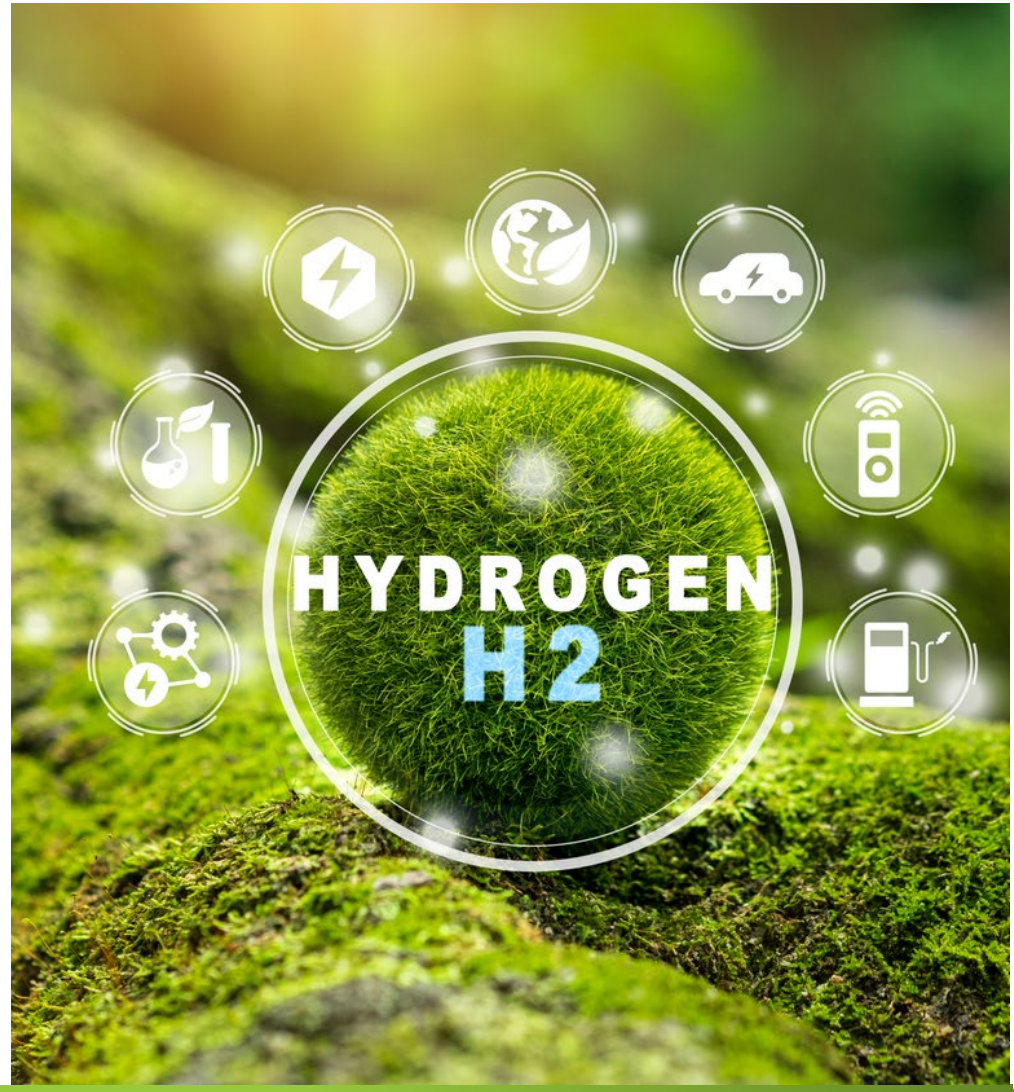
U.S. DEPARTMENT OF ENERGY

Overall Driver

The U.S. has a national goal of achieving a **net zero emissions economy by 2050**. Hydrogen is a clean alternative to replace fossil fuels for power generation to make that goal possible. In order to utilize hydrogen for land-based power generation, **turbine inlet temperatures and pressures will have to increase** to enable efficient and effective use of the fuel.

At current state there is significant R&D needed before a salable product utilizing ceramic matrix composites (CMCs) and environmental barrier coatings (EBCs) in hydrogen power generation is developed. Regardless, if industry wants to move to a hydrogen-based economy, these challenges must be overcome to make use of the fuel in utility turbines feasible.

Although the business case is currently stronger for aerospace and defense applications, there is a strong technical need for R&D in hydrogen-based power generation that will ultimately catalyze the shift to clean energy, improve energy efficiency of turbines, and reduce fossil energy emissions.



Project Goal

NETL is considering establishing a program to conduct research and development in environmental barrier coating (EBC) and ceramic matrix composites (CMC) with a focus on application in utility, land-based hydrogen gas turbines

GOAL

The goal of this project is to identify industry appetite for adoption of CMC/EBC systems in land-based hydrogen turbines and determine high impact research focus areas that could support technological development and cost reduction

1. What are the biggest challenge areas in design, development, and adoption of EBCs/CMCs?

2. What of those challenges could NETL play a unique role in addressing that would make the largest impact in advancing state of the art?

Approach

OVERVIEW

Market Overview

Conducted qualitative market assessment to understand which industries use CMCs/EBCs and for what component applications

R&D Focus Areas

Develop 'value chain' of CMC/EBC development to understand comprehensive list of challenges in commercializing both CMC/EBC systems

Prioritize Opportunities

Prioritize opportunities based on impact if solved, complexity, and NETL's capability alignment

Develop Program Pitch

Develop 'pitches' for program direction and funding that describe highest impact R&D efforts to invest in and why it is needed

Stakeholder Outreach

Conduct stakeholder outreach across small businesses, large OEMs, academia, government to gather insights largest market and technical barriers to commercialization and scaling of component systems across industries

What industries use the materials today?

Where are ceramic matrix composites used today?

Conducted qualitative market assessment to identify areas where CMCs could make an impact and understand industries with high willingness to pay that may impact adoption

Sector	Industry	2021 Revenue ($/domestic)	Projected Growth	Temperature Requirements	Gov. Funding	Private Funding	Current CMC Market Penetration	Current superalloy Demand	Willingness to pay	Mature vs. new market
Aerospace & Defense		800B	2.6%	1400-1800C	High	High	High	High	High	Mature
Automotive	High Performance Vehicles			1000-2000C	Low	High	Low	High	High	Mature
Energy	Natural Gas Power Generation	100B	0.2%	1200-1600C	Medium	Medium	Medium	High	Medium	Mature
	H2 Power Generation	10-30B	5%	1400-1600C	High	High	Low	High	Medium	New
Industrial	Steel	112B	4%	1500-1600C	Low	Low	Low	Medium	Low	Mature
	Cement	30B	3.5%	1450-1500C	Low	Low	Low	Low	Low	Mature
	Chemical Processing				Low	Low	Low	Medium	Low	Mature
Biomedical	Devices	200B	4.5%	--	High	High	Medium	High	High	Mature

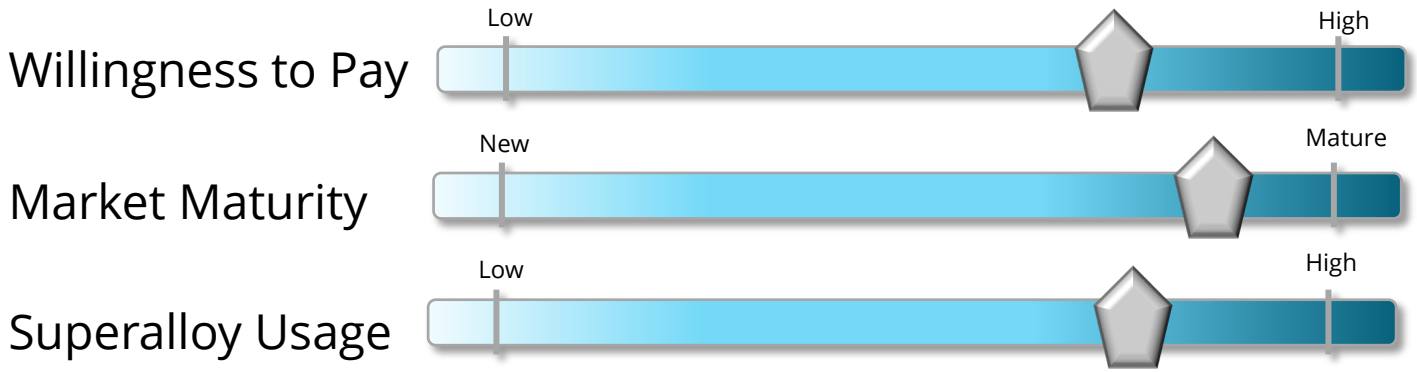
High Performance Automotive Vehicles

Low volume yet high value market with to high willingness to pay, more likely to be an early adopter of CMC/EBC technologies

Market Characteristics

US Market Size
$1-7B

CAGR
1-2.6%



Companies

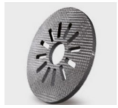
sgl carbon

Audi

PORSCHE

On the Market

SGL Carbon Sigrasic
C/SiC components – clutch disk



Audi R8 V10 Coupe
C/SiC Brake System

Porsche Ceramic Composite Brakes
Porsche 996 Turbo – C/SiC brake system

Components

Brake discs
Clutch plates
Suspension components
Chassis

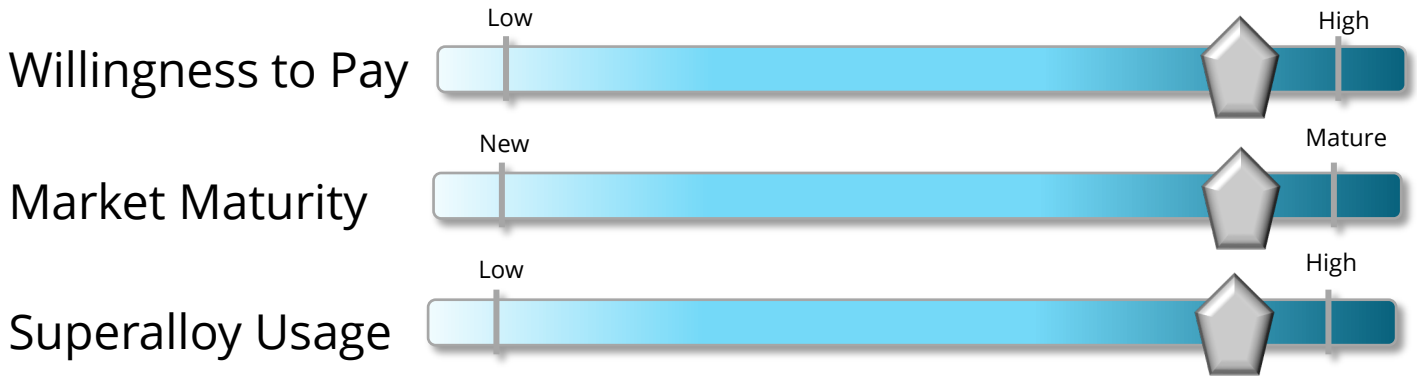
Aerospace and Defense

High volume, high value market due to high willingness to pay, likely first adopters of CMCs and EBCs

Market Characteristics

US Market Size
$800B *(2021)*

CAGR
2-3%



Companies

SIEMENS

DEVCOM

On the Market

GE LEAP Engine
SiC/SiC inner/outer liner, shrouds, blades, nozzles & EBCs

Rolls-Royce UltraFan
SiC/SiC components & EBCs

Siemens & Pratt and Whitney – GTF Advantage Engine
SiC/SiC components and coatings

Components

Turbine Blades
Vanes
Nozzles
Inner/Outer liners
Shrouds

Natural Gas and Hydrogen Power Generation

Hydrogen market low volume and uncertain value, while natural gas power generation high volume, low willingness to pay. Hydrogen market less likely to be first adopters of CMCs/EBCs due to uncertain market development

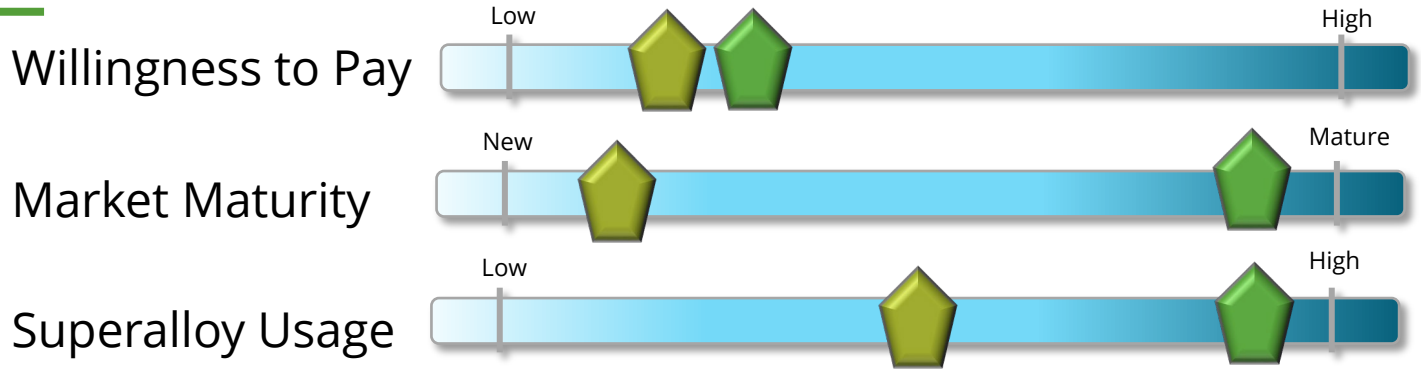
Market Characteristics

Natural Gas Power Generation

US Market Size - $100B CAGR- 0.3%

Hydrogen Power Generation

US Market Size – $10-30B CAGR- 4.%



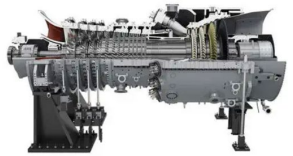
Companies On the Market

SIEMENS

GE 9HA Gas turbine

R&D to develop SiC/SiC CMCs for turbine blades and nozzles, 50% hydrogen capable with technology pathway to 100%

Siemens Gas SGT-8000H Turbine



R&D to develop SiC/SiC combustor liners, TEBC development, can incorporate up to 30% hydrogen

Components

Turbine Blades
Vanes
Nozzles
Inner/Outer liners
Shrouds

What are the biggest material challenges across the supply chain?

Stakeholder Outreach Across Value Chain

10 Interviews Completed

Government

Commercial Value Chain

Technology Innovators

Small Business

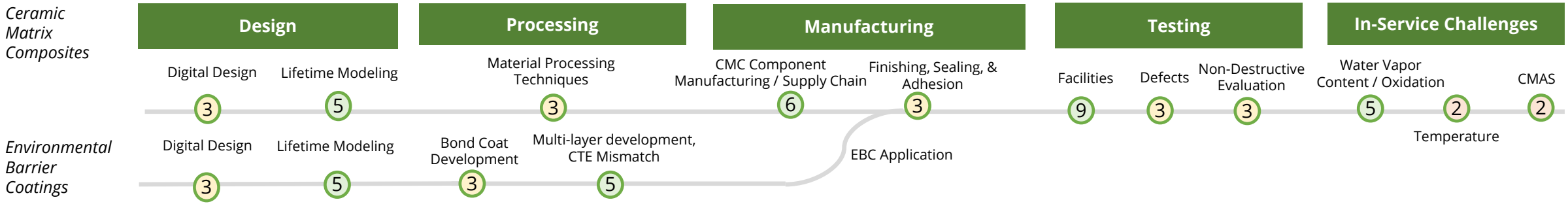
Academic

Non-Profit R&D

Challenges in CMC/EBC Development Process

(#) = number of times mentioned in interviews

**The items listed below do not represent an exhaustive list of steps in the development of CMCs and EBCs, rather highlight main challenges described by industry across the value chain and development of CMCs and EBCs*

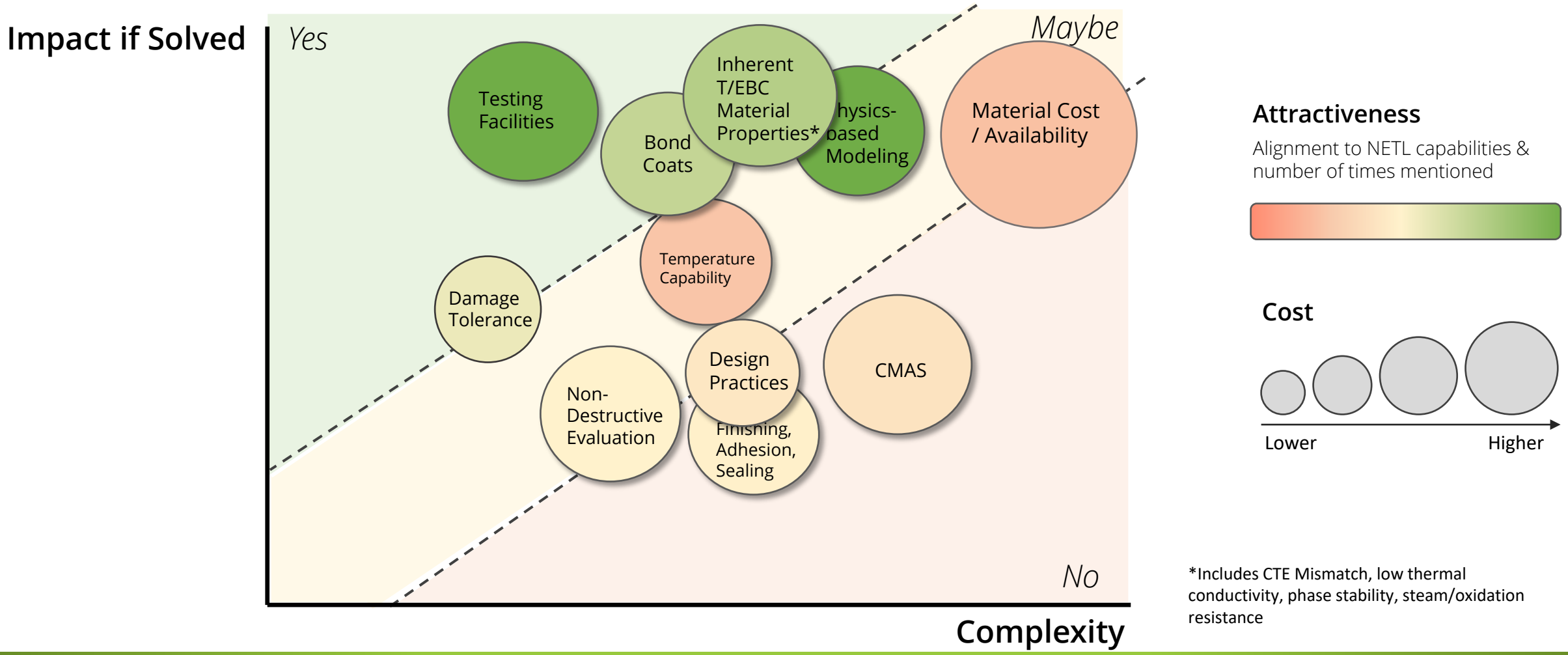


	Design	Processing	Manufacturing	Testing	In-Service Challenges
Challenge	• CMCs/EBCs unique properties require new design tools • Turbines typically have larger, more complex parts that require designing uniquely for application • Modeling tools with databases of quality characterization data is complex and nonexistent	• Significant investment required to acquire materials or develop infrastructure to make the materials • Long lead times to acquire the often-proprietary materials • CTE mismatch • Delamination of Bond Coat, reaching temperature limitations of silicon bond coat	• Establishing a supply chain, both from material processing and equipment/facilities standpoint is the biggest barrier to commercialization • Finishing/sealing important step in ensuring EBC properly joined and will stay attached to CMC component	• Limited testing facilities with realistic environments • Understanding of true failure mechanisms • Non-destructive testing processes and standards • Understanding of 'reasonable' defects	• Increased water vapor content, higher rate of material loss, oxygen attack • Next generation EBCs looking at temperature capabilities higher than current state of the art • CMAS will cause degradation of material at rapid rate
Opportunity	• Concurrent modeling/design and establish design practices • NETL to be 'data-broker' of quality characterization data and develop needed physic-based tool	• Alternative bond coat designs • Opportunity for compatible layer coating systems to mitigate CTE mismatch • Case for simpler EBC designs • Alternative processing techniques that produce less waste	• Tools and standardized practices for finishing and sealing components	• Develop testing rigs that can provide value to various industries • Characterize true failure mechanisms and document in database • Develop standard	• If EBC/CMC can be successfully developed and validated at 1400C, business case will exist • Steam resistant barrier coatings • Systems for managing and mitigation CMAS
Companies	Design tools/Practices Life prediction models	CTE Mismatch Bond Coat Development Material Processing	Manufacturing/supply Chain Finishing, Sealing, Adhesion	Facilities Defects/NDE	Water Vapor / Steam / Oxidation CMAS Temperature

What opportunities should NETL prioritize?

EBC Opportunity Spaces

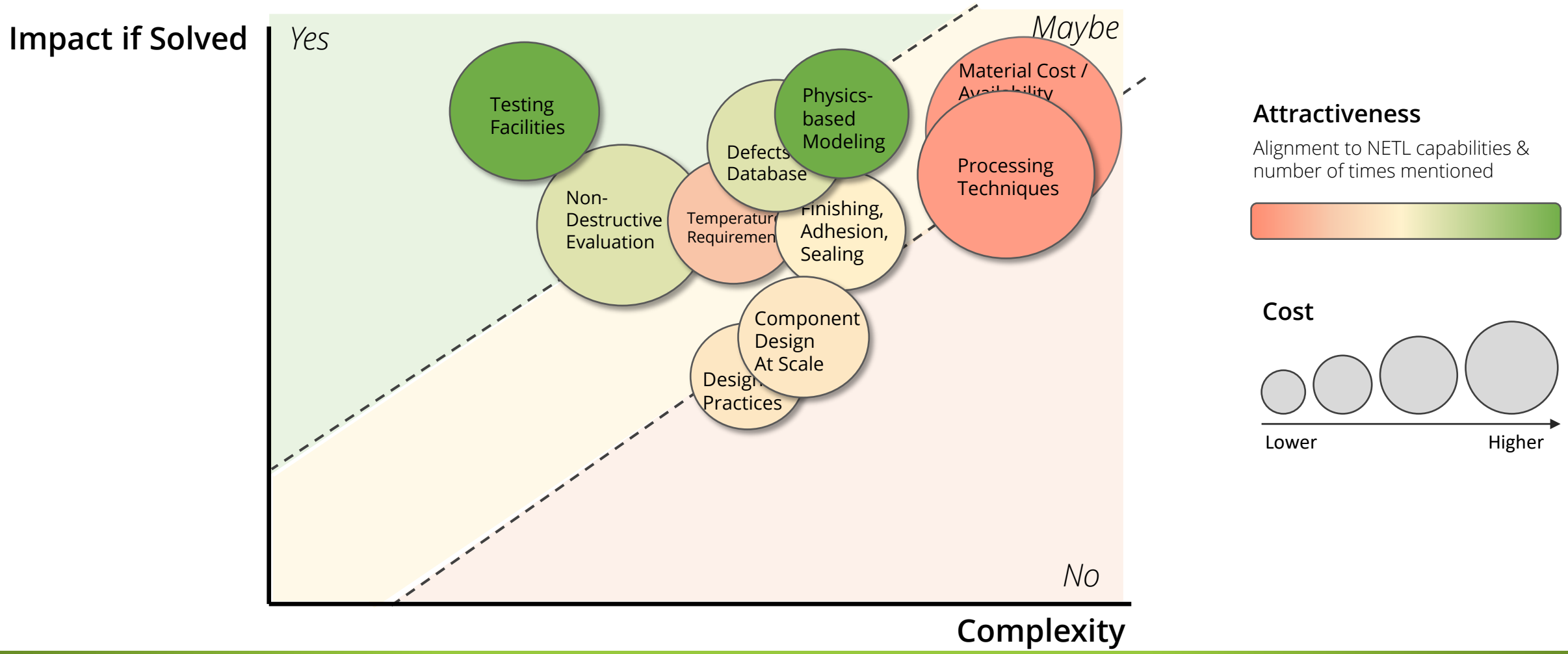
We qualitatively assessed the raw opportunities highlighted by industry as most important challenges to enable adoption of EBC/CMC s



*Includes CTE Mismatch, low thermal conductivity, phase stability, steam/oxidation resistance

CMC Opportunity Spaces

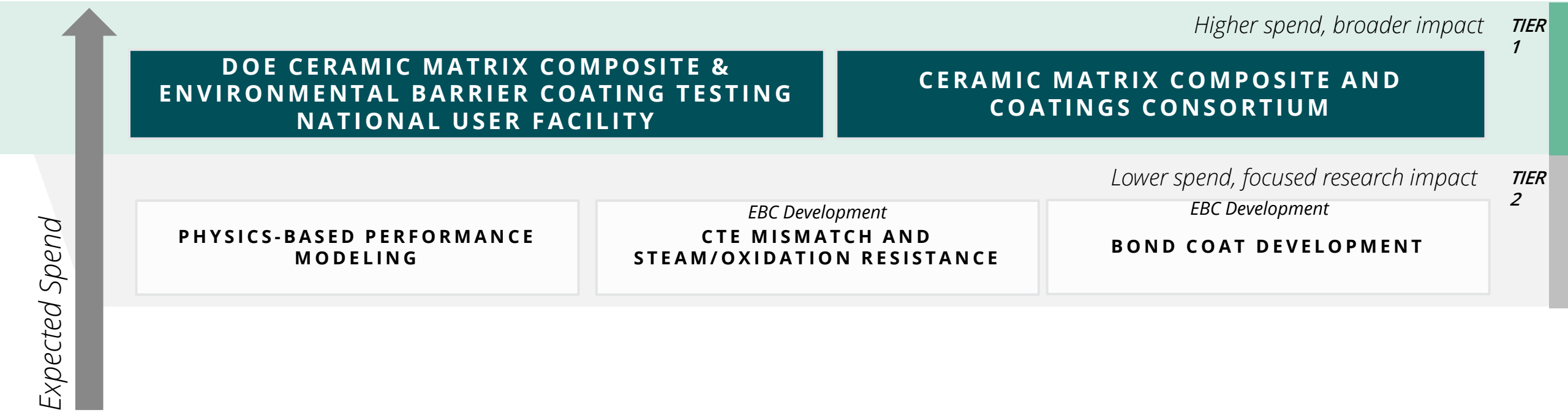
We qualitatively assessed the raw opportunities highlighted by industry as most important challenges to enable adoption of EBC/CMC s



NETL Program Opportunity Summary

Conversations with industry highlighted various persisting technical needs and challenges in EBC/CMC development process and the difficulty with overcoming the value of death in power-generation applications. Given the information NETL has discovered through extensive engagement with industry, the following opportunities ranging from higher spend and broader impact to lower spend and a more specific, focused research impact

NETL Program Initiative Opportunities



NETL Program Focus ‘Pitches’
Why NETL should prioritize these areas

CMC/EBC Testing - National User Facility (1/3)

Testing facilities with robust capabilities that can closely **simulate operating conditions and simultaneously evaluate operational environment synergies** provides performance foresight that **validates component/material durability, provides critical material characterization data, and reduces likelihood of failures**. Unlike basic furnace testing on the market, NETL possesses facilities that are less costly than full engine tests and enables testing of materials in a flexible and controllable way. By establishing the test facilities as a National User Facility (NUF), NETL can provide world-class resources and expertise to accelerate deployment of CMCs/EBCs within the power generation industry and beyond.

Testimonials

> "Testing capabilities that can validate materials across (specified rigs included in next slide) could validate EBCs with fairly high confidence to TRL 4-5"

> "It is very difficult to obtain high-quality characterization data at the right pressures, enthalpy flow rates, and in an adjustable and collectible way."

> "There is a lot of interest in use of our facility, however system can only be used at rate that is determined by staff who know how to operate and use it."

Impact Summary

Who mentioned it?

Impact if Solved

Whether in aerospace, hypersonic/missile, or land-based power generation applications, testing facilities were mentioned by nearly every organization as a persisting need relevant to any industry implementing CMCs/EBCs to component systems

NETL Capability Alignment

CMC/EBC Testing - National User Facility(2/3)

Industry challenges

Capability Gaps

Testing facilities often lack the capabilities/rigs to test materials in the relevant operating environments, such as cycling/steam cycling rig, laser rig for testing high temperature gradient, natural gas rig/hydrogen environment rig to simulate steam

Limited Availability

For the facilities that do possess the required capabilities, wait times and availability is limited

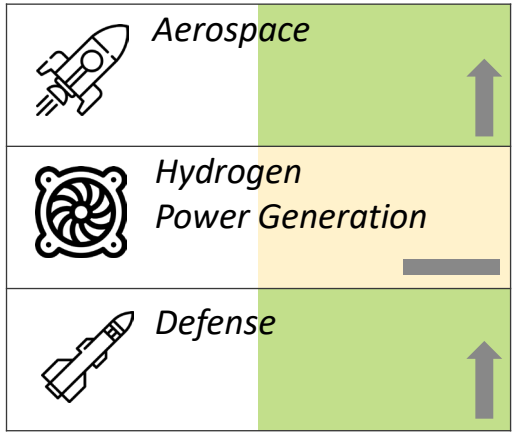
Quality Data Capture

It is difficult to generate high-quality data in an adjustable and collectible way

Limited Staff

Industry players with established facilities indicated challenges with keeping the doors open due to limited number of personnel with know how to operate the facility

Applicable Markets & Growth



Opportunities:

NETL to build off testing facility development to establish a National User Facility that can accelerate state of the art for CMCs and EBCs for power generation applications and beyond.

CMC/EBC Testing - National User Facility(3/3)

NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL BUDGET REQUEST

$5M

For continued development of infrastructure, to stand up user facility, and operate the facility long term

3 Years

Industry Survey	Facility Structure	Mission Establishment	Acquire Infrastructure	Acquire Members	Operation	Branding
Survey industry and decide on priority capabilities and equipment most needed to advance state of art using starting list: • Cycling/steam cycling rig • Laser Rig/high temperature gradient infrastructure • Natural gas/kerosene simulation	Decide on structure of facility (public/private partnership, incubator, National User Facility with associated Consortium Connect with Oakridge for lessons learned on CMC Fiber NUF, Haydn Wadley at University of Virginia, and Kang Lee at NASA,	Establish vision for the facility and overall mission/objectives	Begin build out and acquisition of capabilities prioritized as highest impact	Acquire list of members who will use the facility and co-location space	Acquire, train, upskill faculty and personnel to operate the facility	Develop website to showcase the facilities capabilities