Forced Flow Thermal Gradient Chemical Vapor Infiltration (FCVI) of Complex-Shaped Turbine Components

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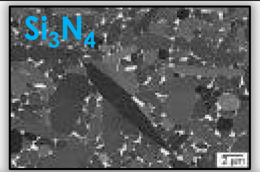
ORNL advanced materials development: history and future

1950's ORNL Develops Advanced Ceramics
Aircraft Nuclear Propulsion Program

ORNL Ceramic Technology Project
Structural ceramics for auto and gas turbines
- Si_3N_4, SiC, Oxides
- Monoliths & CMCs
- SiC Whiskers
- CVI of SiC matrix
- Metal Carbides



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ORNL MSTD & MSD Revitalizes Ceramic & Composite R&D
Ceramics, composites and hybrid materials for extreme environments
- New vapor reactors
- New ceramic fab labs
- Strategic hires
- Retained expert staff
- Development of novel materials, processes and components

html HIGH TEMPERATURE MATERIALS LABORATORY

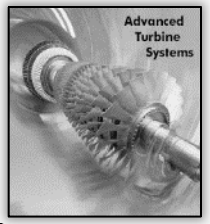
Advanced ceramics and composites for heavy vehicle engines and gas turbines
- Advanced processing & characterization
- Toughened ceramics – monolithic Si_3N_4
- SiC/SiC & Oxide CMCs

ORNL's FUTURE: Develop novel extreme environment materials, microstructures, and fibers, and the advanced manufacturing processes required to fabricate them

1950 — 1980 — 1990 — 2000 — 2010 — 2022

CFCC

DOE CFCC Program
SiC/SiC Continuous Fiber Ceramic Composites
- Materials Development
- Engine Demonstrations



DOE ATS Program
60% Turbine Efficiency
- Single Crystal Alloy Blades
- Advanced Coatings
- Engine Demonstrations

CARBON FIBER TECHNOLOGY FACILITY

DOE User facility for carbon fiber innovation
- 42,000 sq ft, 25 tons/year
- C fiber, SiC fiber, ??? fiber

Manufacturing Demonstration Facility
Improving competitiveness of American manufacturing
- 110,000 sq ft facility
- Manufacturing 4.0
- Simulation & analysis
- AM equipment across all scales
- Polymers, PMCs, metals, ceramics and CMCs

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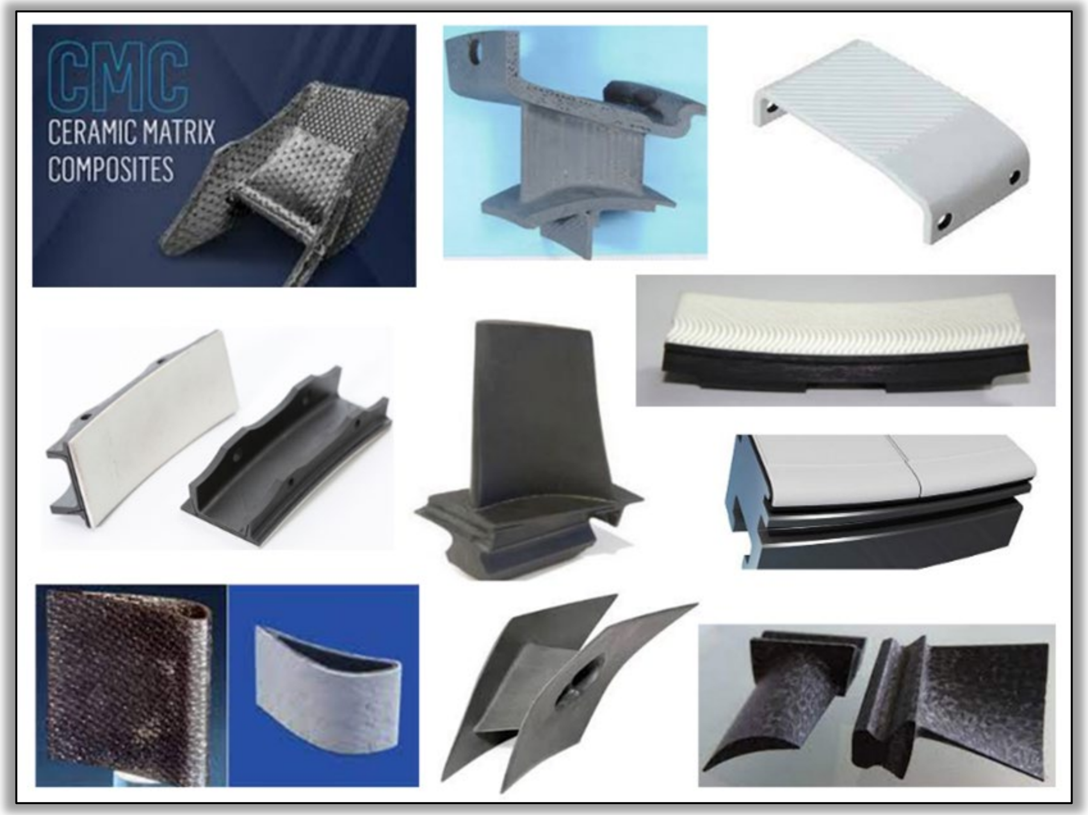
CMCs are advancing energy efficiency and decarbonization

- In 1970's DOE established the Advanced Research and Technology Development Program
- Structural ceramics was a thrust topic
- CFCC Program further developed SiC/SiC CMCs with industry & academia
- SiC/SiC CMCs currently employed in GE LEAP aircraft engines
- **CMCs must be more cost-effective for deployment in industrial gas turbines**

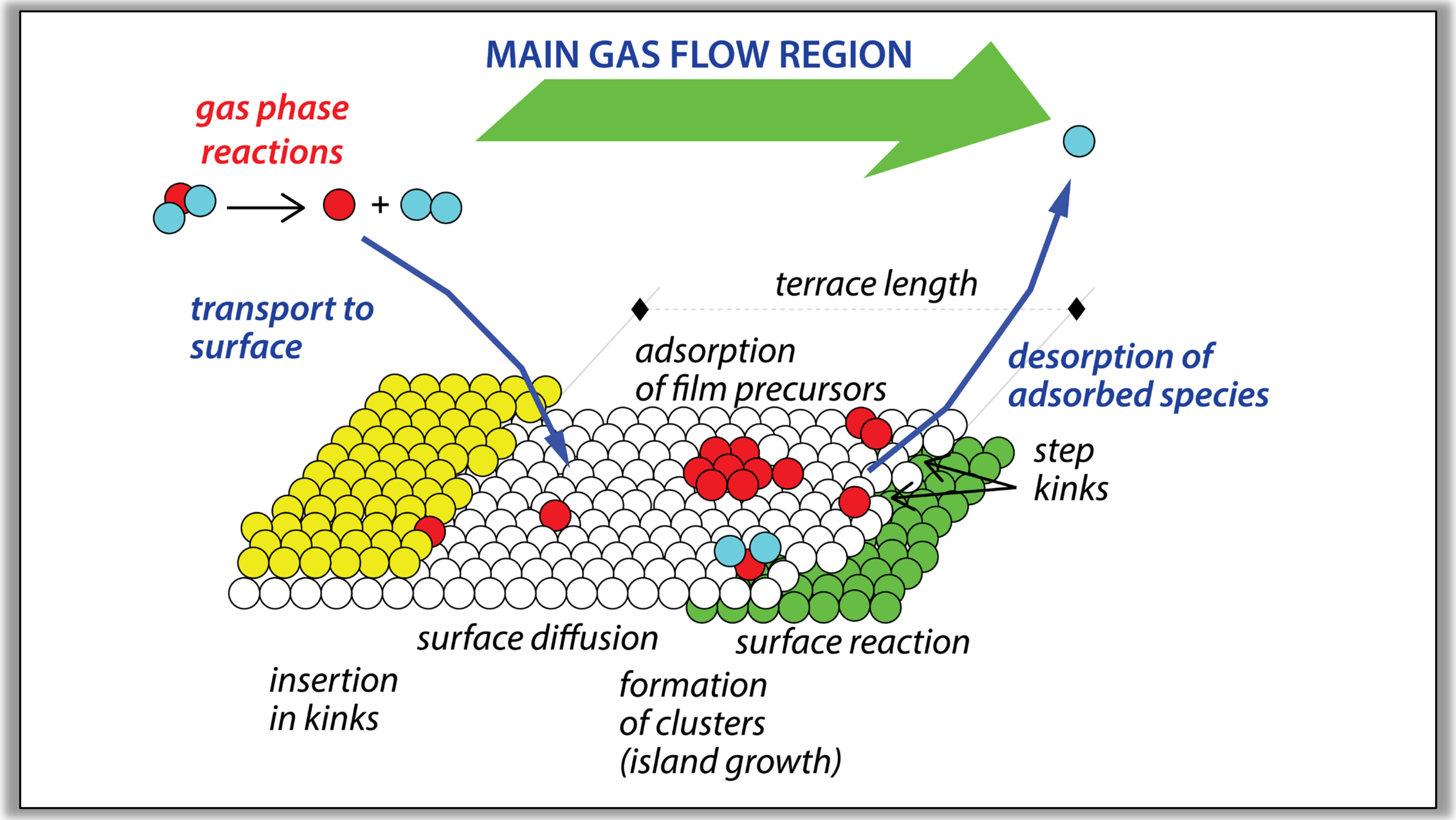


CFCC
CONTINUOUS FIBER CERAMIC COMPOSITE MATERIALS

Ceramic composites were the focus of the Structural Ceramics thrust area!

Chemical vapor processing produces phase-pure materials

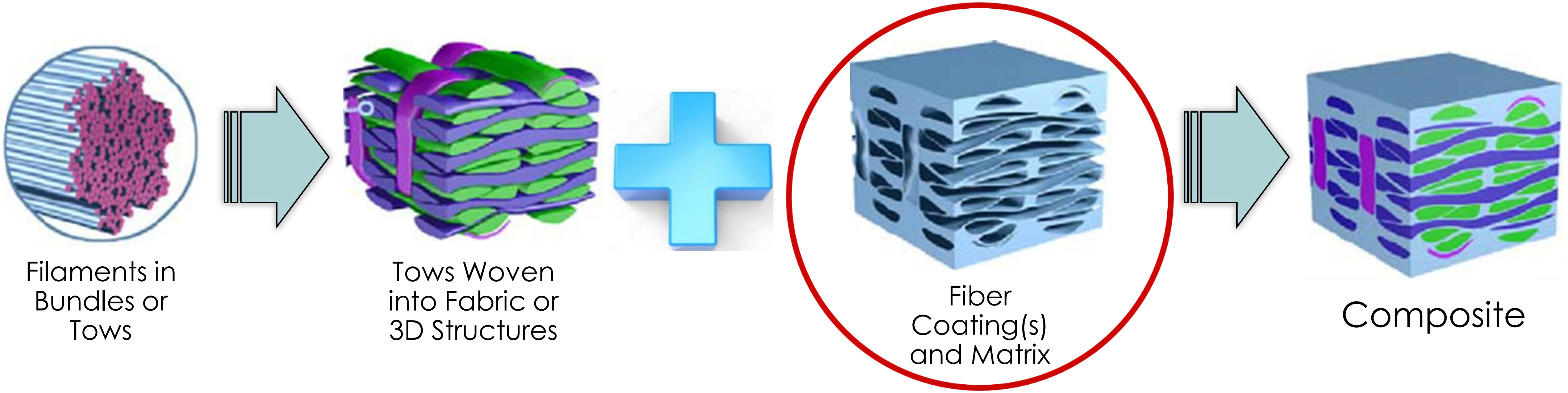
- Gases react or decompose to form solid layers on surfaces.
- Can deposit coatings and/or fabricate free-standing bodies and CMCs



CVD is simply gas-to-solid additive manufacturing!

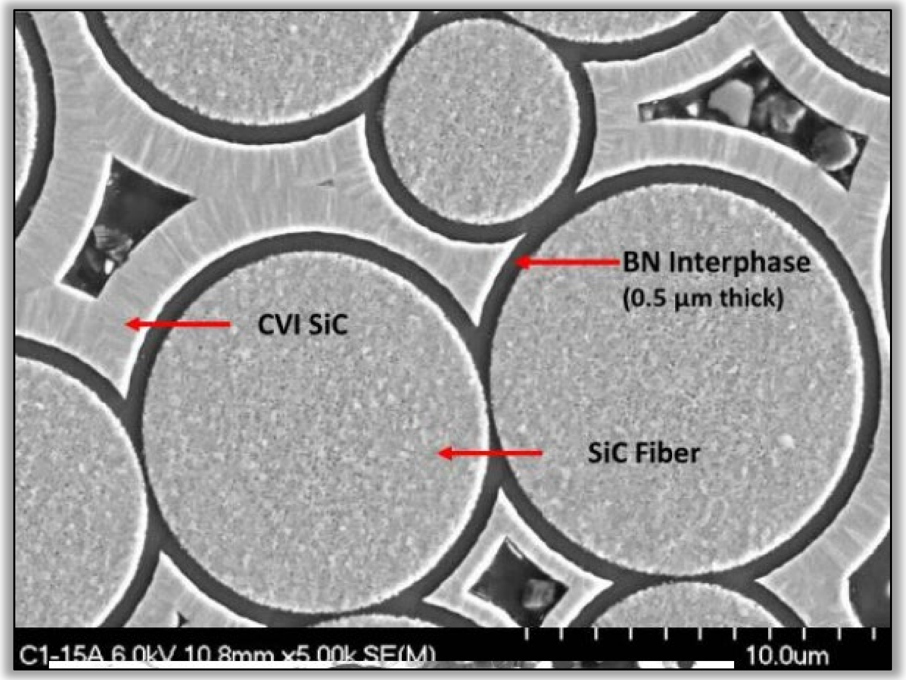
CVI can provide a near-stoichiometric, crystalline SiC matrix

- CVI capable of depositing a highly stoichiometric crystalline SiC matrix material at a relatively low temperature
- Reactive Melt-Infiltration (MI) results in residual silicon
- Polymer Infiltration and Pyrolysis (PIP) leaves residual carbon and amorphous SiC
- CVI currently provides the highest temperature capable SiC matrix of up to ~1700C



CVI forms an excellent matrix, but takes **months** to process

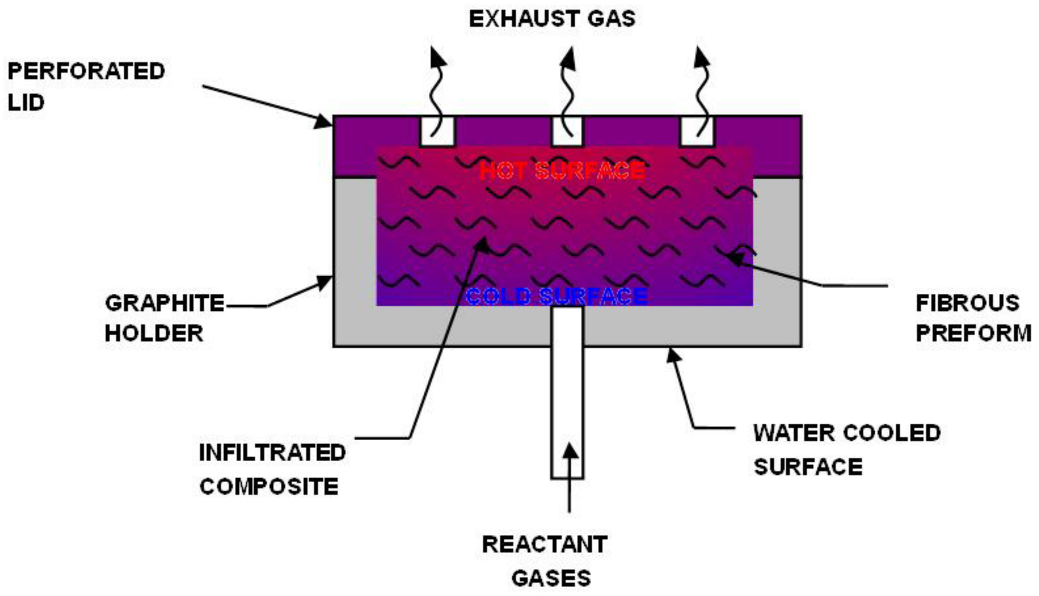
- Isothermal isobaric ICVI fills the void space in the composite uniformly
- Low temperature and pressure to allow filling voids before skinning, preventing additional gas entry (SLOW!!)
- Commercial ICVI process requires removing parts often multiple times to grind the SiC outer skin off and continue the ICVI process

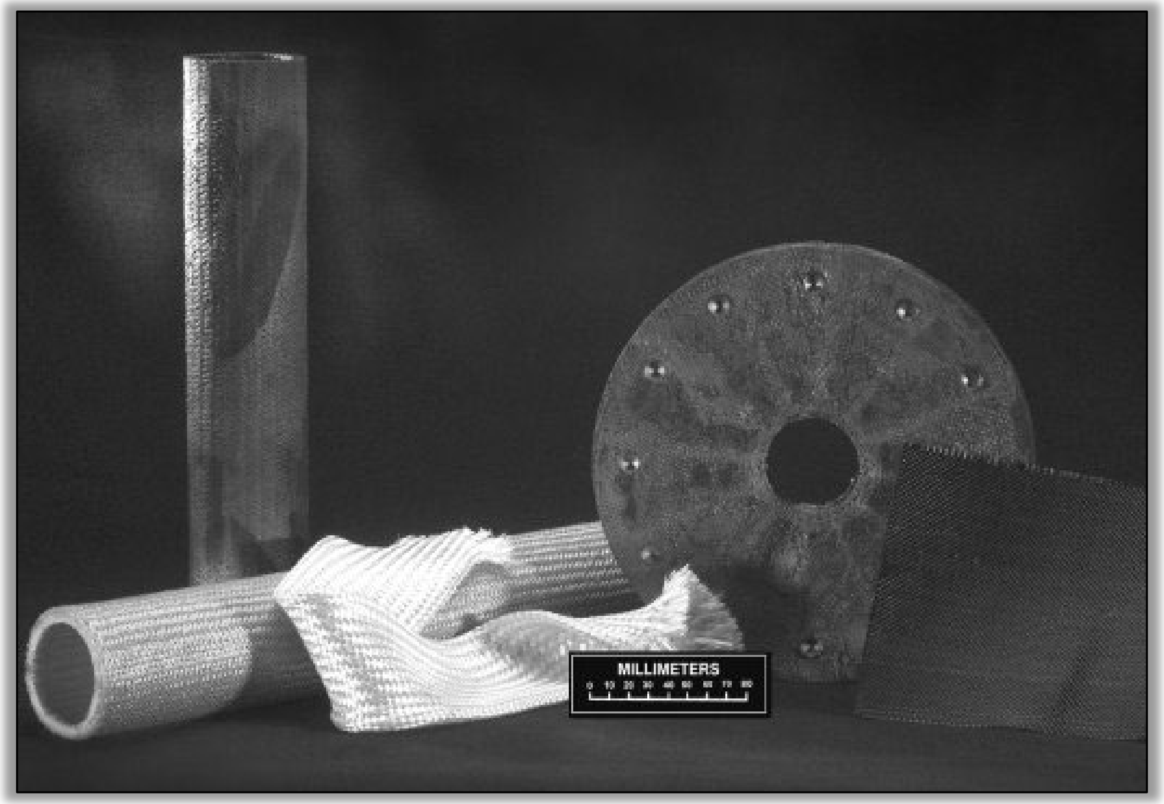


Takes months to process a set of parts via ICVI

Gen 1 FCVI process developed at ORNL orders of magnitude faster

- Forced flow thermal gradient chemical vapor infiltration (FCVI) **reduced process time from months to < 1 day**

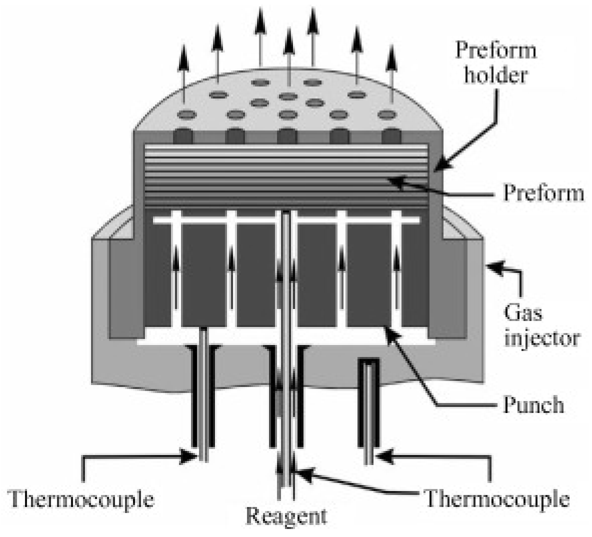


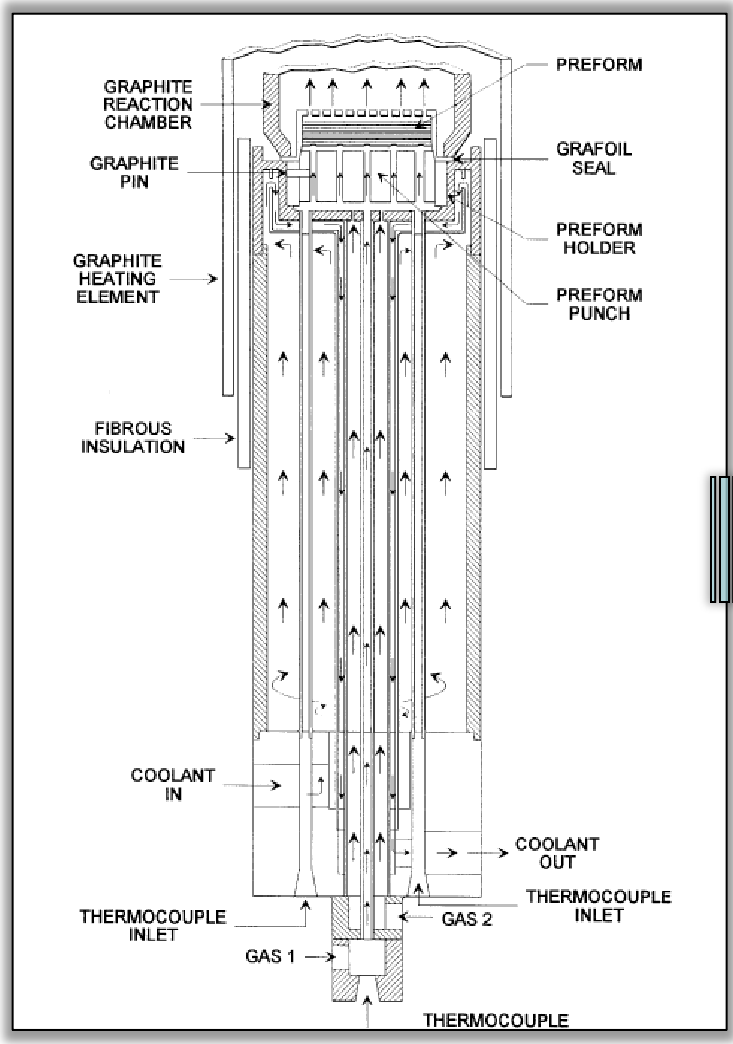


FCVI at ORNL began in 1982 with funding from Fossil Energy and the Air Force

Gen 1 FCVI reactor and process was limited to simple flat shapes

- First generation FCVI process used machined graphite mandrels with machined holes for cooling air
- Component shapes possible were limited to pucks, disks and tubes by conventional graphite machining





Gen 1 Reactor Configuration

AM can create complex graphite shapes and internal passages

- AM can create complex shapes with internal cooling passages of nearly infinite size and shape
- ORNL has demonstrated printing complex carbon structures followed by graphitization
- Complex shaped graphite hot and cold side CMC preform holders can be fabricated, enabling FCVI of complex shaped components!

FCVI of complex shapes is enabled by AM of carbon plus graphitization

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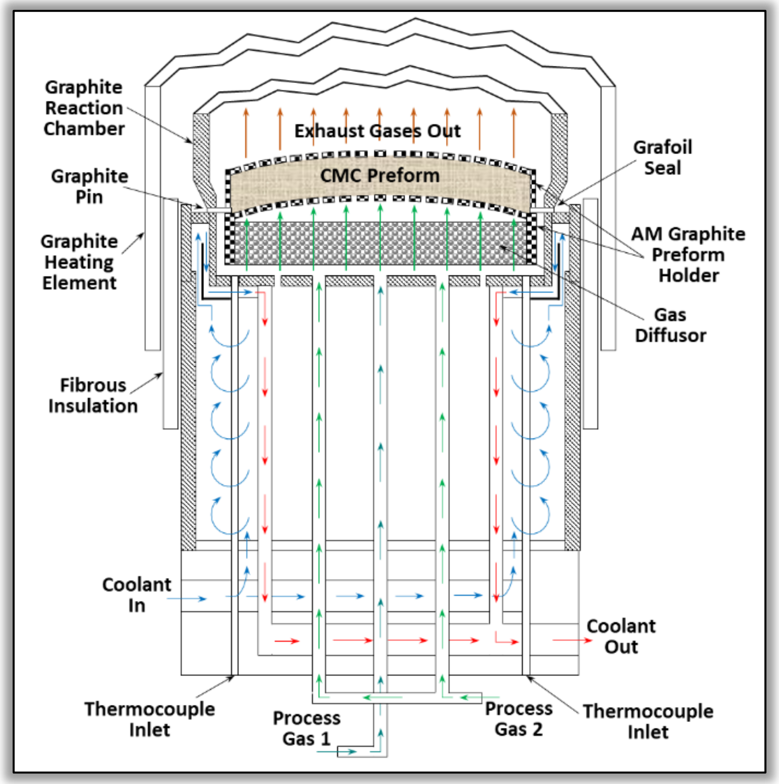
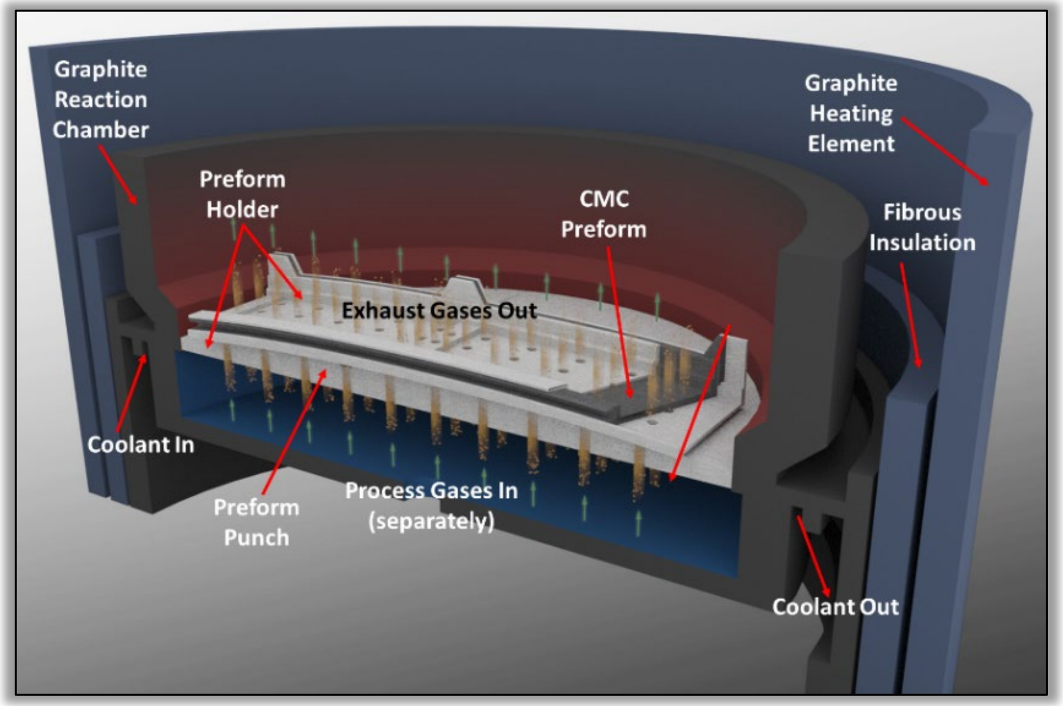
Gen 2 FCVI reactor for complex-shaped components concept

- Gen 2 FCVI reactor design will be a vertical tube furnace reactor configuration
- Working with power generation turbine manufacturer to fabricate a relevant component shape
- Reactor has complex shaped graphite preform mandrels being fabricated at via robocasting, then graphitized

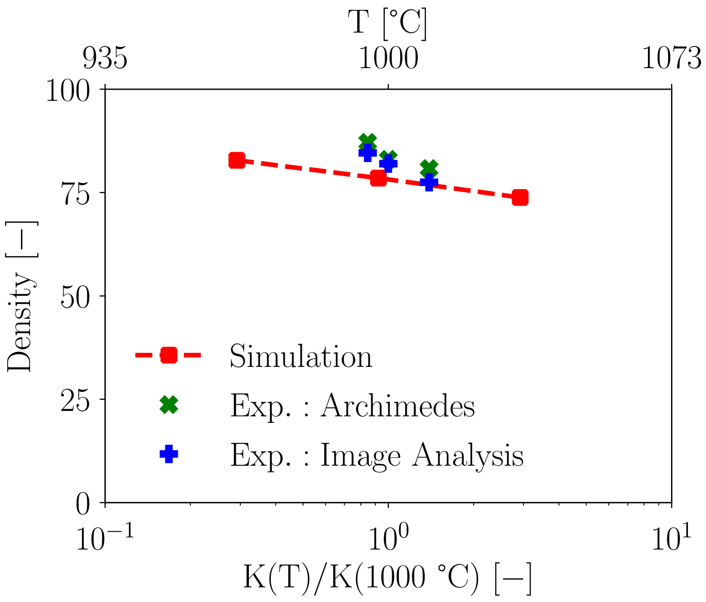


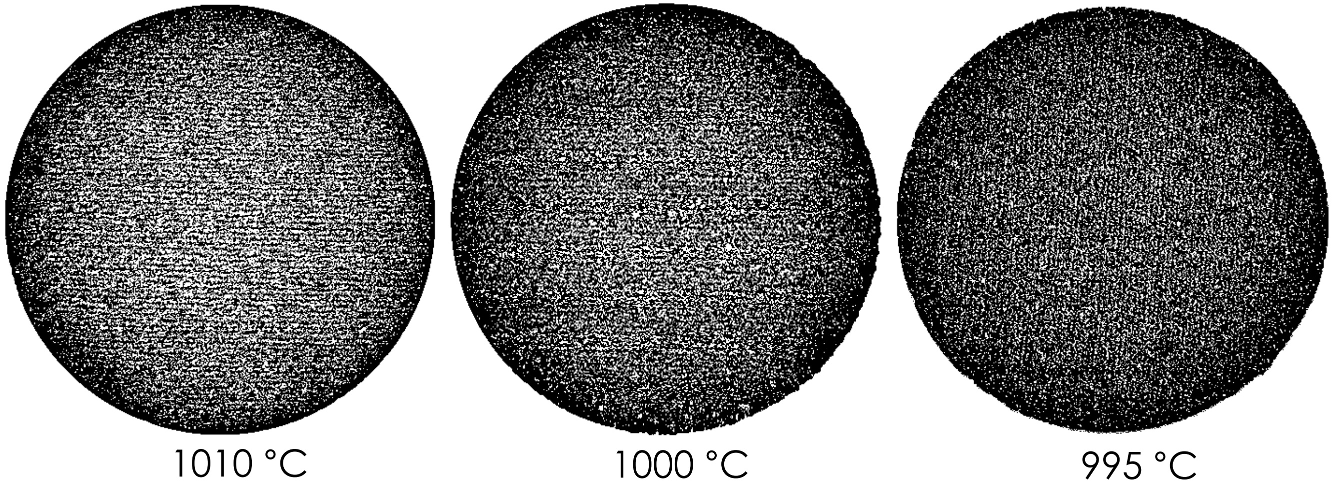
Gen 2 Reactor CMC Preform Section



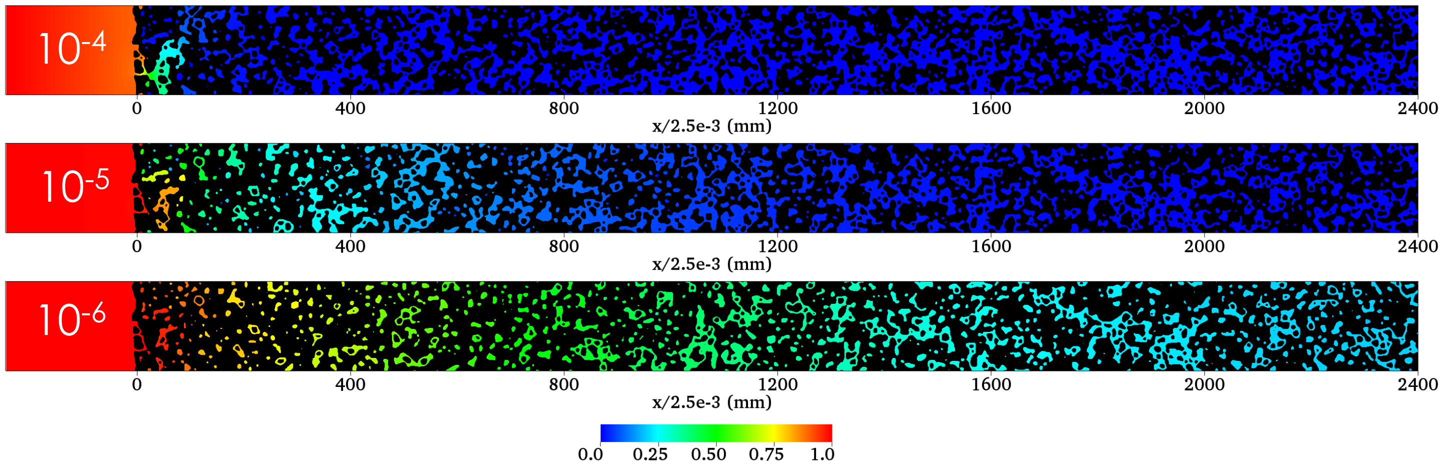
Modeling isothermal CVI deposition process inside porous body

- Quilt is a HPC code for reactive transport through porous media
- Simulations validated against CVI in Additively Manufactured Preforms





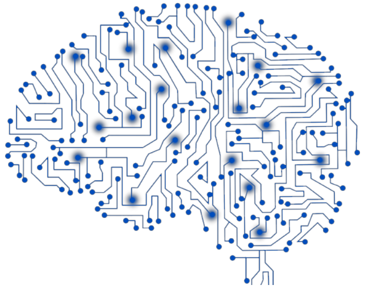
Chemical Vapor Synthesis of Additively Manufactured Porous Spherical Preforms at three different Temperatures



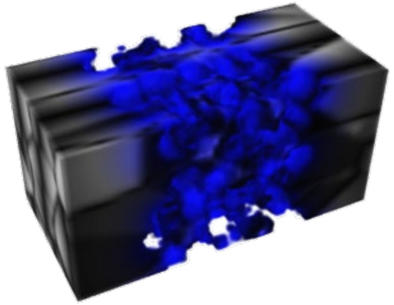
Pore resolved direct numerical simulations (DNS) showing densified preform along with concentration distribution

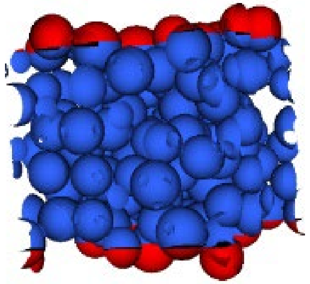
V. Ramanuj, R. Sankaran, B. Jolly, A. Schumacher, and D. Mitchell, "Chemical vapor infiltration of additively manufactured preforms: Pore-resolved simulations and experimental validation," JACerS, 2022, doi: 10.1111/jace.18226.

FCVI modeling used to guide reactor design of experiments



- Develop heat transfer model to capture the thermal gradient
- Simulate reactive flow and densification under non-uniform temperature
- Analyze the densification characteristics
  - Total and spatial distribution, terminal state, processing time, etc.
- Calibrate model variables with data from FCVI reactor experiments
  - Apparent activation energy, transport models
- Use parametric FCVI simulations to guide design of experiments



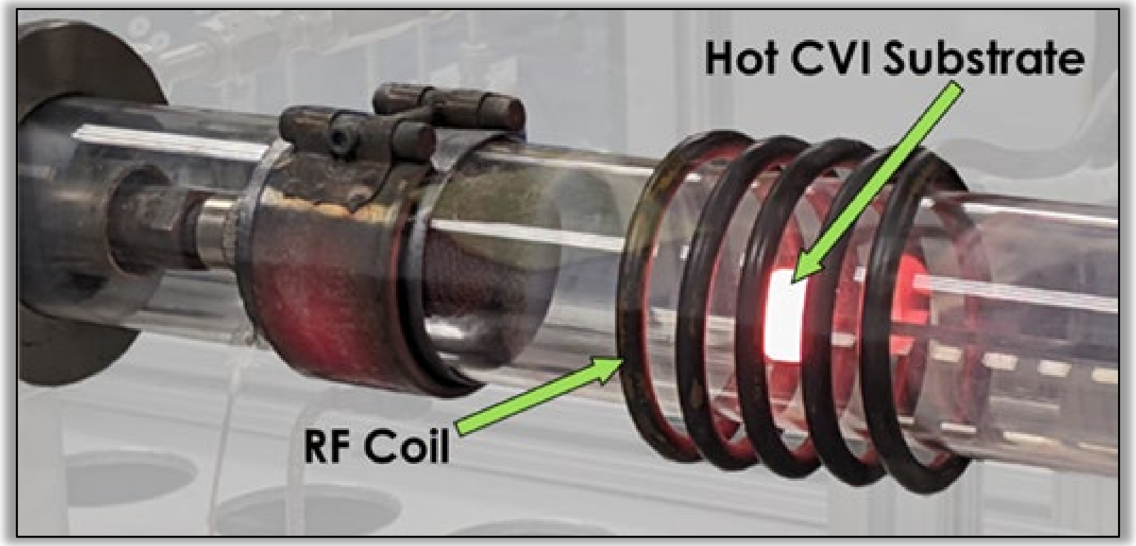


Development schedule for FCVI of complex shapes

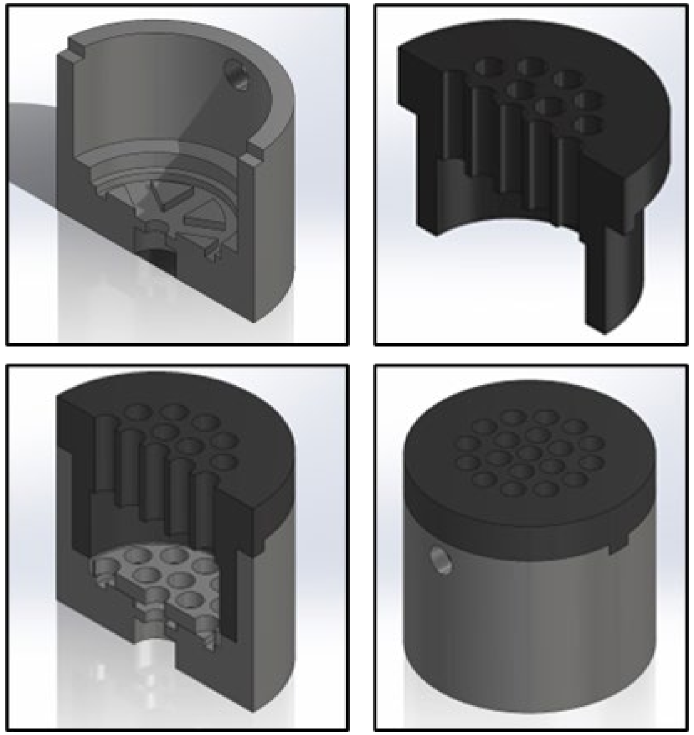
Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Fabricate New FCVI Reactor			1				4					
Process Modeling of FCVI				3					6			
Fabricate AM Graphite Tooling				2								
Fabricate Airfoil Composite Components								5		7		
Microstructure and mechanical properties												8

Innovative cold-wall reactor concept will undergo feasibility testing

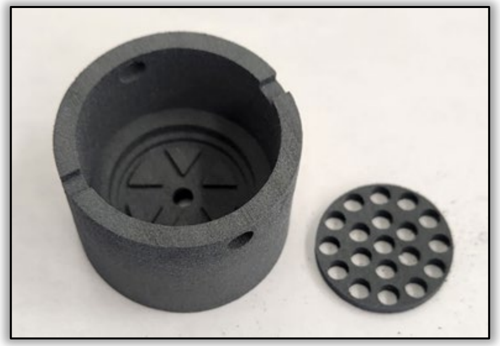
- Alternative cold-wall CVD/CVI reactor concept
- RF generator heats graphite/SiC integrated tooling
- Feasibility demonstration being pursued
- SiC and graphite tooling designed
- SiC tooling BJAM fabricated and CVI densified
- Graphite tooling ordered



CAD model of a graphite/SiC preform tooling for cold-wall CVI reactor.



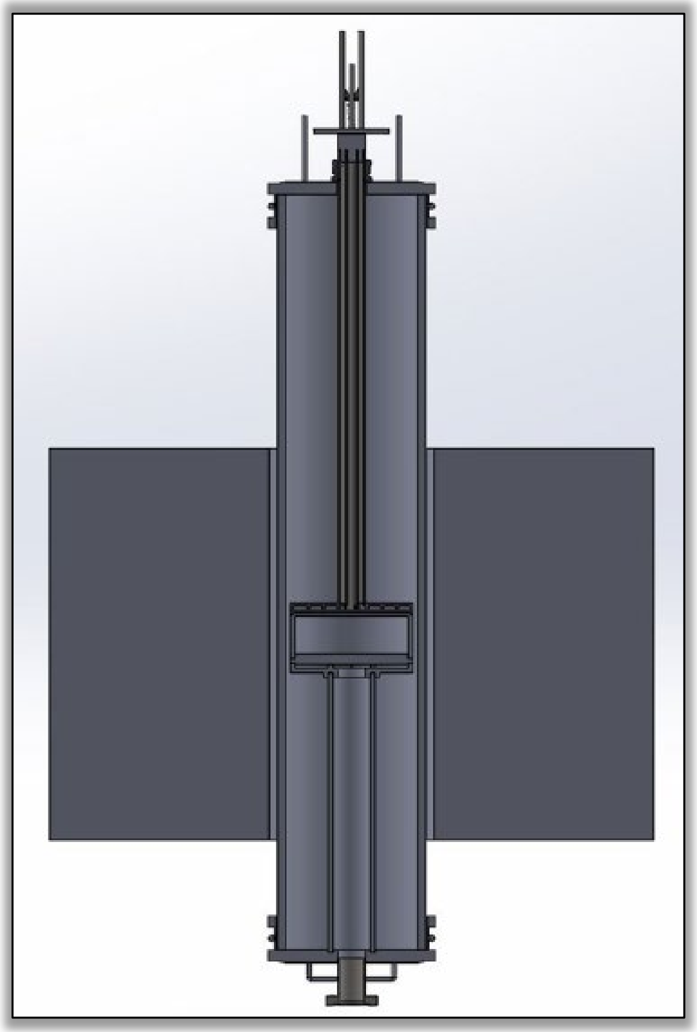
SiC tooling BJAM fabricated



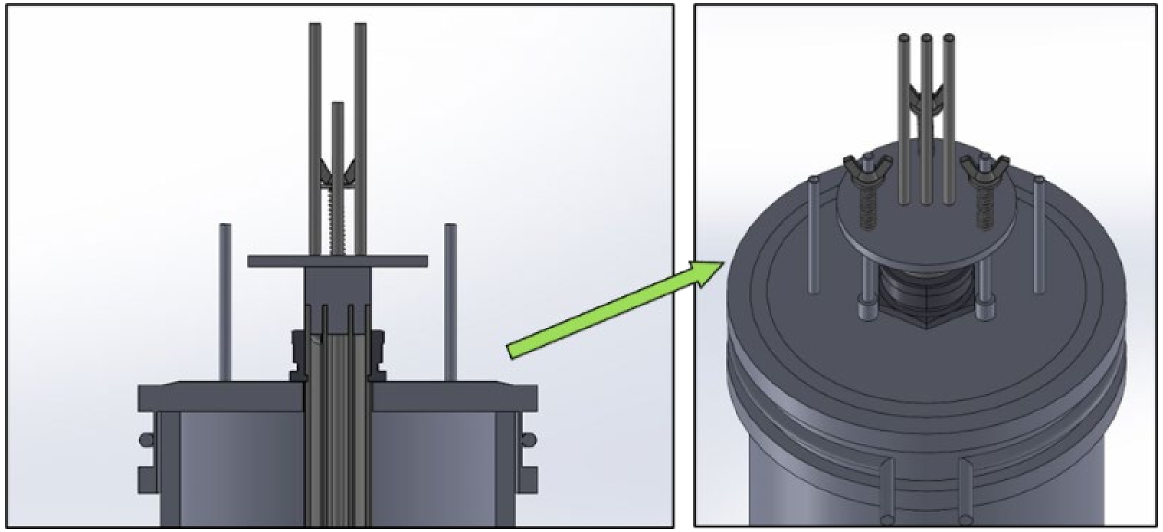
SiC tooling CVI densified

Vertical hot-wall furnace reactor design in progress

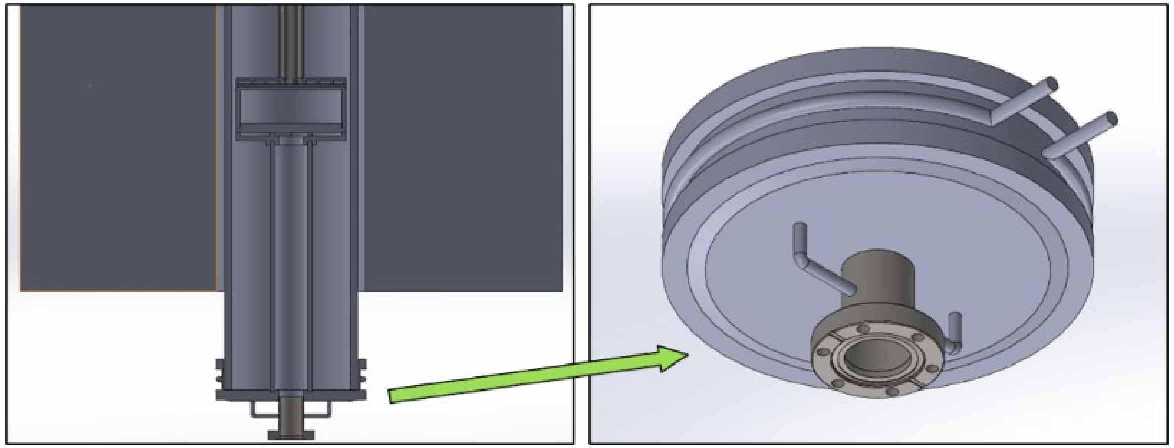
- Hot-wall furnace design in progress
- Incremental level of detail
- Long lead time items designed first: furnace, SiC tubes, end caps



Inlet flange



Exhaust flange



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Ordering and assembling of the reactor system is in progress

- Ventilated enclosure fabricated
- Vertical tube furnace ordered
- SiC tubes ordered
- Vacuum pump and end caps received

Acknowledgements

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Thanks!

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