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Improving Turbine Performance with Ceramic Matrix Composites

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Under the new NASA Fundamental Aeronautics Program, efforts are on-going within the Supersonics Project aimed at the implementation of advanced SiC/SiC ceramic composites into hot section components of future gas turbine engines. Due to recent NASA advancements in SiC-based fibers and matrices, these composites are lighter and capable of much higher service temperatures than current metallic superalloys, which in turn will allow the engines to operate at higher efficiencies and reduced emissions. This presentation briefly reviews studies within Task 6.3.3 that are primarily aimed at developing physics-based concepts, tools, and process/property models for micro- and macro-structural design, fabrication, and lifing of SiC/SiC turbine components in general and airfoils in particular. Particular emphasis is currently being placed on understanding and modeling (1) creep effects on residual stress development within the component, (2) fiber architecture effects on key composite properties such as design strength, and (3) preform formation processes so that the optimum architectures can be implemented into complex-shaped components, such as turbine vanes and blades.

SUP 06. Lightweight Durable Engines

Improving Turbine Performance with Ceramic Matrix Composites

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Background

A major thrust under a variety of recent NASA and DoD aero-propulsion programs has been to develop and demonstrate advanced ***Ceramic Matrix Composite (CMC) turbine components*** with optimized structural and environmental durability at service temperatures significantly higher than current metallic alloys

***Potential Benefits for Supersonic Engines**:*

- *Higher engine efficiency and thrust*
- *Reduced weight, cooling, and emissions*
- *Longer and more reliable component life*
- *Enabling of other aerospace applications not attainable with metals*

SiC Fiber/SiC Matrix (SiC/SiC) CMC Out-Perform Competing High-Temperature Structural Materials

versus Superalloys:

- Lower density (~30% metal density)
- Higher temperature capability (>1100^{o}C)
- Lower thermal expansion

versus Monolithic Ceramics:

- Non-catastrophic failure
- Higher toughness, better damage tolerance
- Capability for larger and more complex shapes

versus Carbon Fiber Composites (C/SiC, C/C):

- Higher oxidative durability, longer and more predictable life
- Lower permeability

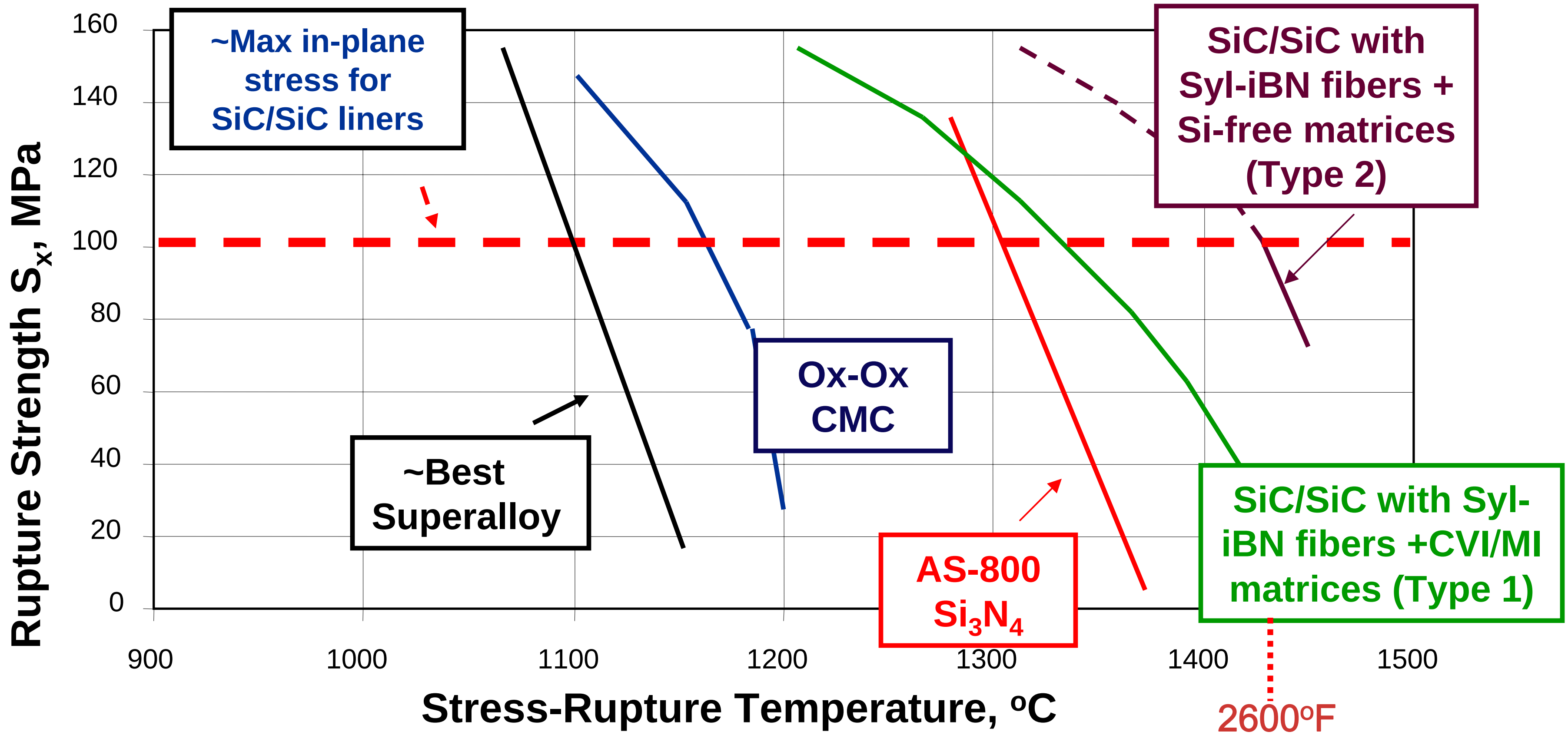
versus Oxide/Oxide Ceramic Composites:

- Higher strength, temperature capability, creep-rupture resistance, thermal conductivity, emissivity
- Lower permeability

NASA Advancements in Constituent Materials and Processes that address Key Property Needs for SiC/SiC Turbine Components

- ***Sylramic-iBN fiber*** (creep resistant stoichiometric SiC with protective in-situ grown BN coating and thermal stability >1600^{o}C)
- ***Improved 2D and 3D Fiber Architectures*** (stress-free and high thermal conductivity)
- ***Improved CVI SiC Matrices*** (higher thermal conductivity and creep-resistance)
- ***Hybrid CVI + PIP SiC Matrices*** (silicon-free for thermal stability >1500^{o}C)
- ***Advanced Environmental Barrier Coatings (EBC)*** (thermal stability >1500^{o}C in combustion environments)

500-Hour Rupture Strength in Air for <u>Reusable</u> High-Temperature Structural Materials



Thermostructural capability for NASA Type 2 SiC/SiC system is state-of-the art. FA program is attempting to improve temperature capability to 3000°F under the Hypersonics project.

SUP.06 Lightweight Durable Engines

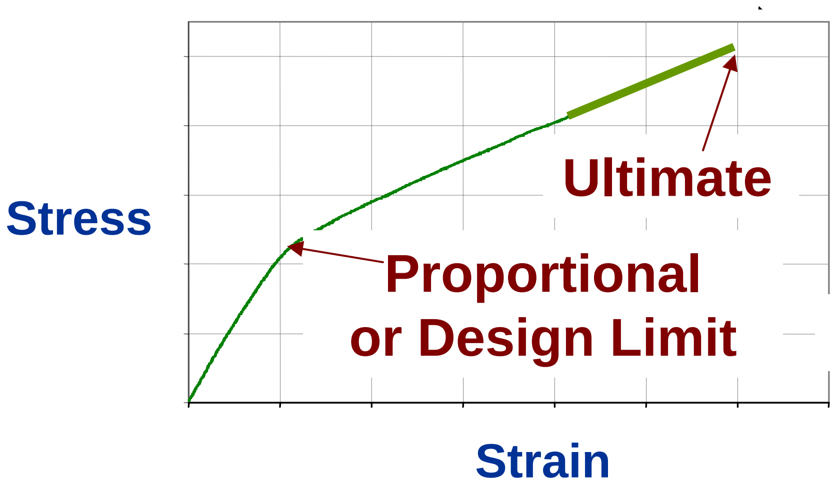
<u>Task 06.03.03</u> – *Advanced Physics-Based Tool Development for CMC Components*

Objectives:

- Understand the key challenges currently limiting the implementation of SiC/SiC CMC into turbine section components of supersonic engines
- Address these challenges in a generic manner by the development of physics-based concepts, tools, and process/property models for micro- and macro-structural component design and lifing
- Verify property and lifing predictions by development of specialized sub-element testing facilities
- Work with DOD and CMC industry for optimization of efforts and demonstration of advanced concepts

Key SiC/SiC Property Requirements for Turbine Components

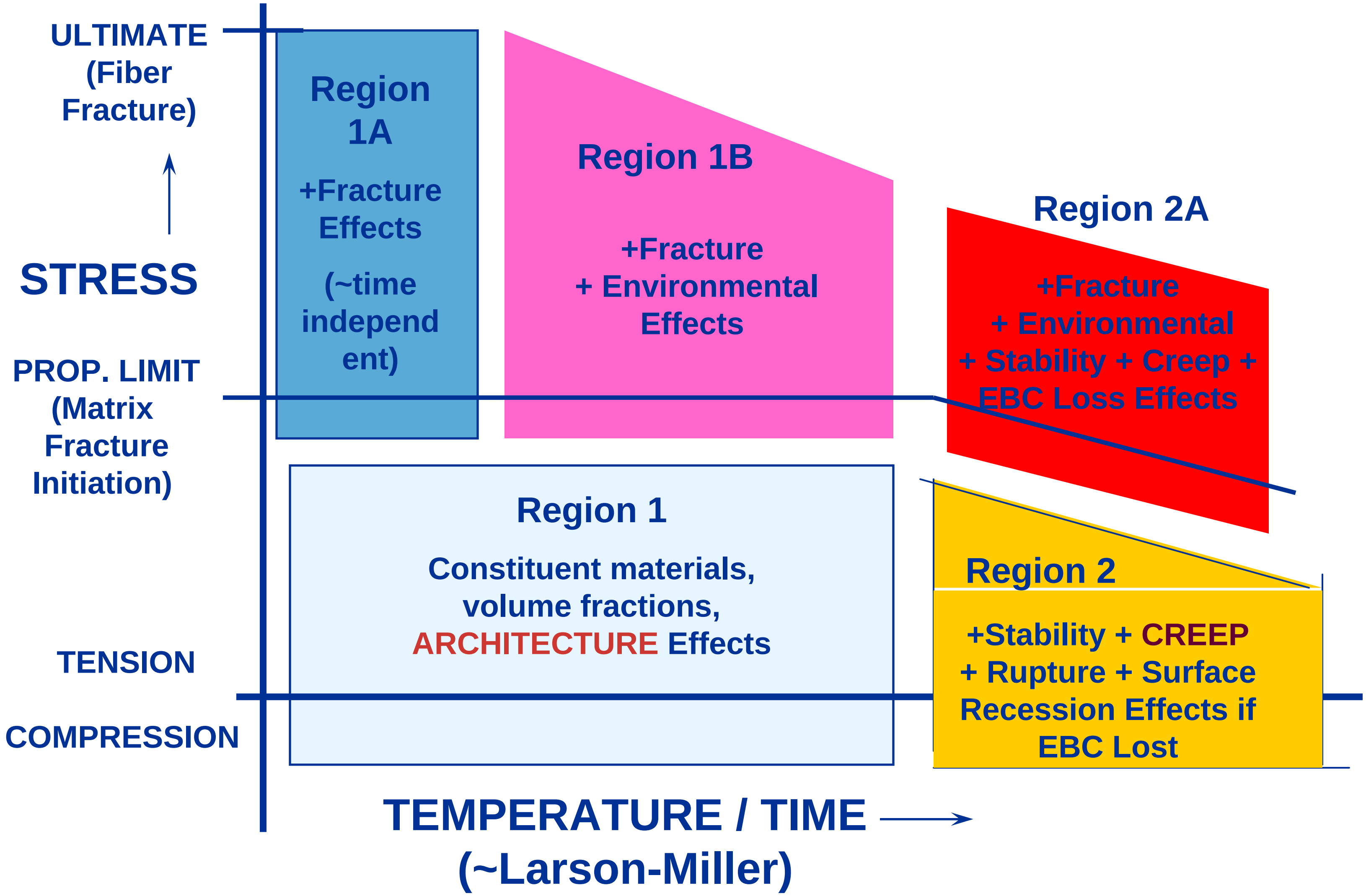
- **Multi-Directional Tensile Strength and Damage Tolerance**



- ***High PL Strength/Strain***
- ***High Ultimate Strength/Strain***
- ***UTS > PLS <u>in all directions</u>***

- **Intrinsic Time/Temperature Structural Capability**
  - Constituent microstructural stability
  - Creep and rupture resistance
- **Thermal Conductivity** (minimize thermal stress)
- **Environmental Durability** (oxygen, water vapor)

Physics-Based Mechanistic Effects Controlling Key SiC/SiC Structural Properties



Current Challenges for Viable SiC/SiC Turbine Components and Physics-based Tool Development

- ***Lifing Methodologies:***
  - Creep effects on component life
- ***Higher matrix cracking strength:***
  - Architecture effects on in-plane and thru-thickness strength
- ***Complex Shape Producibility:***
  - Fiber architecture processes for high-performance turbine airfoils
- ***Prime Reliant EBC:***
  - Durable and compatible with SiC/SiC

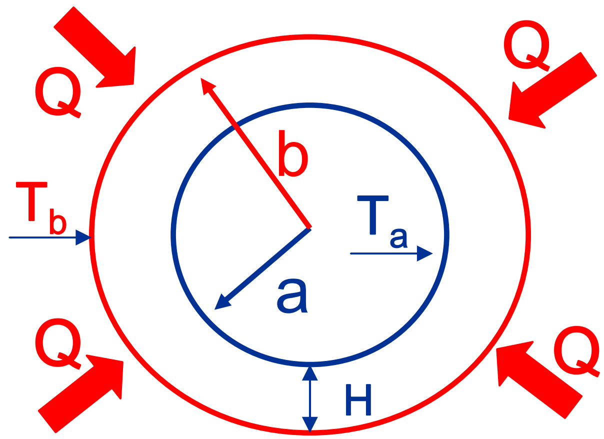
Challenge: *Lifing Concerns for SiC/SiC Creep*

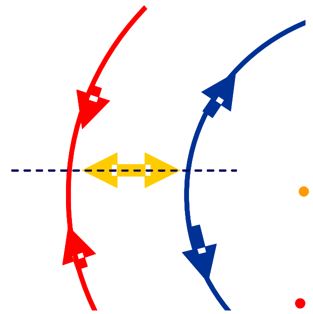
- ***Dimensional changes*:** Not important because creep strains for SiC/SiC rupture are currently < 1%

- ***Constituent Rupture*:** As with monolithic ceramics, creep implies flaw growth and time-dependent weakening of the fiber and matrix (~0.5% creep)

- ***Residual Stress Development*:** Can put matrix in more internal tension with time, resulting in reduction of matrix cracking stress. A particular concern for components with stress and thermal gradients, such as turbine airfoils. Adverse effects can occur as low as 0.05% creep strain.

Simple Internally-Cooled Tube Model for Leading Edge of SiC/SiC Airfoil





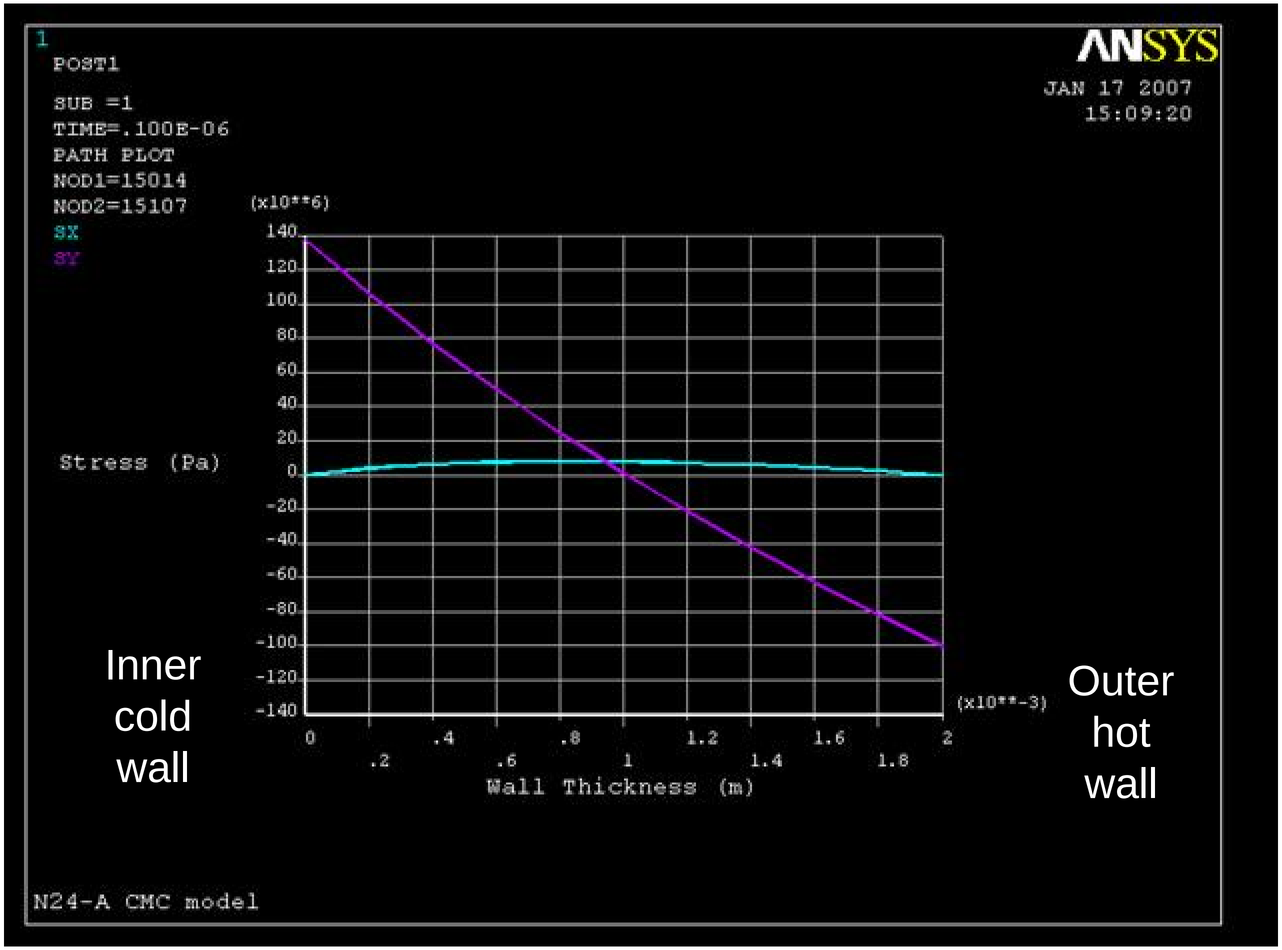
- **Tensile hoop on cold inner wall**
- **Tensile radial near wall center**
- **Compressive hoop on hot outer wall**

Advantages

- **Allows a best-case evaluation of SiC/SiC leading edge temperature and thermal stress capability by elimination of mechanical stresses that depend on specific airfoil designs**
- **Allows generic examination of effects due to thermal stresses, curvature, wall thickness, creep, stress relaxation, and other properties of different SiC/SiC systems**
- **Allows both analytical and Finite Element (FE) analyses**
- **Useful also for analyzing SiC/SiC tubular heat exchangers**

FE Modeling of Time-Dependent Thermal Stress in SiC/SiC Tube with ΔT that Avoids Initial Cracking

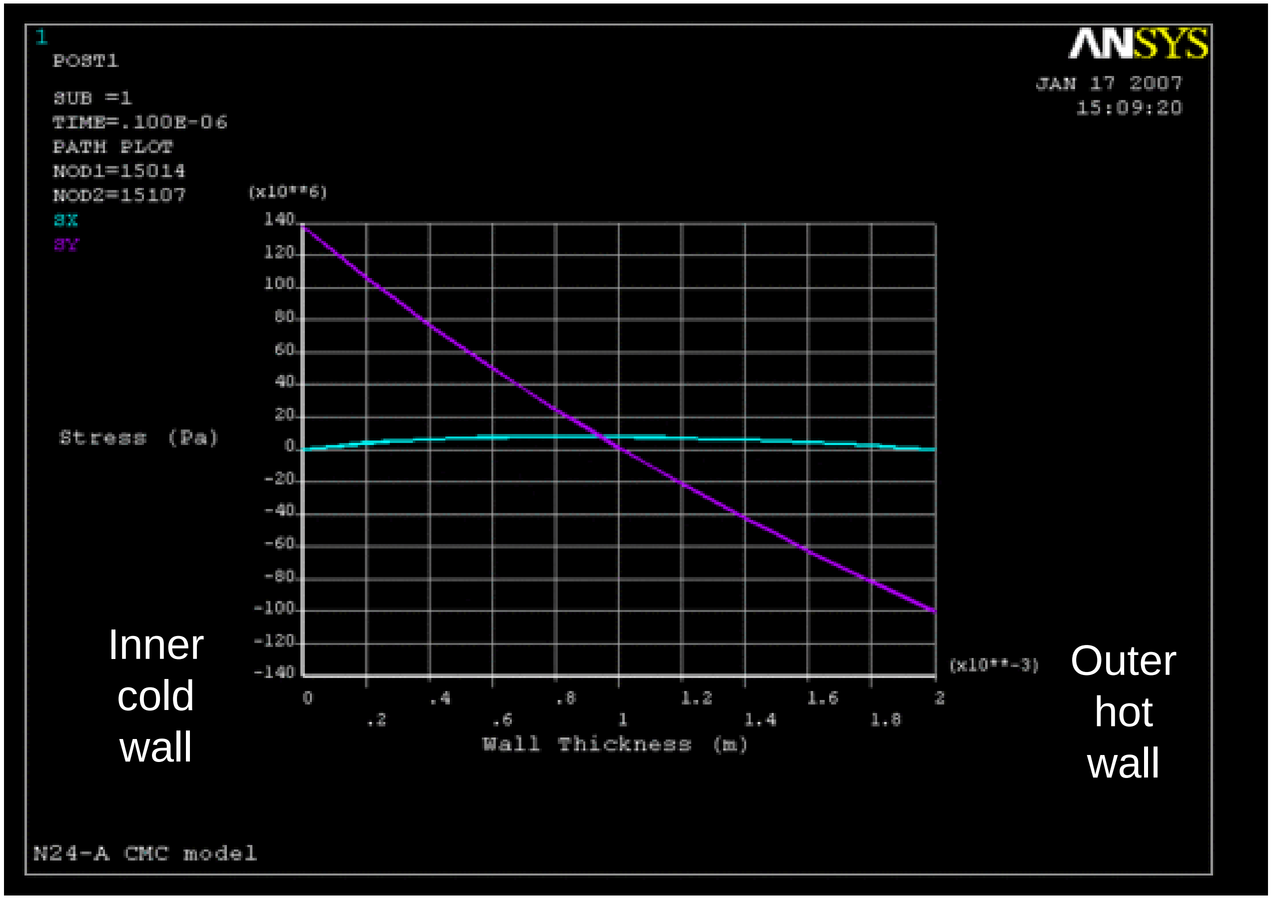
Conditions: ΔT = 300°F, a = 6 mm, H = 2 mm, H/a = 0.33



FE Modeling of Time-Dependent Thermal Stress in SiC/SiC Tube with ΔT that Avoids Initial Cracking

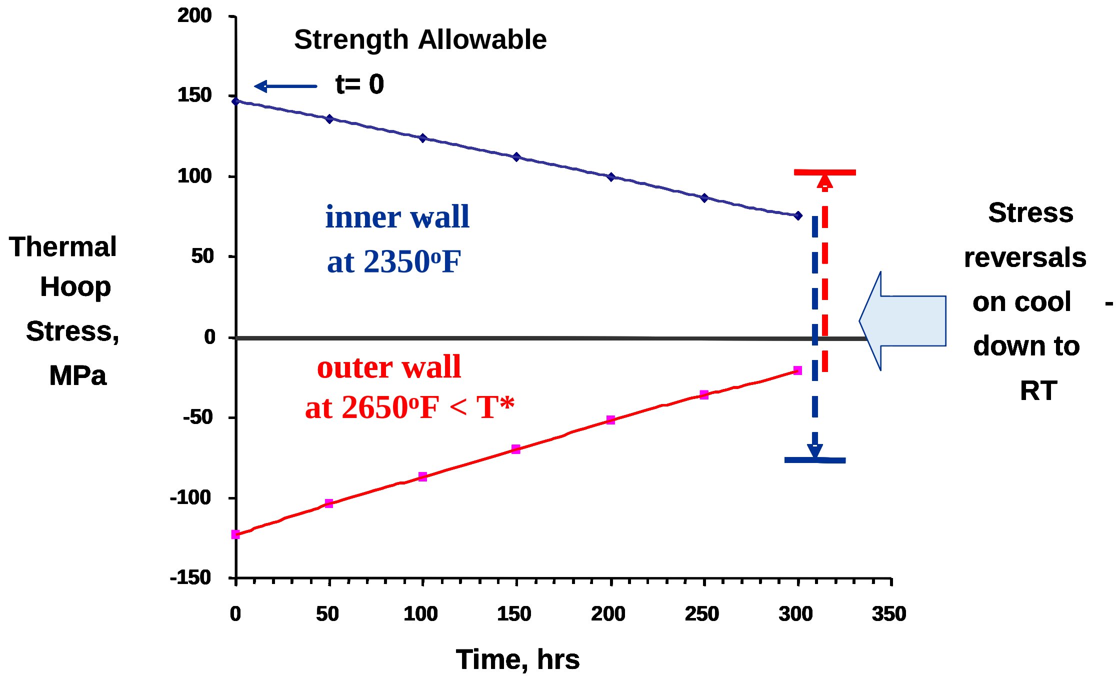
(Animation)

Conditions: $\Delta T = 300^oF$, a = 6 mm, H = 2 mm, H/a = 0.33



Hoop Stress Relaxation Near Max Thermal Conditions for Type 2 SiC/SiC Tube Model

Conditions: ΔT = 300°F, H/a = 0.33, Linear Creep, A_1 = 0.08



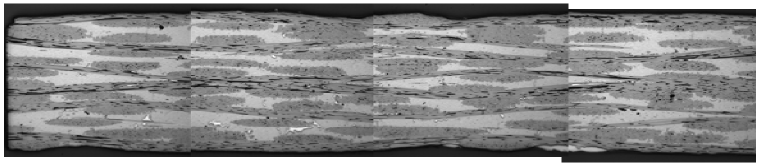
- ***Inner wall tensile stress relaxes with time, thereby increasing material reliability at temperature. Outer wall compression decreases faster due to higher temperature.***
- ***Residual stress build-up during cool down indicate ΔT* should be kept below ~300°F at all times to avoid cracking of outer wall.***

Challenge: *Higher Matrix Cracking Strength*

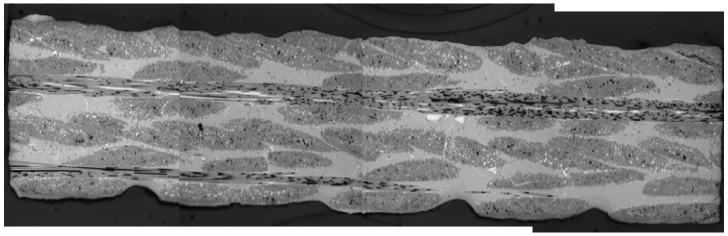
- Understand the sources of SiC/SiC matrix cracking both in-plane (~150 MPa) and thru-thickness (2D: ~15 MPa) and then develop approaches to minimize their influence and improve composite design strength.
- For highly dense matrices, such as those formed by melt infiltration, the ***fiber architecture*** plays a strong role in the initiation of matrix cracks.
- NASA is currently studying and modeling this effect using ***Acoustic Emission*** and SiC/SiC tensile specimens reinforced by a wide variety of different Sylramic-iBN fiber architectures.

Architecture Effects on SiC/SiC In-Plane Matrix Cracking

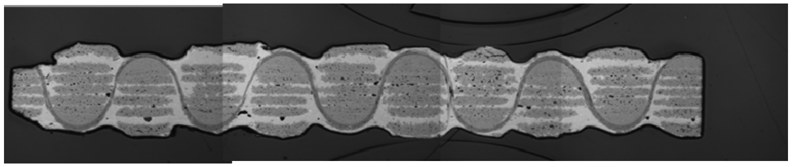
2D Five-harness Satin



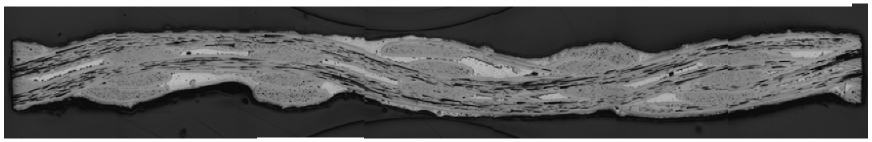
Braid

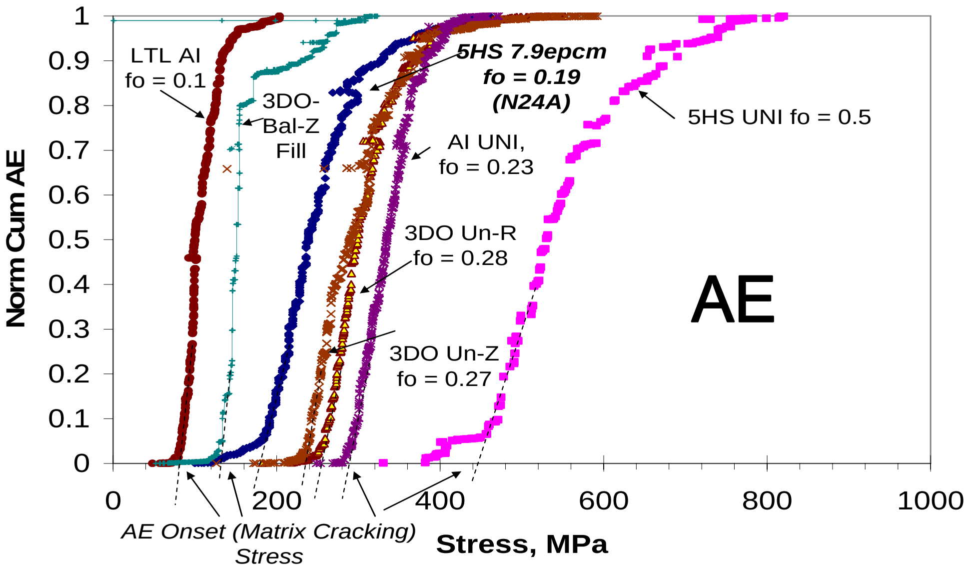


3D Orthogonal



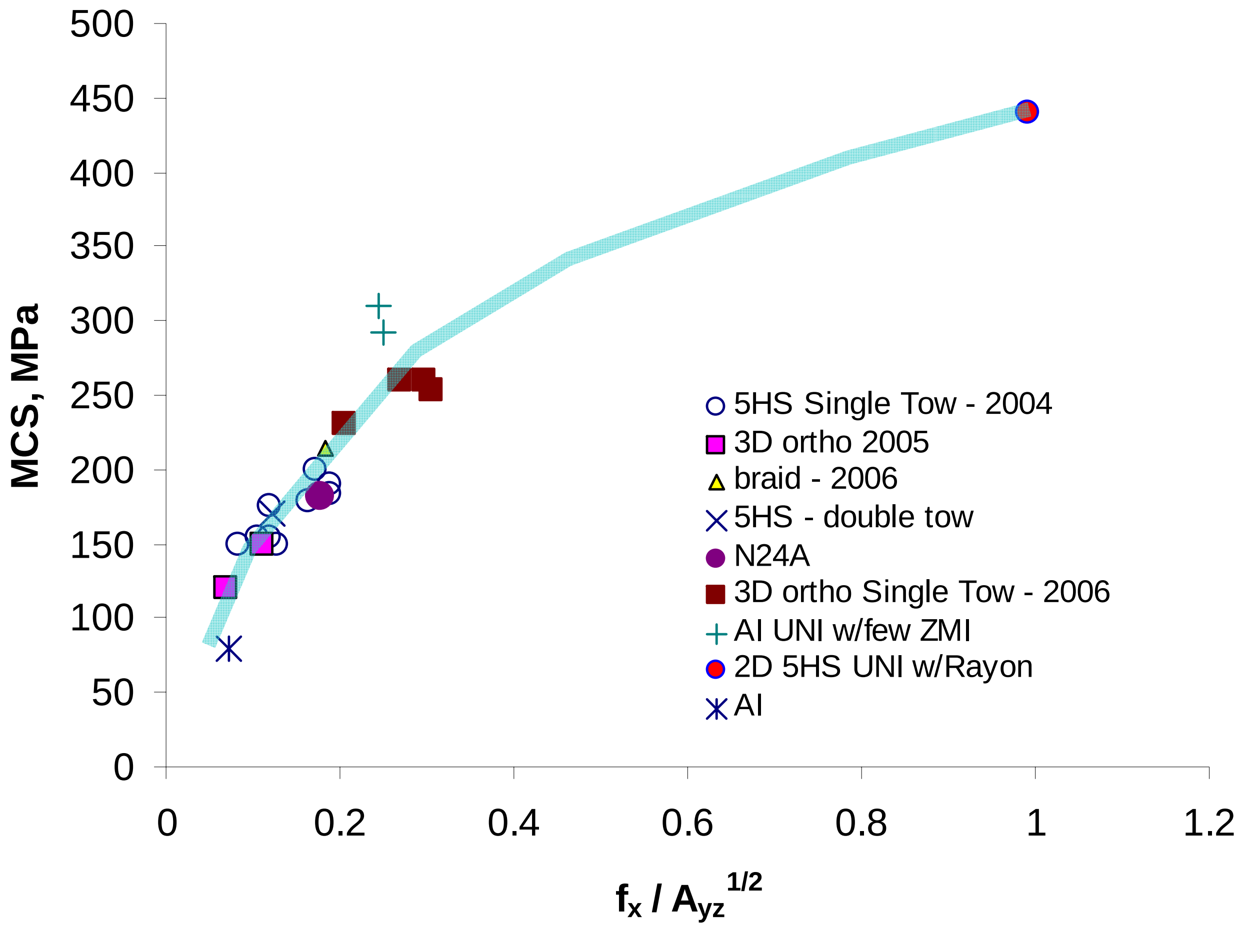
Angle Interlock





The in-plane onset stress for thru-thickness cracking can be increased from 100 to ~300 MPa by ***proper architecture selection***

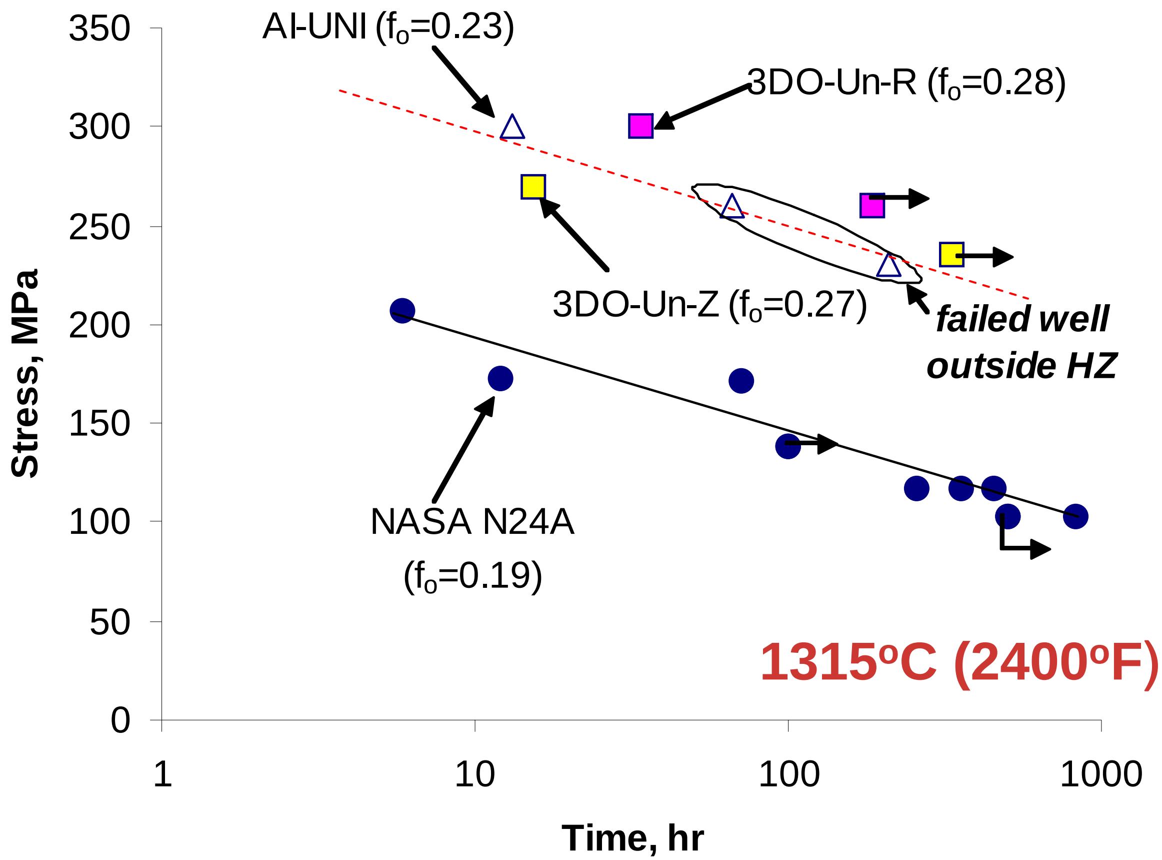
Architecture Design Model for SiC/SiC
In-Plane Matrix Cracking (Onset) Stress



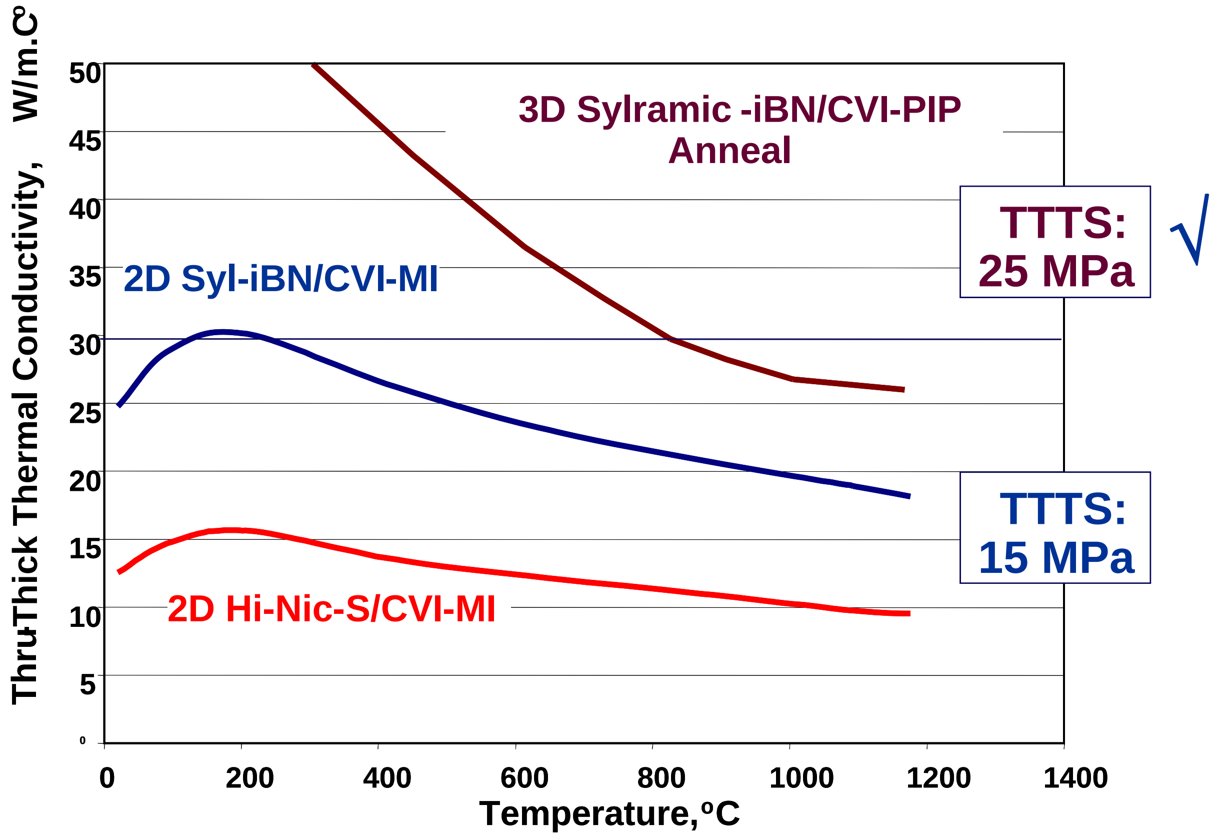
f_x is fiber volume fraction in the tensile test direction x;

A_{yz} is the effective area of tows perpendicular to test direction

Fiber Architecture also Strongly Affects SiC/SiC In-Plane Rupture Strength



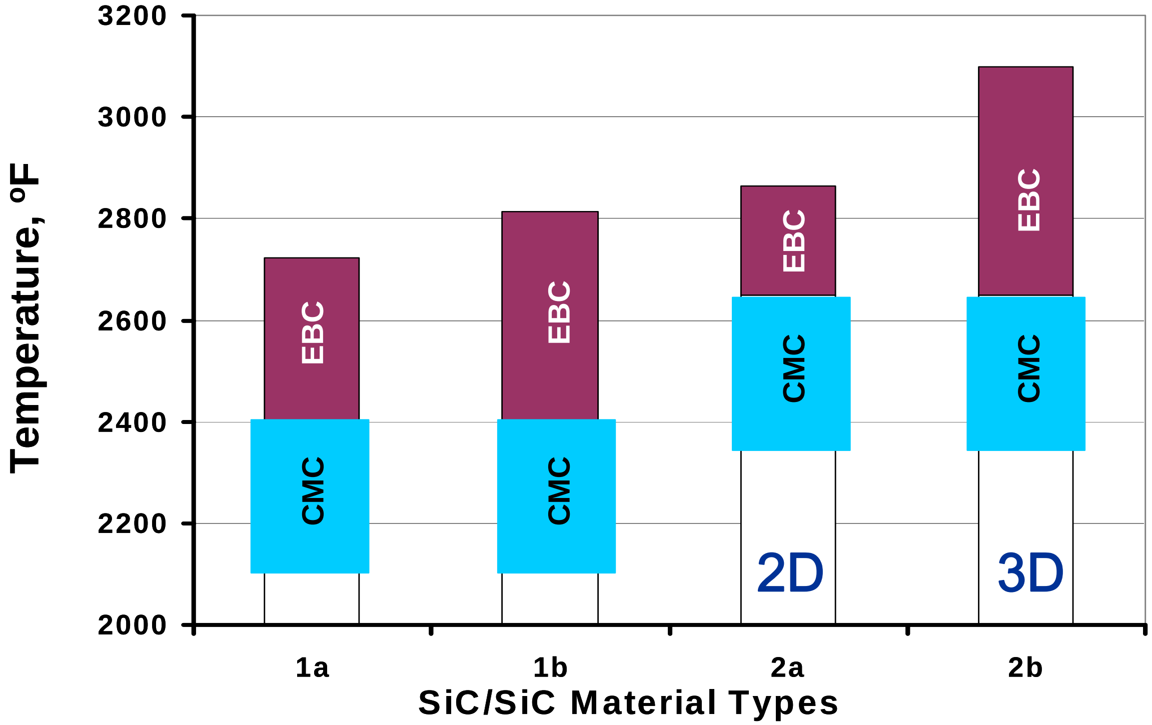
Fiber Type and Architecture also Strongly Affect Key SiC/SiC Thru-thickness Properties



3D Architectures and Sylramic-iBN Fibers significantly Improve SiC/SiC Thru-thickness Conductivity and Thru-Thickness Tensile Strength (TTTS)

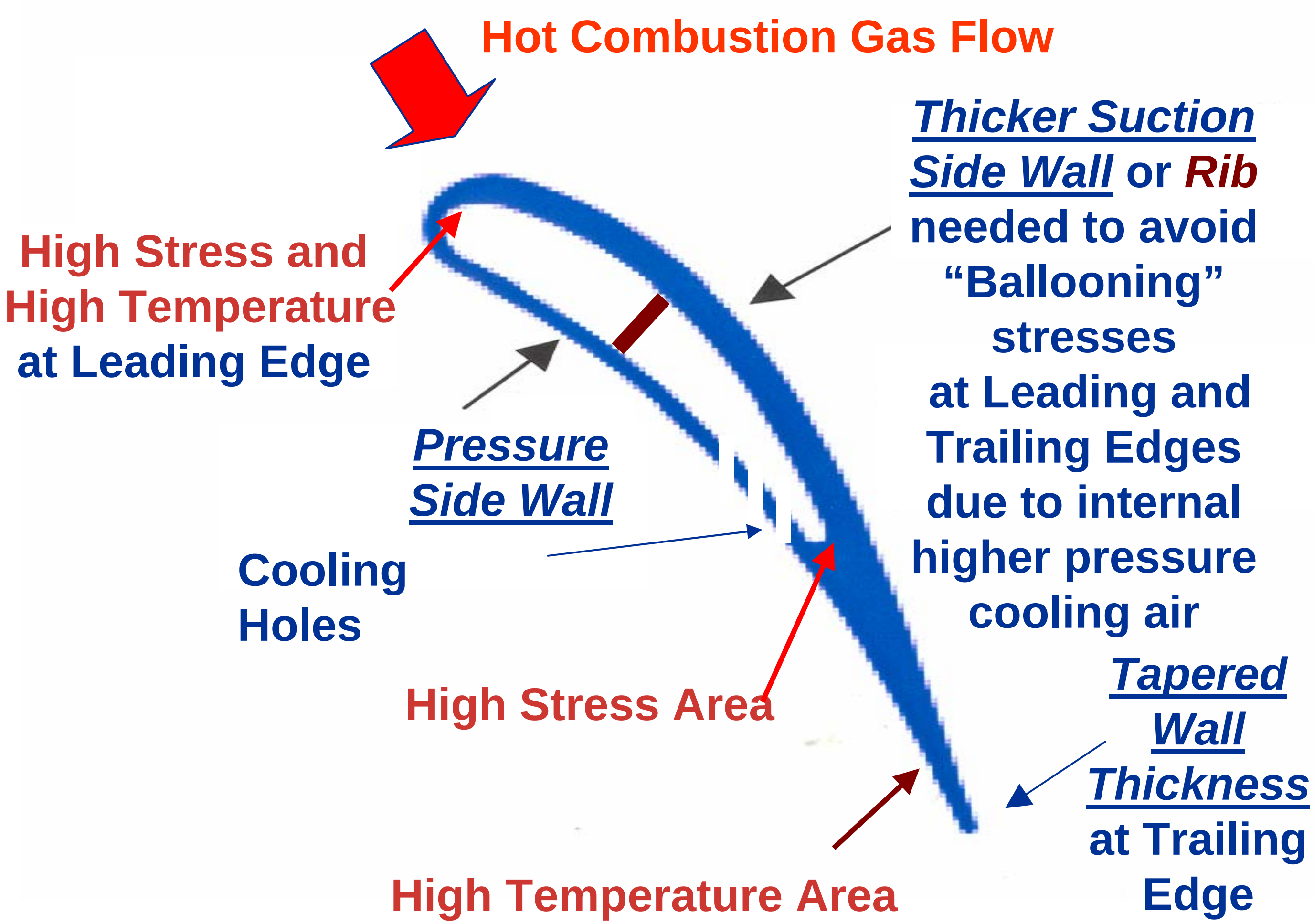
Maximum Temperature Predictions from Tube Model of SiC/SiC Airfoil Leading Edges

Assumptions: $\Delta T^* = 300^oF$, $H_{CMC} = 1.5$ mm, $a_{CMC} = 6$ mm, $H_{EBC} = 0.2$ mm, $k_{EBC} = 2$ W/m.^oK



3D Type 2 SiC/SiC material offers the highest range of thermal capability

Challenge: *Fiber Architecture Design and Processes for Complex-Shaped CMC Turbine Airfoils*



Current Task Approaches to 3D Airfoil Architectures

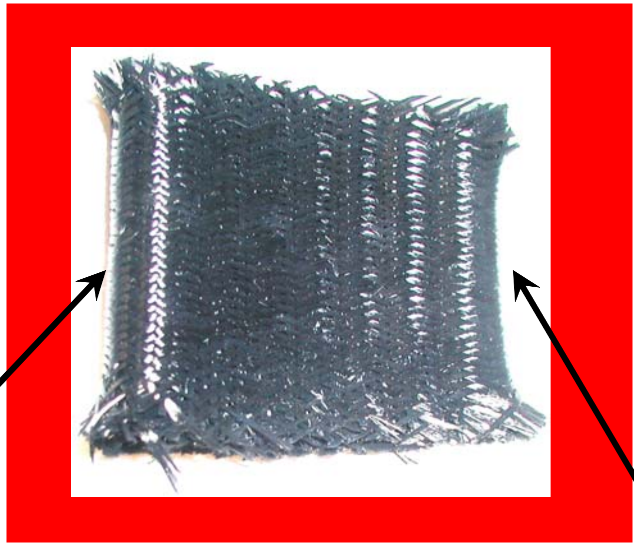
- Collaborate with AFML and Goodrich under VAATE contract for the development of advanced technologies for SiC/SiC blades:
  - Transfer NASA advancements to Goodrich for materials, processes, property modeling, architecture design
  - Support efforts with high-temperature testing
- Initiate new NRA awards for airfoil-shaped preforms using
  - 3D forming methods and high-stiffness SiC fibers
- Conduct in-house studies on forming airfoil preforms using
  - 3D filament winding
- Conduct in-house studies on feasibility of creep-forming airfoil preforms using NASA-developed heat treatment methods

NASA-Developed Method For Creep-forming SiC Fiber Architectures Into High-strength Complex-shaped Airfoil Preforms

2 in. diameter 2D-braided 3-ply *Sylramic* tube

shape and heat treat

Sylramic-iBN
vane pre-form



Leading Edge: R = 300 mil

Trailing Edge: R = 70 mil

Summary

- ***NASA SiC/SiC systems*** are capable of outperforming the best superalloys and Ox/Ox CMC systems in weight-savings, structural capability, use temperature, and thermal conductivity.
- However, these systems currently face key technical challenges that need to be overcome before they can be widely implemented in hot-section turbine components; for example,
  - ***Advanced lifing design methodologies*** **that can account for environmental effects, and also residual stress effects due to creep.**
  - ***3D fiber architectures*** **that not only yield high matrix cracking strengths both in-plane and thru-thickness, but also are conducive for the fabrication of complex-shaped components. If the proper SiC fibers are selected, such as Sylramic-iBN, 3D systems should also provide improved thru-thickness thermal conductivity and impact resistance.**
- For the more complex-shaped and higher performing components, such as turbine vanes and blades, many of these key challenges are currently being addressed under the FA Supersonics project.