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Current Computational Challenges for
CMC Processes, Properties, and Structures

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In comparison to current state-of-the-art metallic alloys, ceramic matrix composites (CMC) offer a variety of performance advantages, such as higher temperature capability (greater than the ~2100°F capability for best metallic alloys), lower density (~30-50% metal density), and lower thermal expansion. In comparison to other competing high-temperature materials, CMC are also capable of providing significantly better static and dynamic toughness than un-reinforced monolithic ceramics and significantly better environmental resistance than carbon-fiber reinforced composites. Because of these advantages, NASA, the Air Force, and other U.S. government agencies and industries are currently seeking to implement these advanced materials into hot-section components of gas turbine engines for both propulsion and power generation. For applications such as these, CMC are expected to result in many important performance benefits, such as reduced component cooling air requirements, simpler component design, reduced weight, improved fuel efficiency, reduced emissions, higher blade frequencies, reduced blade clearances, and higher thrust.

Although much progress has been made recently in the development of CMC constituent materials and fabrication processes, major challenges still remain for implementation of these advanced composite materials into viable engine components. The objective of this presentation is to briefly review some of those challenges that are generally related to the need to develop physics-based computational approaches to allow CMC fabricators and designers to model (1) CMC processes for fiber architecture formation and matrix infiltration, (2) CMC properties of high technical interest such as multidirectional creep, thermal conductivity, matrix cracking stress, damage accumulation, and degradation effects in aggressive environments, and (3) CMC component life times when all of these effects are interacting in a complex stress and service environment. To put these computational issues in perspective, the various modeling needs within these three areas are briefly discussed in terms of their technical importance and their key controlling mechanistic factors as we know them today. Emphasis is placed primarily on the SiC/SiC ceramic composite system because of its higher temperature capability and enhanced development within the CMC industry. A brief summary is then presented concerning on-going property studies aimed at addressing these CMC modeling needs within NASA in terms of their computational approaches and recent important results. Finally an overview perspective is presented on those key areas where further CMC computational studies are needed today to enhance the viability of CMC structural components for high-temperature applications.

Current Computational Challenges for CMC Processes, Properties, and Structures

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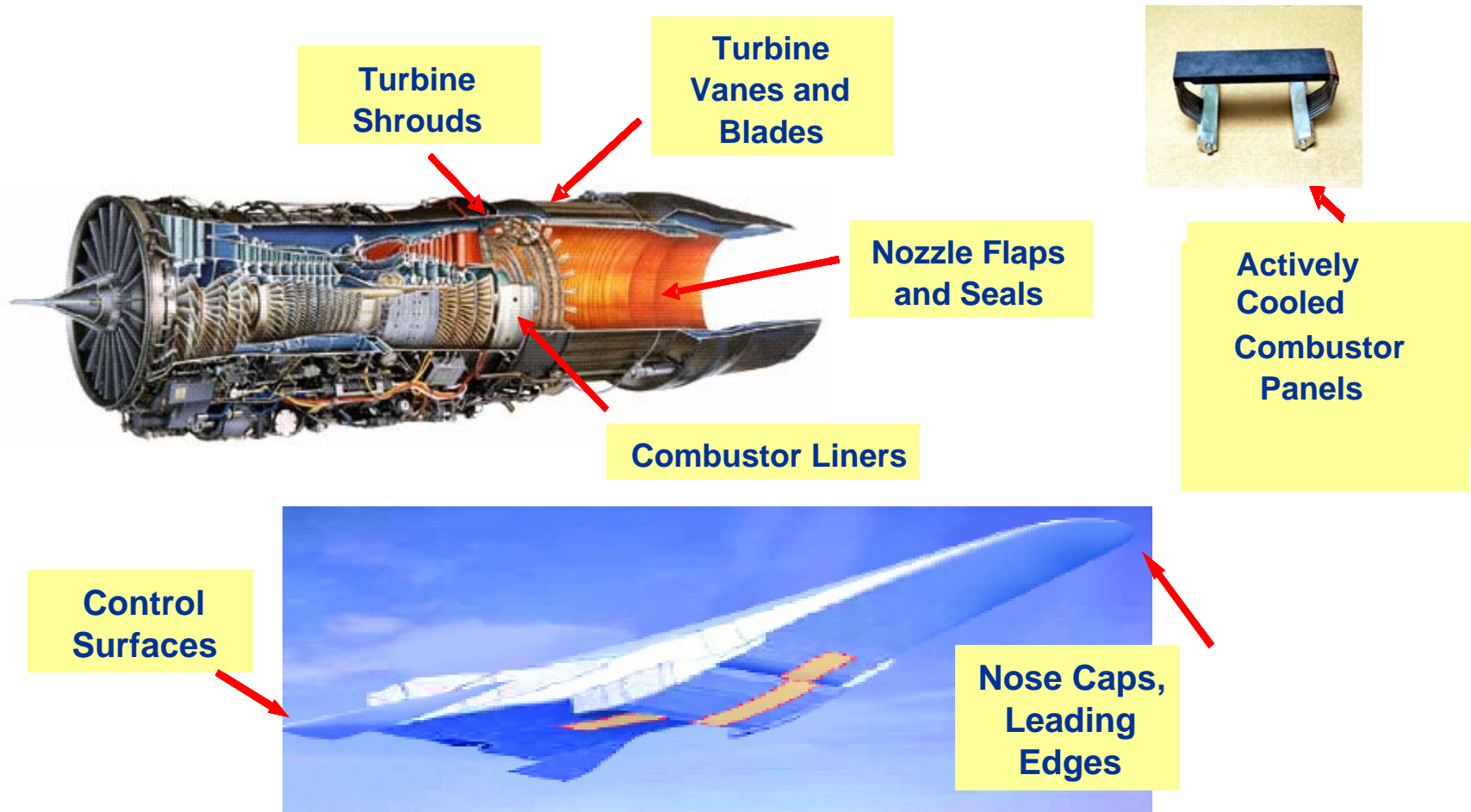**Presented at ICCES-08**
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Background

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

Potential Benefits for Aero-Propulsion Engines:
- *Higher efficiency and thrust*
- *Reduced weight and emissions*
- *Longer and more reliable component life*
- *Enabling of other aerospace applications not attainable with metals*

NASA and DoD Need Lightweight Reusable High-Temperature Structural Materials for Multiple Aero-Propulsion Components

Turbine Shrouds

Turbine Vanes and Blades

Nozzle Flaps and Seals

Actively Cooled Combustor Panels

Combustor Liners

Control Surfaces

Nose Caps, Leading Edges

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

versus _Superalloys_:
- Lower density (~30% metal density)
- Higher temperature capability (>1100°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-
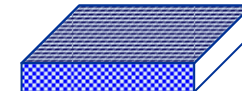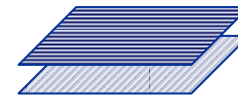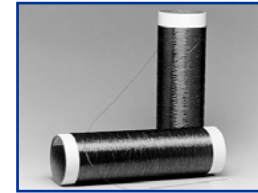 rupture resistance, thermal conductivity, emissivity
- Lower permeability

Objectives / Outline

- Review briefly current status of processes and properties for some state-of–the-art **SiC/SiC CMC material systems**

- Discuss major technical challenges that still remain for implementation of SiC/SiC materials into viable engine components, **with emphasis on those challenges that are related to the industry-wide need to develop physics-based computational approaches to model**

  – CMC processes for fiber architecture and constituent formation

  – CMC properties of high technical interest as function of constituent materials, processes, and geometries

  – CMC component life times in complex stress and service environments.

- Present some examples for some key SiC/SiC technical properties where empirical data exist, but **computational approaches and models are needed for prediction beyond data**.
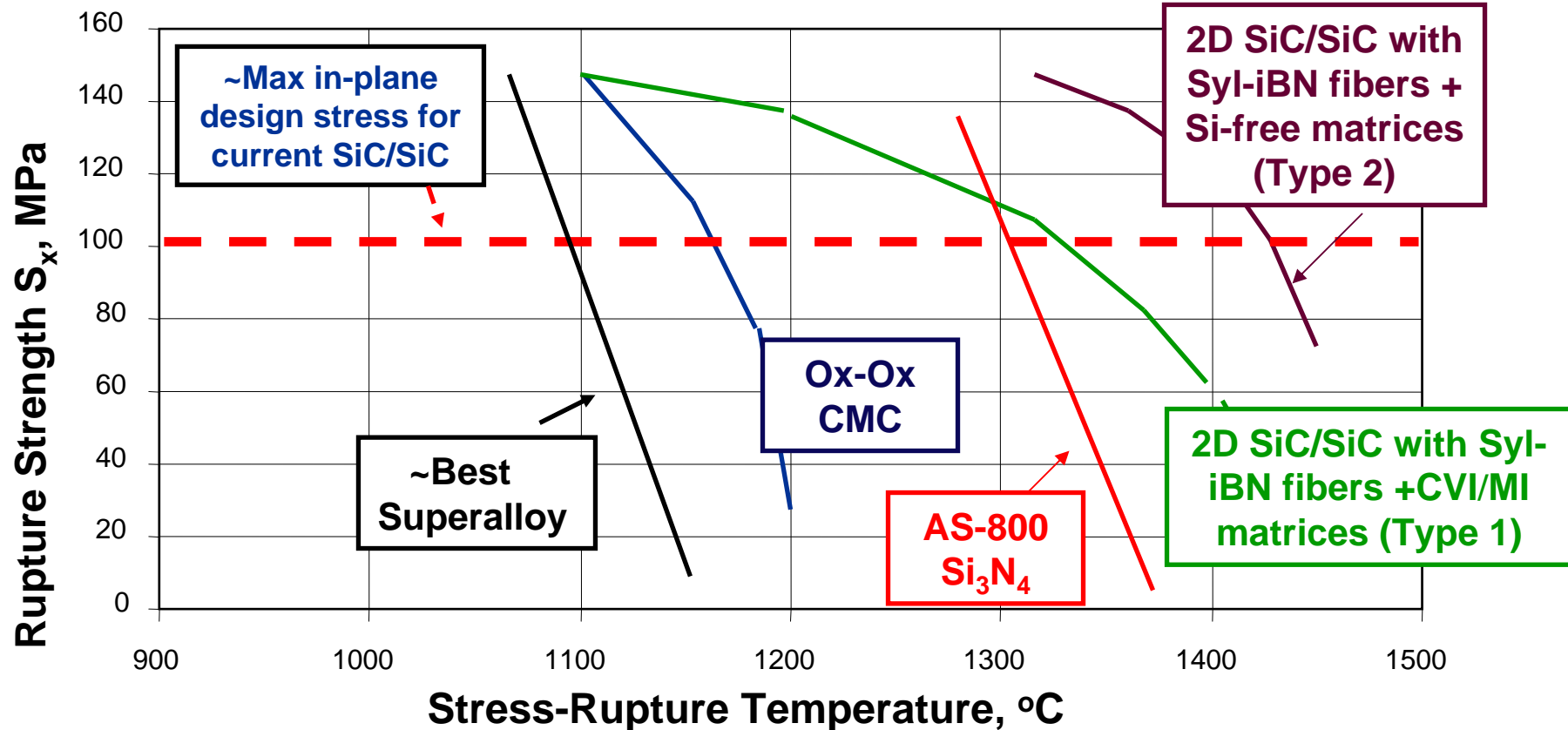
Typical Fabrication Steps for SiC/SiC Components

- Select SiC **fiber** type in commercial tow form:

- Form 3D Component Preform by textile forming:

  - **2D Fabric Route :** Weave or braid tows into 2D fabric or cylindrical plies, and lay up plies into 3D architectures

  - **2D Prepreg Route:** Form unidirectional plies from straight tows, and lay up plies into 3D architectures

  - **3D Preform Route:** Weave or braid tows into 3D architectures with fibers thru-thickness for *improved through-thickness properties*

- Coat fibers in tow with thin BN-based **interphase** material using CVI (chemical vapor infiltration).

- Form **matrix** by infiltrating final 3D architecture with various SiC-forming materials using CVI gases and/or liquids such as polymers, slurries, and molten metals, for example, silicon Melt Infiltration (MI).

- Apply Environmental Barrier Coating (EBC) if needed

500-Hour In-Plane Rupture Strength in Air for Reusable High-Temperature Structural Materials

2D SiC/SiC with Syl-iBN fibers + Si-free matrices (Type 2)

~Max in-plane design stress for current SiC/SiC

Ox-Ox CMC

~Best Superalloy

AS-800 Si$_3$N$_4$

2D SiC/SiC with Syl-iBN fibers +CVI/MI matrices (Type 1)

Rupture Strength S$_x$, MPa

Stress-Rupture Temperature, °C

*Current thermostructural capability for **2D SiC/SiC composites** is state-of-the art with upper use temperature of ~1450°C (2640°F), **but concepts for higher in-plane and thru-thickness strengths are still needed***
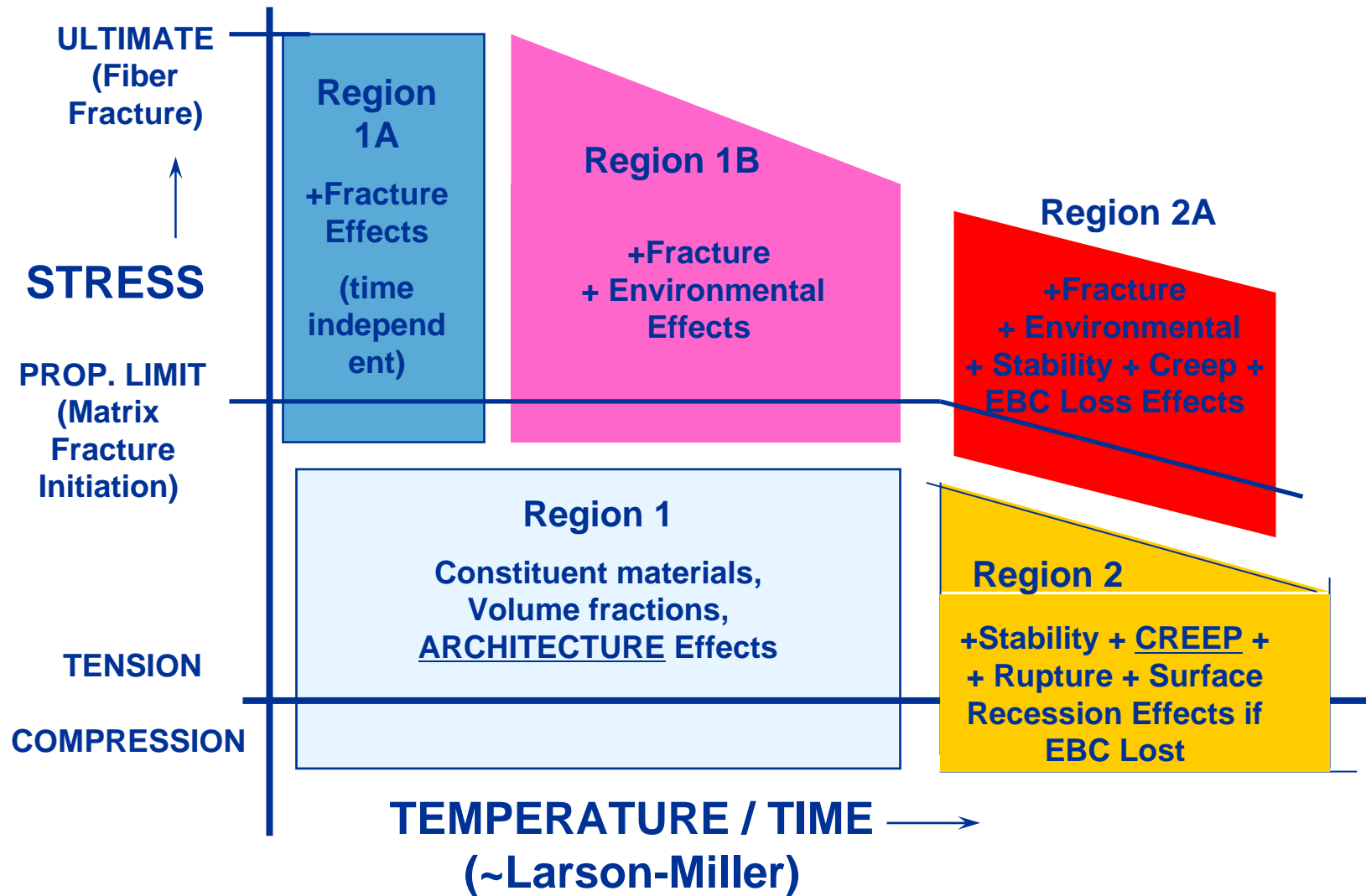
Current Computational Challenges:
CMC Processes and Properties

- *Industry Need:* Design and lifing approaches for selection of constituent materials, processes, and architectures that will yield CMC microstructures with directional strength properties safely below predicted stress states from the beginning to the end of the desired component service life.

- *General Modeling Needs for SiC/SiC:*
  - Prediction of key SiC/SiC properties. Current data are limited due to multiple SiC/SiC fabrication approaches, continual developmental efforts for property improvement, a small vendor base, and high cost for materials and testing.
  - Process and Property models for 3D architectures.
  - Better understanding of Physical/Chemical Mechanisms controlling all important properties in both a deterministic and probabilistic manner (A and B-base allowables).
  - Finite Element approaches for converting the numerous SiC/SiC mechanisms into user-friendly design and lifing codes.

Mechanisms Controlling
SiC/SiC Properties and Life are Complex

STRESS

ULTIMATE
(Fiber
Fracture)

PROP. LIMIT
(Matrix
Fracture
Initiation)

TENSION

COMPRESSION

Region 1A

+Fracture
Effects

(time independent)

Region 1B

+Fracture
+ Environmental
Effects

Region 2A

+Fracture
+ Environmental
+ Stability + Creep +
EBC Loss Effects

Region 1

Constituent materials,
Volume fractions,
ARCHITECTURE Effects

Region 2

+Stability + CREEP +
+ Rupture + Surface
Recession Effects if
EBC Lost

TEMPERATURE / TIME ⟶
**(~Larson-Miller)**

NEED: Mechanistic Models for Thru-Thickness Properties

- **Thru-Thickness Modulus**:
  - *2D panel data show lower values than current model predictions*

- **Thru-Thickness Tensile and Shear Strength:**
  - *Fracture mechanisms are complex*
  - *Need architecture models and concepts for major improvement*

- **Thru-Thickness Thermal Conductivity:**
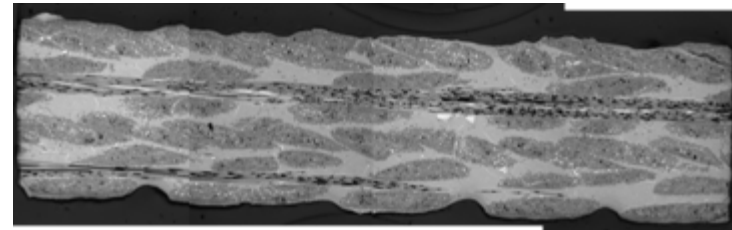 - *Constituent, Interface, and Architecture effects need to be modeled*
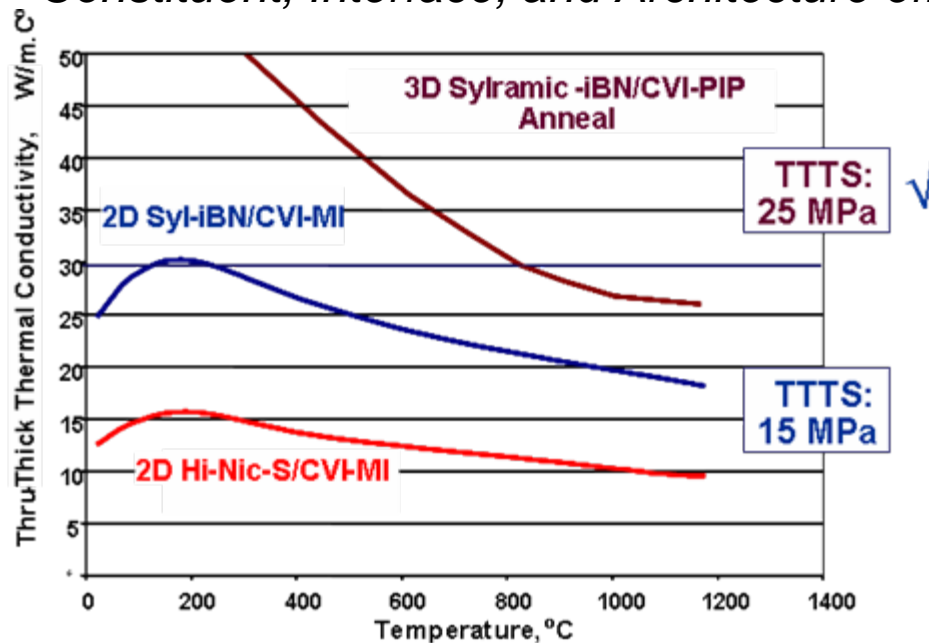
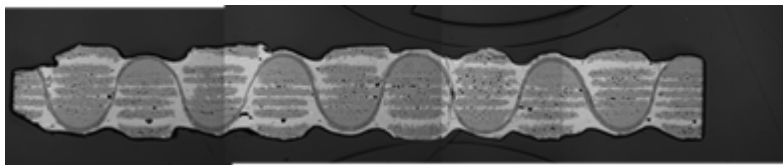*Change in fiber and 3D (V_z ~3%) significantly improves thru-thickness conductivity and tensile strength*

NEED: Architecture Models to Understand, Predict, and Enhance SiC/SiC In-Plane Cracking
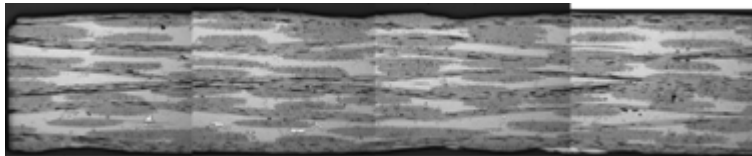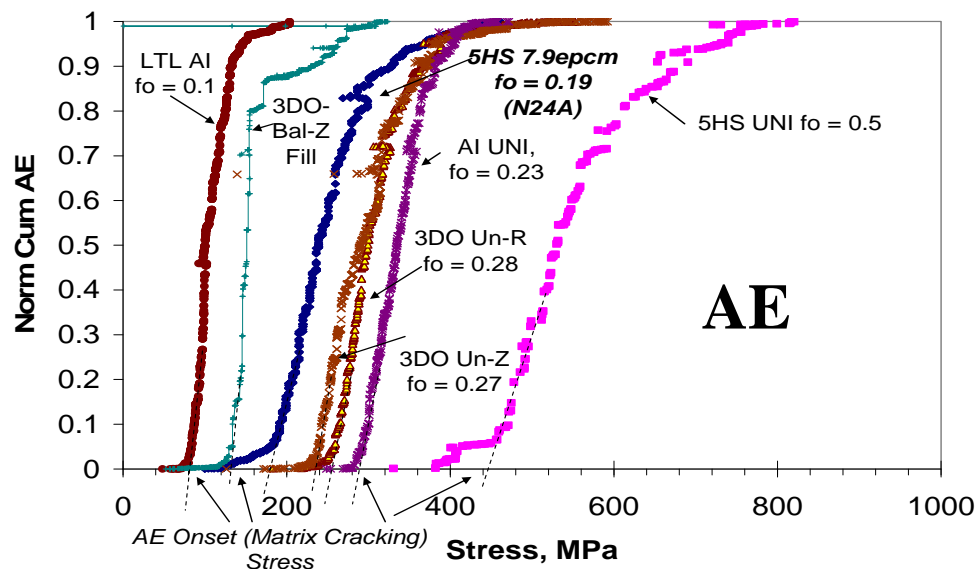

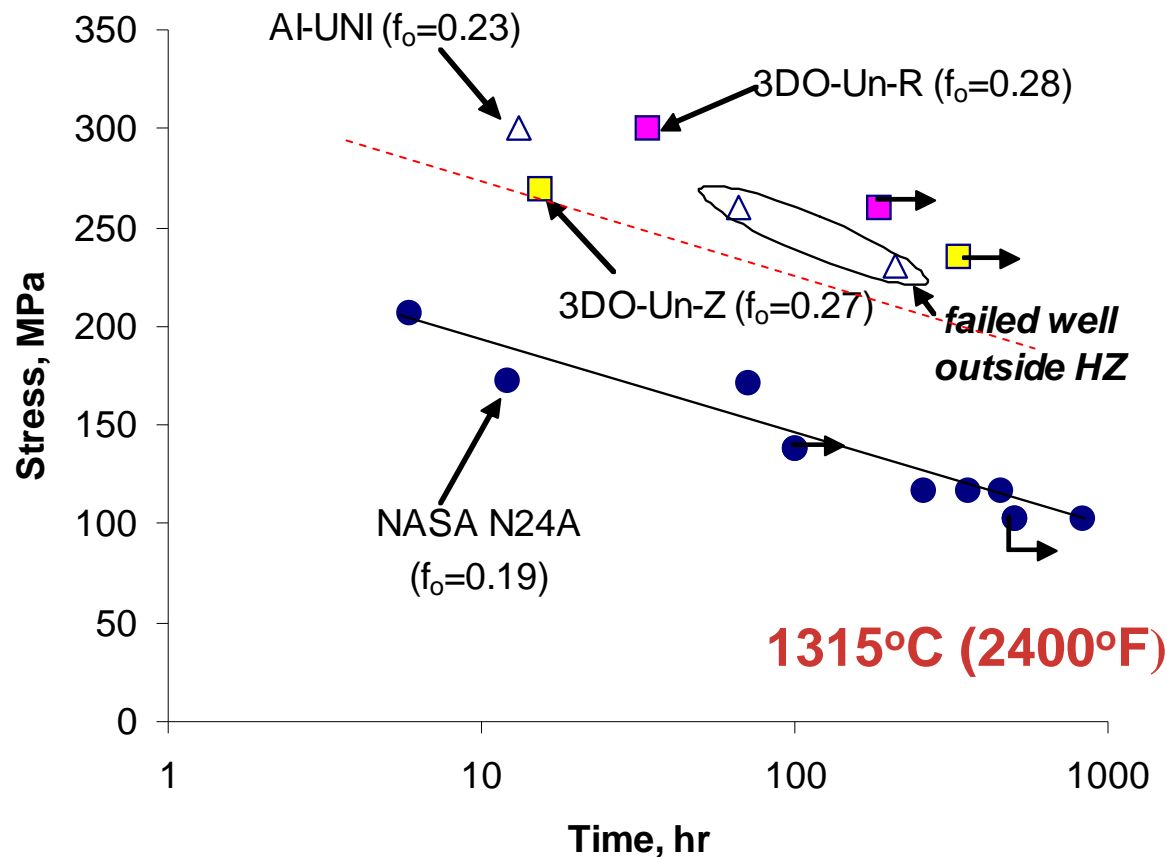**2D Five-harness Satin**

Braid

3D Orthogonal

Angle Interlock

In-plane onset stress for thru-thickness cracking can be increased from 100 to ~300 MPa by _proper architecture selection_

NEED: Architecture Models to Maximize SiC/SiC In-Plane Creep and Rupture Resistance?

AI-UNI (f_o=0.23)

3DO-Un-R (f_o=0.28)

3DO-Un-Z (f_o=0.27)

failed well outside HZ

NASA N24A (f_o=0.19)

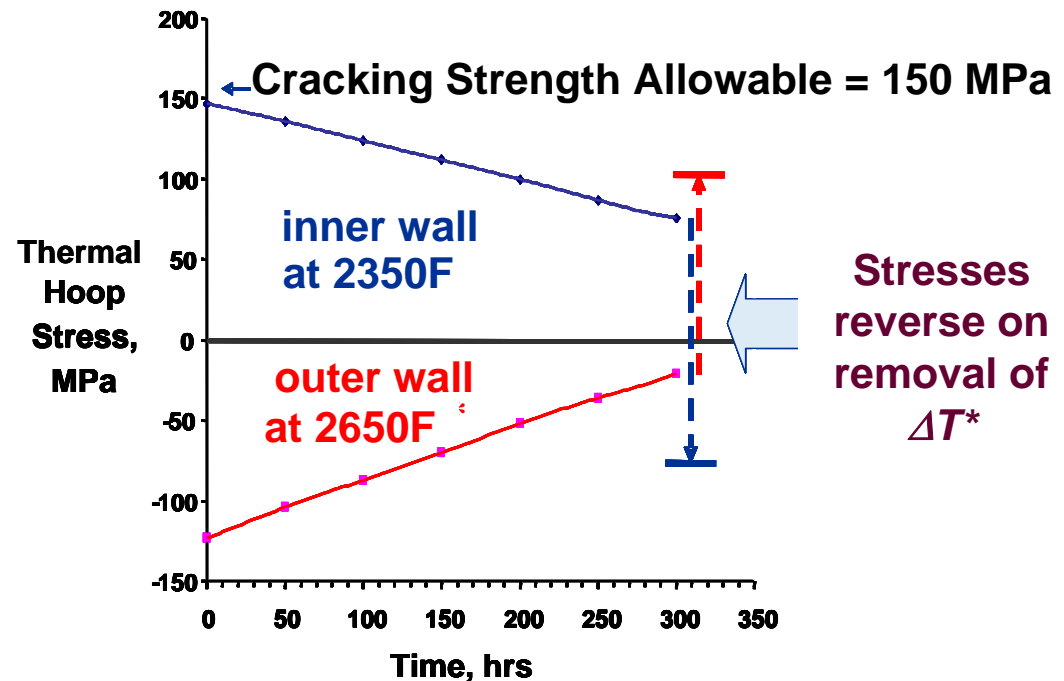Stress, MPa

Time, hr

1315°C (2400°F)

Higher fiber content in loading direction raises rupture stress for a given life, or rupture time for a given stress

NEED: Understanding of Creep-Related Residual Stress Development in SiC/SiC due to Stress and Thermal Gradients

Tube Dimensions: H/a = 0.33

Cracking Strength Allowable = 150 MPa

inner wall at 2350F

outer wall at 2650F
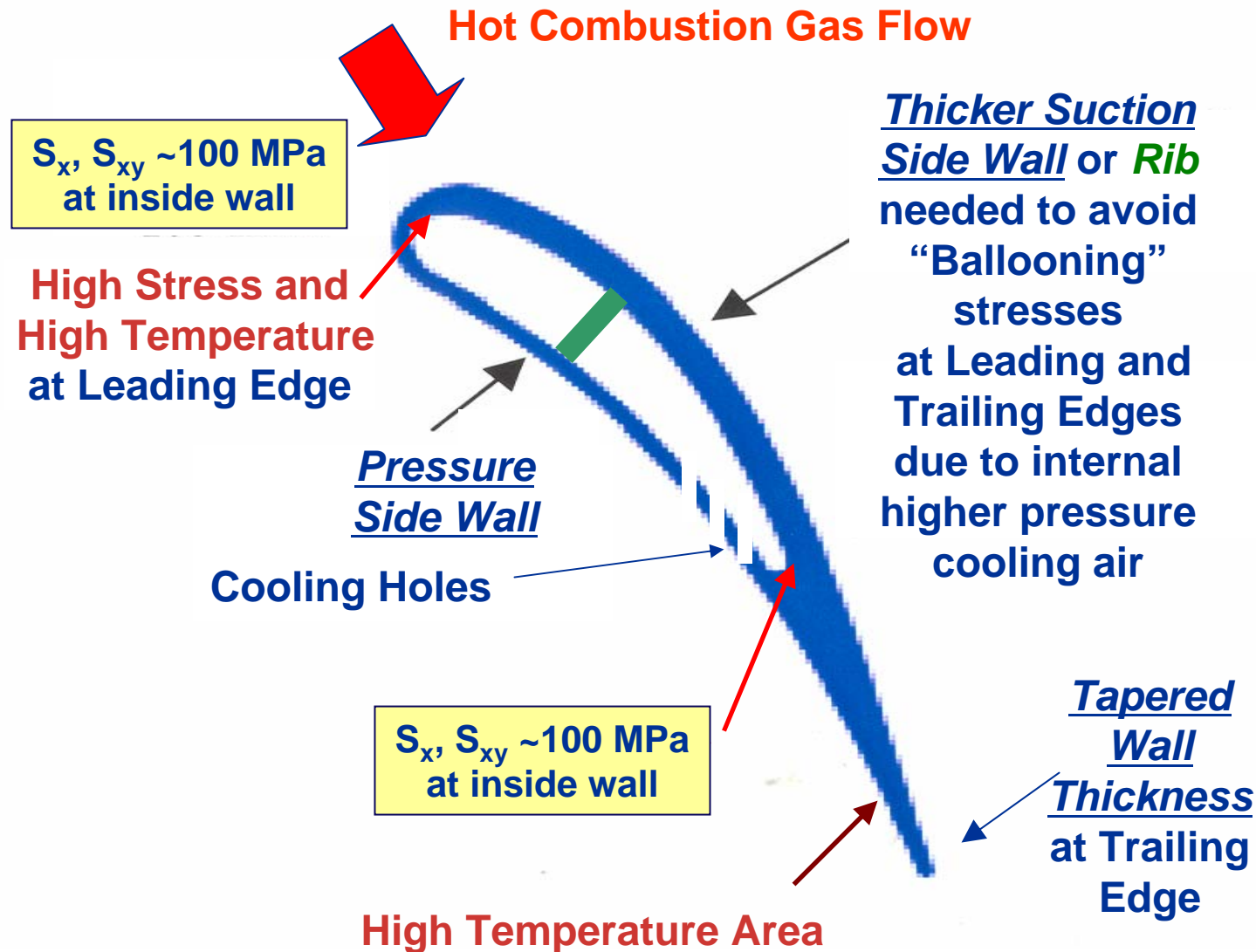
Thermal Hoop Stress, MPa

Stresses reverse on removal of ΔT^*

Time, hrs
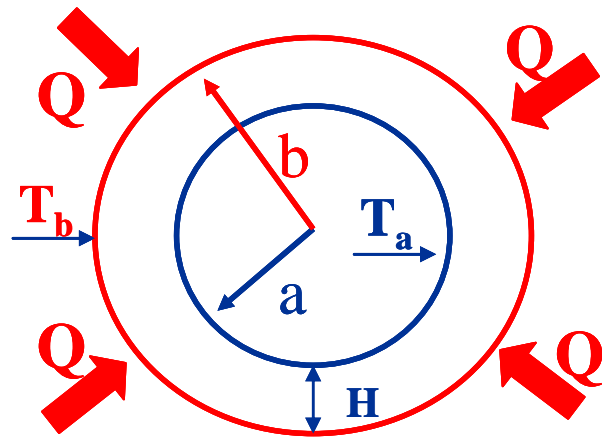
Both Inner and Outer Wall Stresses relax with time, thereby increasing material reliability at temperature. But Outer Wall goes into tension on ΔT^* removal (e.g., during component cool-down). Outer wall residual tension adversely increases with time at temperature.

Technical Challenge: Shape and Thermo-Structural Requirements for SiC/SiC Components are Complex

Hot Combustion Gas Flow

S_x, S_{xy} ~100 MPa at inside wall

High Stress and High Temperature at Leading Edge

Thicker Suction Side Wall or *Rib* needed to avoid "Ballooning" stresses at Leading and Trailing Edges due to internal higher pressure cooling air

Pressure Side Wall

Cooling Holes

S_x, S_{xy} ~100 MPa at inside wall

Tapered Wall Thickness at Trailing Edge

High Temperature Area

Current Computational Challenges:
CMC Structures

Industry Need: Component Producibility Models needed to down-select the optimum 2D and/or 3D architectures and CMC processes that can *simultaneously* meet component shape, process, and performance requirements

Key Issues for SiC/SiC Components:

- ***Shaping:***

  - *Formability without fracture of high-modulus SiC fibers*
  - *Smooth component surfaces*
  - *T-sections and Rapid transition areas*

- ***Processing:***

  - *Ease of infiltration of uniform fiber coatings and SiC matrices*
  - *Component processes are often different than panels*
  - *Need for zero or low permeability*

- ***Performance:***

  - *Fiber content and direction that can provide sufficient thermostructural properties at practically all locations in component*

Perspective on Current CMC Computational Needs

- CMC hot-section components will continue to be considered for a variety of engine markets due to their capability to outperform monolithic ceramics in damage tolerance and metallic superalloys in upper use temperature and reduced weight.

- Although constituent materials and processes have reached a high level of maturity, particularly for SiC/SiC CMC, key computational challenges still need to be overcome:
  - *Approaches and models to select the processes, microstructure, and macrostructure for meeting the design requirements of complex-shaped CMC components*
  - *Approaches and models to predict the failure modes of these components under their complex service conditions*

- Based on current needs for long-life components, these computational needs appear to center primarily on the development of models for
  - *Component fiber architecture and its effects on shaping, constituent infiltration, multi-directional thermo-mechanical properties, and failure modes*
  - *Component creep-related behavior and its effects on residual stress development and constituent rupture life*