UTSR 2016 Conference

“Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency” DE-FE0023955

http://siemens.com/energy/power-generation/gas-turbines

CMC Advanced Transition for η > 65% CC Program Overview

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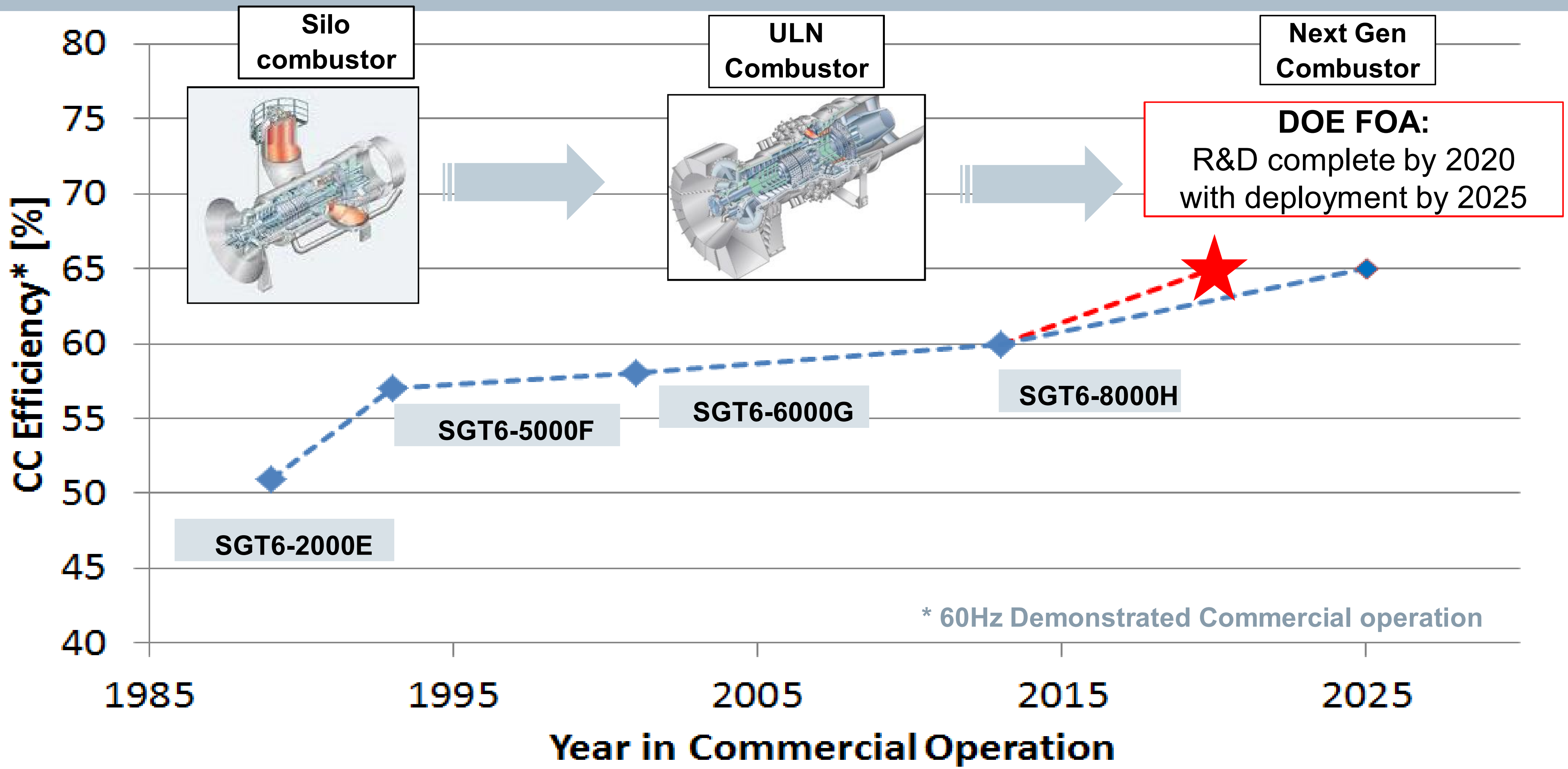
Content of Today's Presentation

1. Towards a 65% CC efficient power plant
2. Proposed CMC AT for high TIT / Low NOx
3. CMC Technology Development
4. Conclusions & Next Steps

Towards a 65% CC system



DOE targets are driving a step change in GT combustion technology

Towards a 65% CC system

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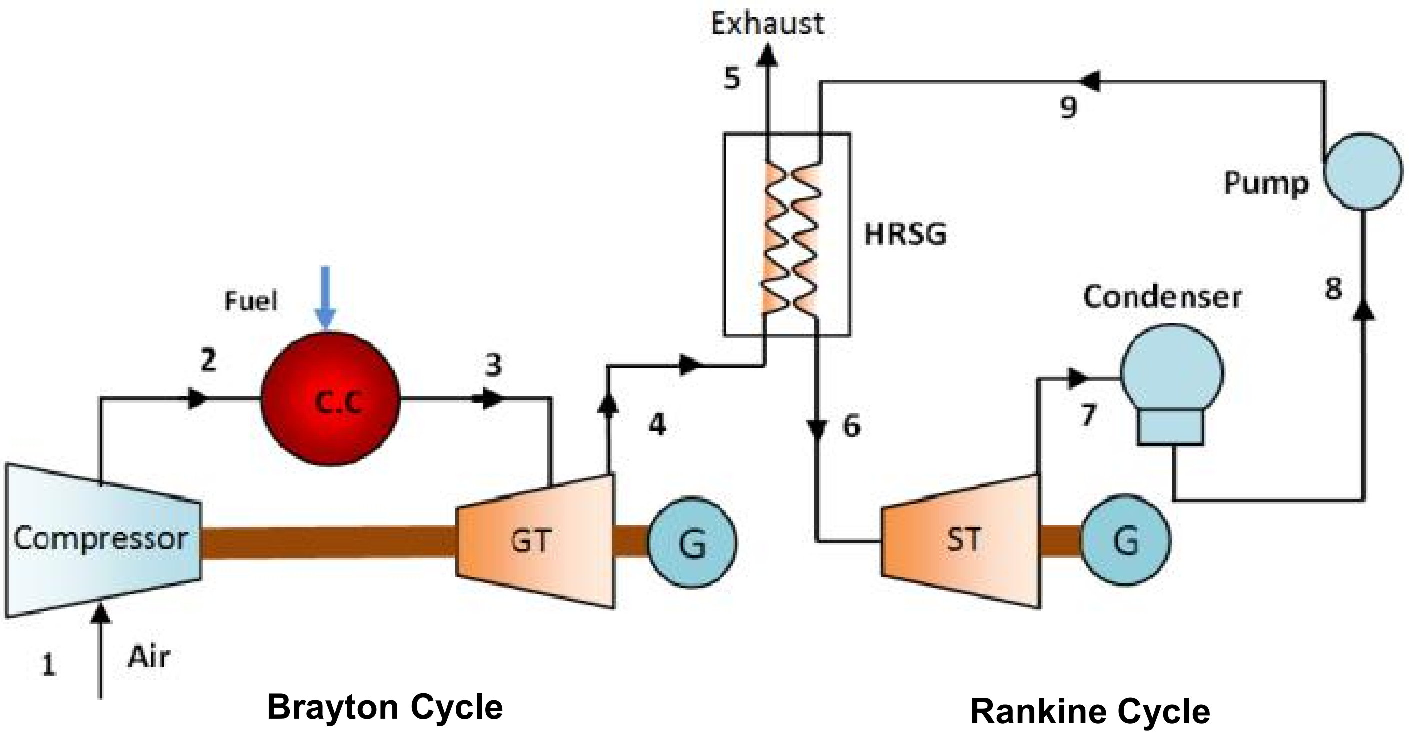

Source: Ibrahim et. al (2012)

Brayton Cycle

- Plant output and efficiency improved by raising the top of the cycle
- i.e. **Higher firing temperature** and **pressure**.

Rankine Cycle

- Plant output and efficiency improved with better utilization of GT Exhaust energy.
- i.e. Higher bottoming steam temperature and pressure.

65% CC efficiency targets Firing Temperature > 1700ºC

Siemens Solution to Program Challenge: Combustion Development

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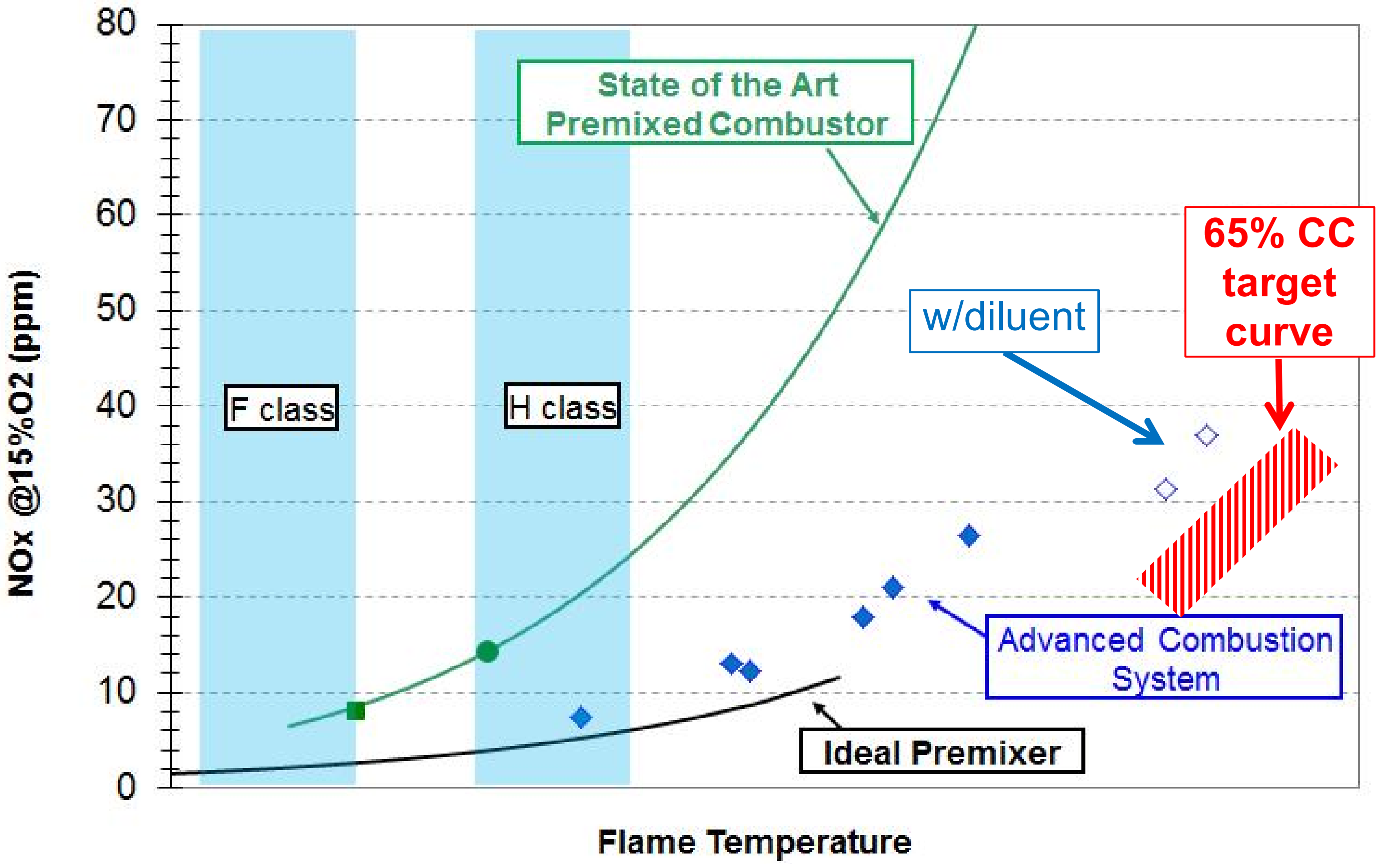

Combustion Technology "jumps" are required to shift NOx curve right

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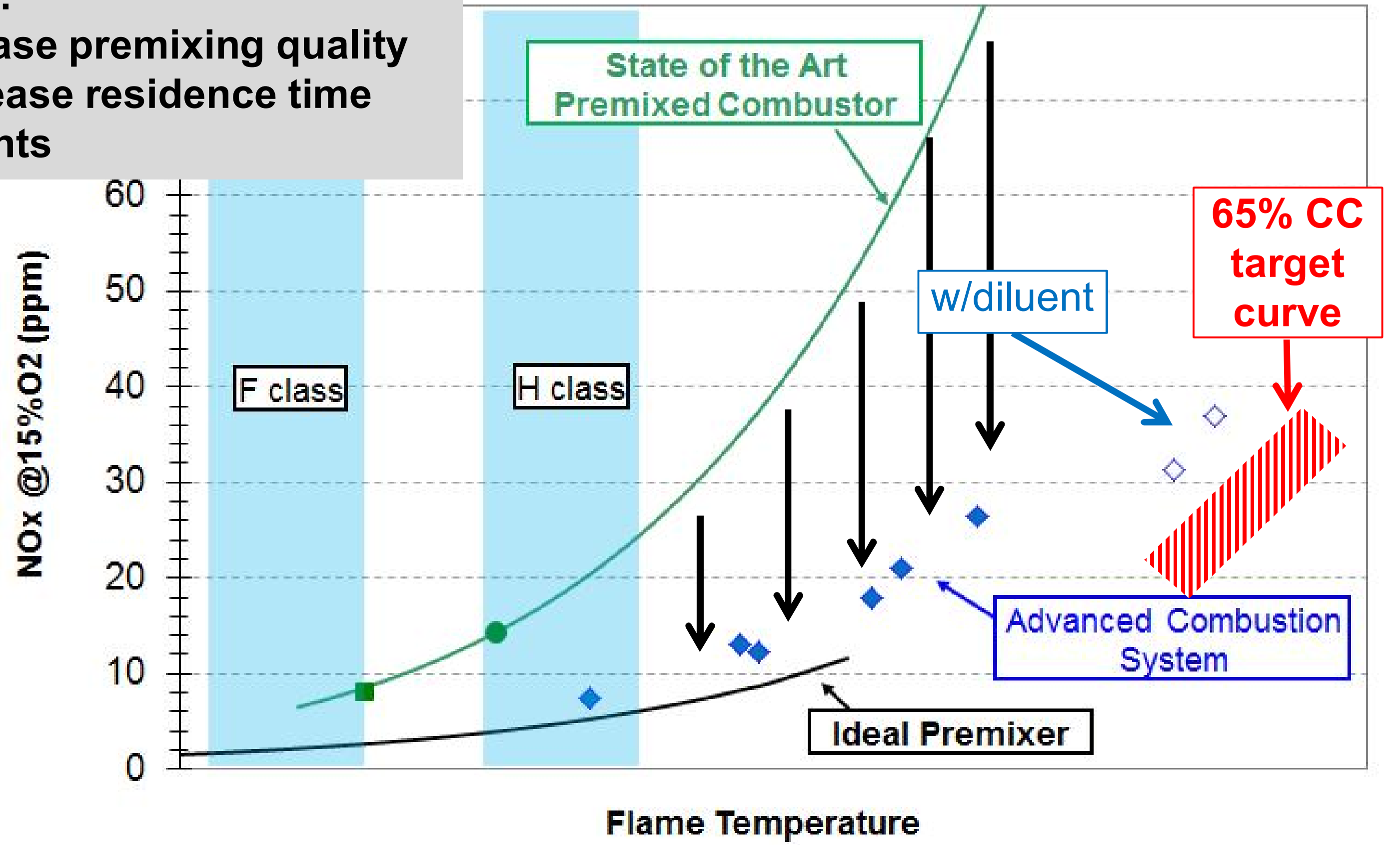
Siemens Solution to Program Challenge: Combustion Development

Enablers:
- Increase premixing quality
- Decrease residence time
- Diluents



Parallel Combustion approaches for NOx reduction

Siemens Solution to Program Challenge: Combustion Development

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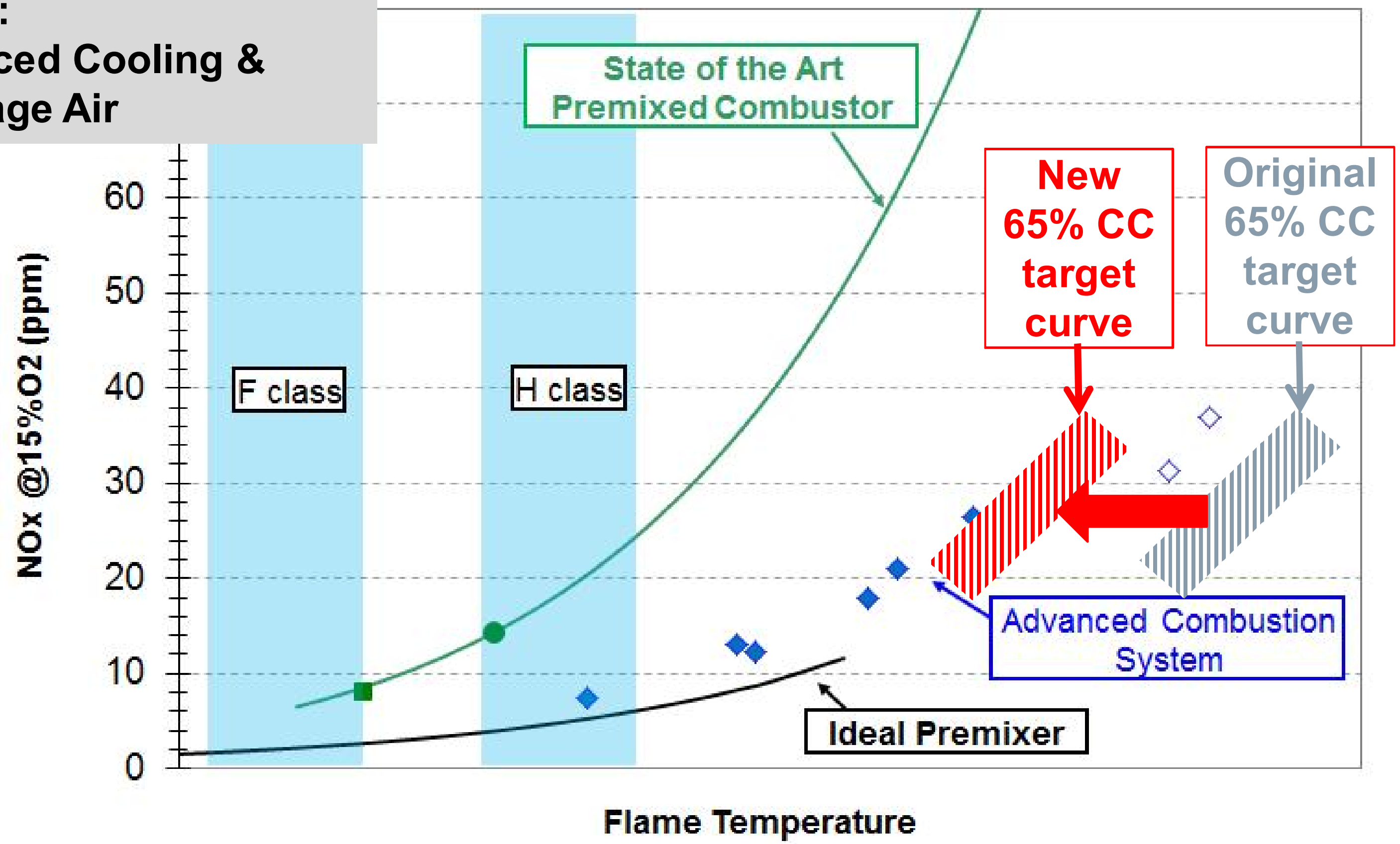
Enablers:
- **Reduced Cooling & Leakage Air**



- **Focus of this program is on Cooling & Leakage Air Reduction for Low NOx**
- **Lower required flame temperature for a given TIT → Reduced NOx**

Enablers: Advanced Transitions (AT)

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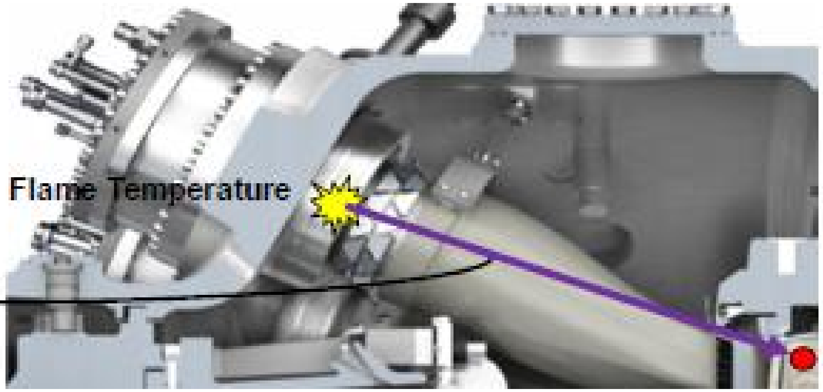
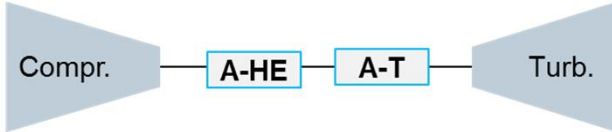
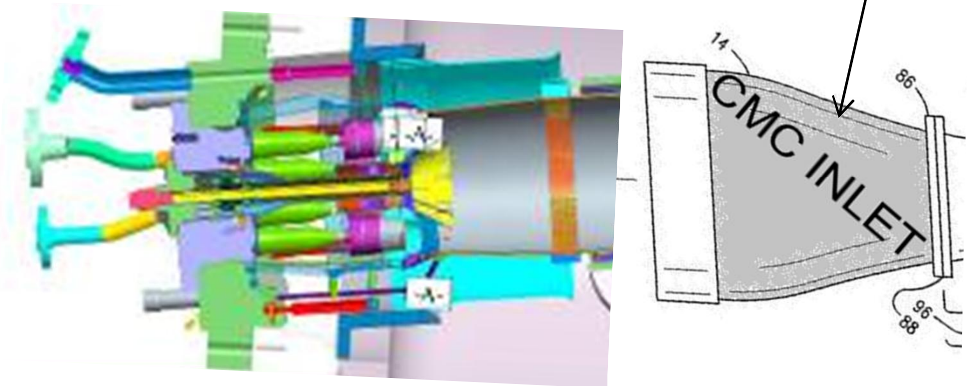


Reduced cooling & leakage air between flame and turbine rotor



Advanced Transition (AT)



AHE + AT

- Developed during DOE-H2 program (DE-FC26-05NT42644)
- Allows for reduction of cooling air
- Low NOx at J-class conditions
- **System residence time not optimized for 65% CC operating conditions**

Advanced Transition (AT) →Reduced Cooling air consumption

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Introduction

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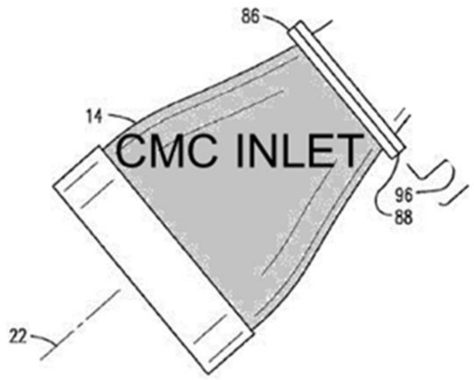
- **Objective:**
  - Phase 2: Design a CMC inlet for Siemens Advanced Transition
- **Benefits:**
  - Reduction in Cooling Air → NOx reduction or RIT increase
  - CO reduction (eliminate wall quenching)
  - Reduced aero losses
    - Due to cooling air mixing
    - Due to cooling air ducting
- **Premise:**
  - Existing Siemens' CMC material
  - No through-wall cooling (backside only)
  - Shape conducive to CMC manufacture
  - Durability demonstrated in 25K hr test
  - Readily tested in combustor rigs

Concept schematic

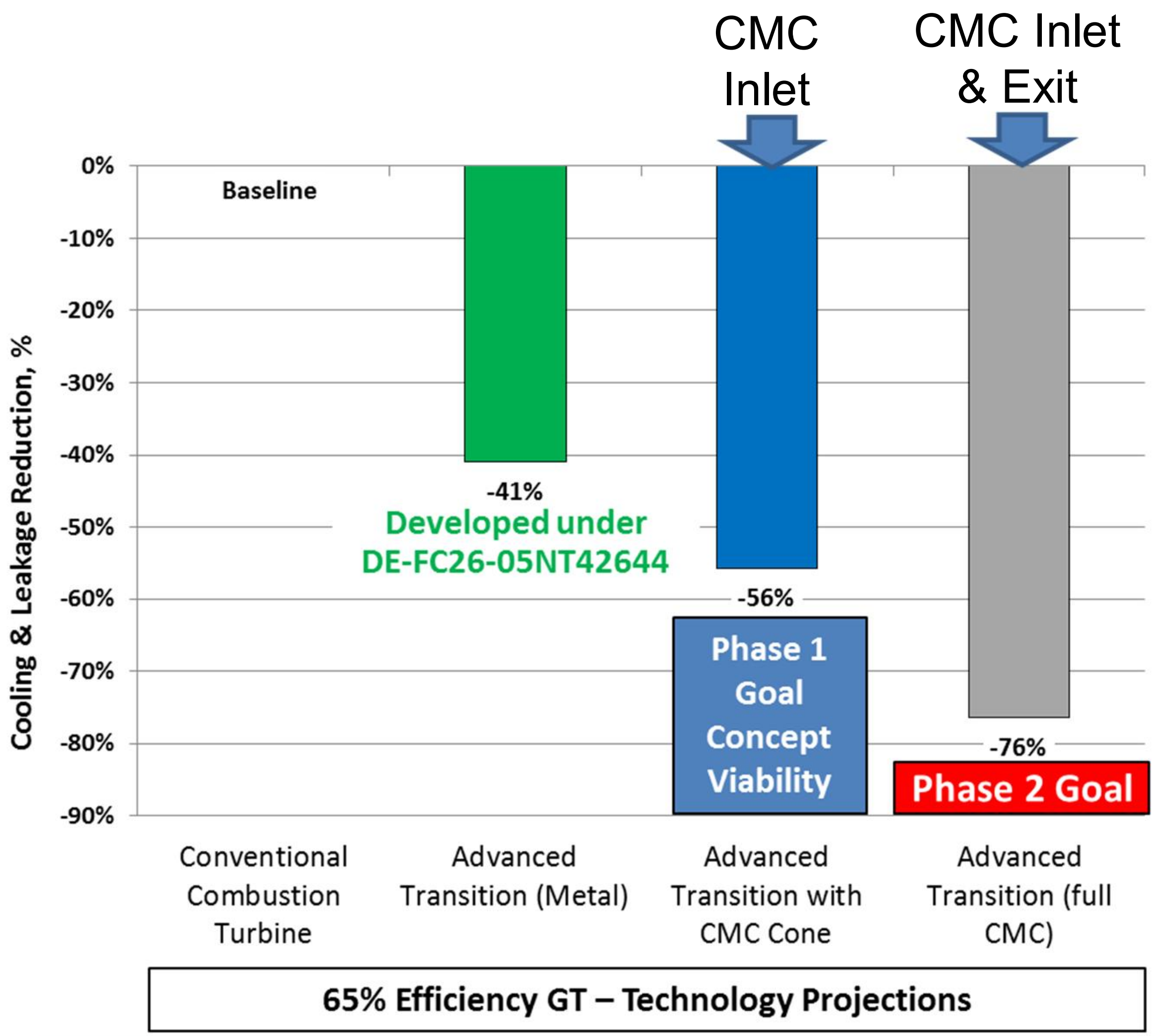


Experience base

- Siemens Hybrid Oxide CMC system (FGI thermal barrier)
- Filament wound combustor outer liner (made by COIC)
- Operated in Solar Centaur 50™ engine.
  - 25,404 hours / 109 cycles;
  - Bakersfield, CA
  - Still serviceable
- Surface & CMC temperatures representative of AT inlet

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Benefits: Cooling Air Reduction



Phase 2 objectives:

- **Validate CMC Cone concepts developed in Phase 1 via rig testing.**
- **Develop design concepts for full CMC Advanced Transition**

→ NOx emissions reduction at High Firing Temperatures

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

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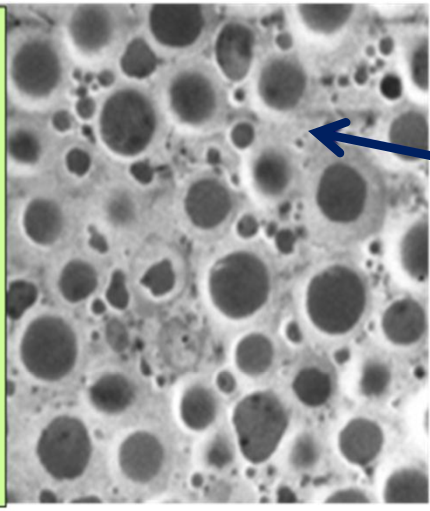
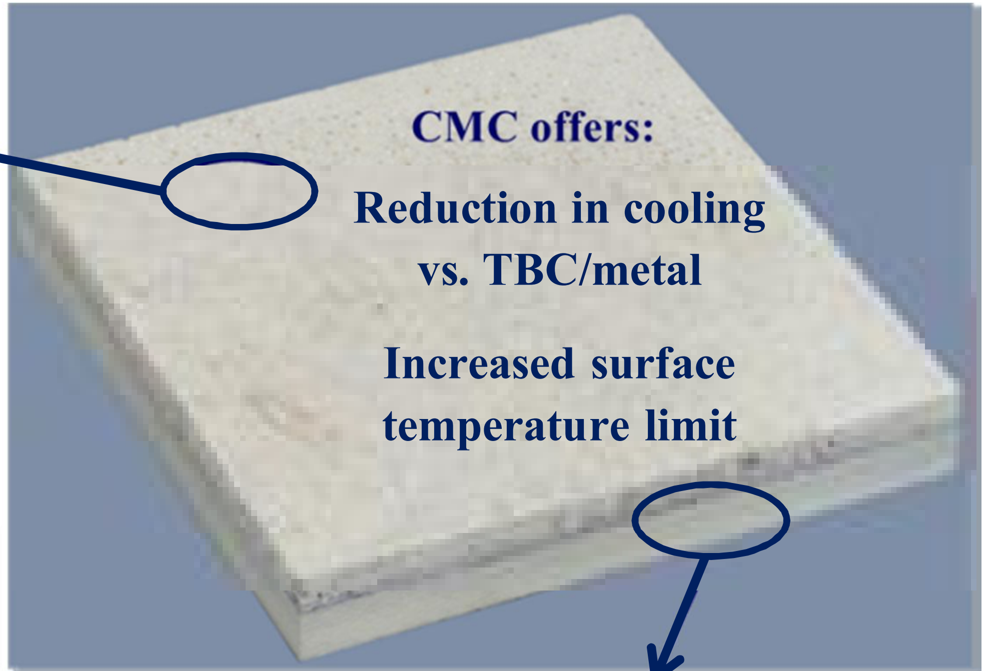
Siemens' Hybrid CMC Technology

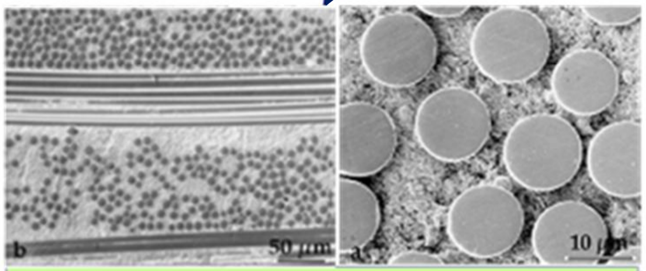
Coating: FGI (Friable Graded Insulation) – Siemens patented material consisting of thermally stable hollow ceramic spheres closely packed in a ceramic matrix binder.





The HYBRID concept is a Siemens patented approach

- The Siemens system is a HYBRID system: Oxide CMC coated with a unique TBC → FGI
- This keeps the oxide CMC at lower temp while providing overall system high temp capability
- This hybrid system overcomes a lot of the issues previously perceived for oxide CMCs



Substrate: COI Ceramic's AN720 oxide-oxide CMC system providing strain-tolerant, notch-insensitive behavior up to 1200°C

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

CMC Technology Status

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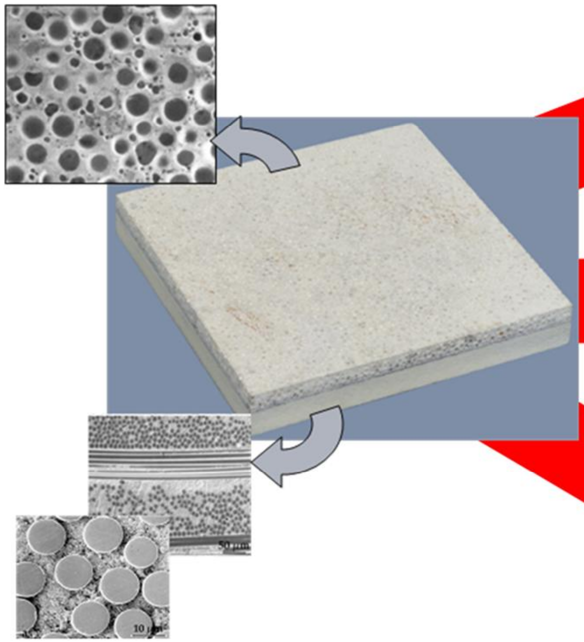
Benefits:

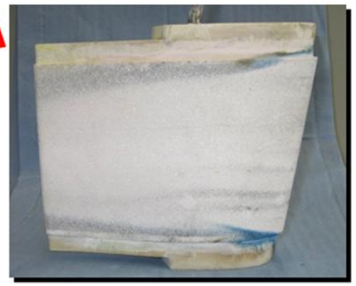
- *Ultra-low cooling requirements*
- *Oxidatively stable constituents*

TRL5-6 Reached on Key Engine Components



Solar Turbines combustor liner. 25,000+ hrs (completed 2006)

Blade Tip Seals engine tested



Airfoils demonstrated in rig testing

- *Low cost*
- *Millions of engine operating hours (tiles)*
- *>25,000 hours proven in combustors*

+ Siemens' Advanced Transition

Combining two high pay-off technologies individually developed & tested

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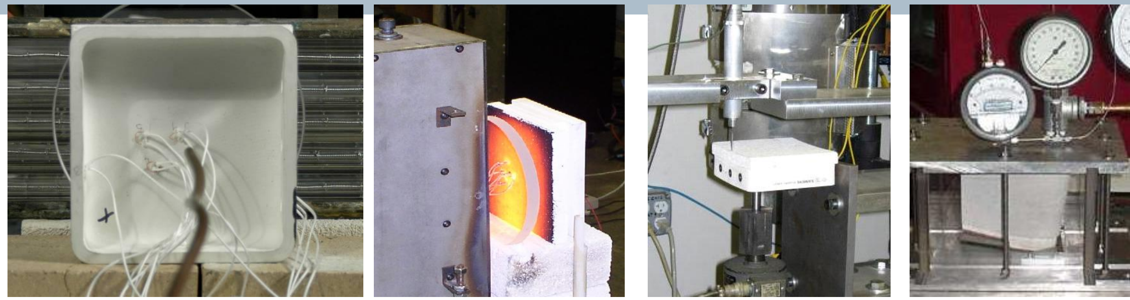
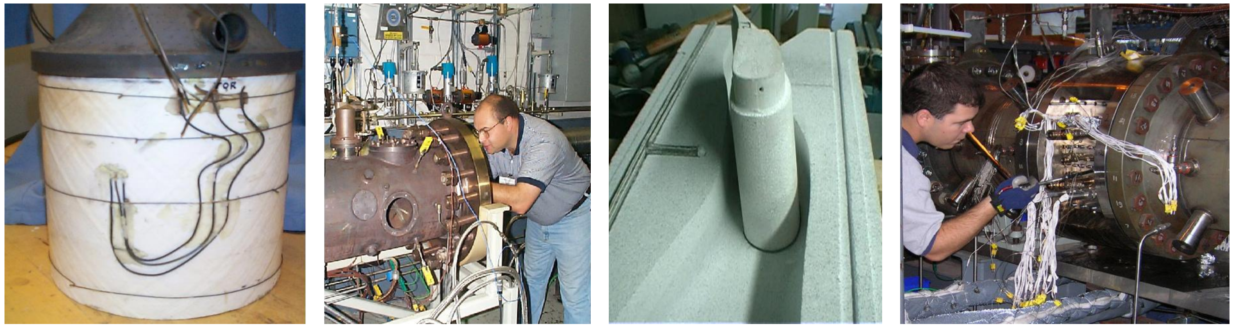
CMC Component Testing Summary

- Bench testing
  - Mechanical, thermal, fatigue, impact, etc.



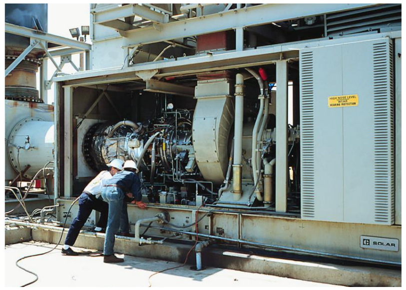
Ring segments (4 types), airfoils, subelements

- Rig testing
  - Simulated engine conditions
  - Durability under combined loadings
  - Subscale & Full Scale components

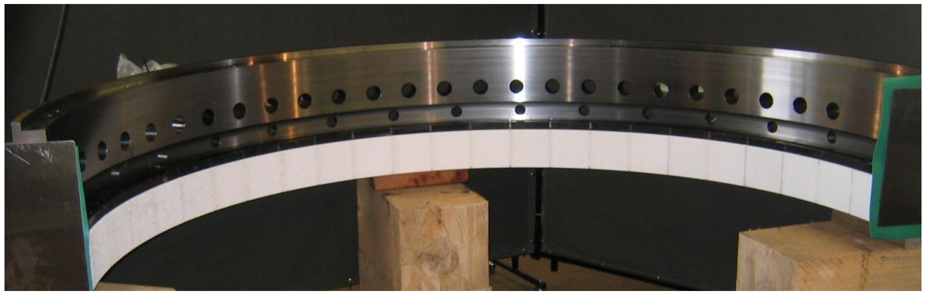


Combustors, Airfoils, Ring segments (4 types)

- Engine testing
  - Customer site / durability
  - BTF engine



Combustor



Ring Segment

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Hybrid Oxide CMC Combustor Liner

- Siemens Hybrid Oxide CMC system (FGI thermal barrier)
- Filament wound combustor outer liner (made by COIC)
- Operated in Solar Centaur 50™ engine.
  - 25,404 hours / 109 cycles;
  - Bakersfield, CA
  - Still serviceable
- Surface & CMC temperatures representative of AT inlet

This test demonstrated CMC durability in a turbine engine environment for representative component lifetime

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CMC Manufacturing Options

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Fabric Lay-up Vs. **Filament Winding**

- **Both manufacturing approaches are feasible for most AT inlet concepts**
- **Concepts with out-of-plane features more conducive to fabric lay-up**

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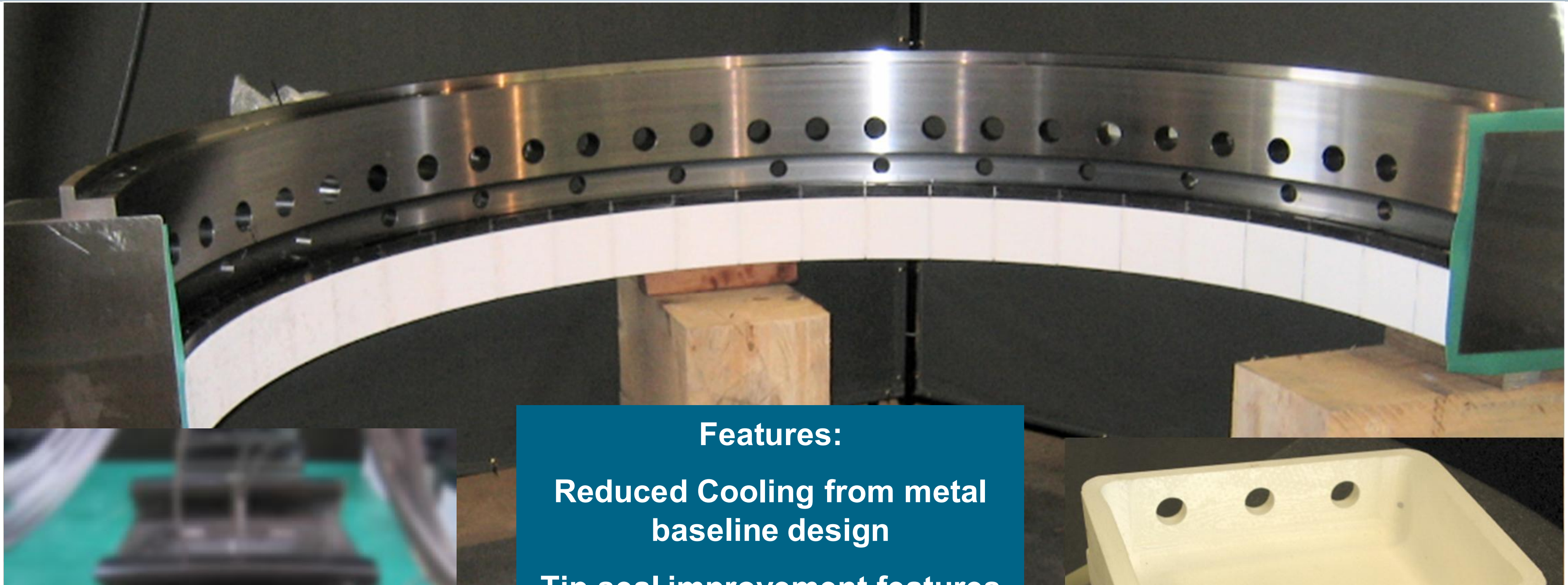
CMC Ring Segment Engine Test



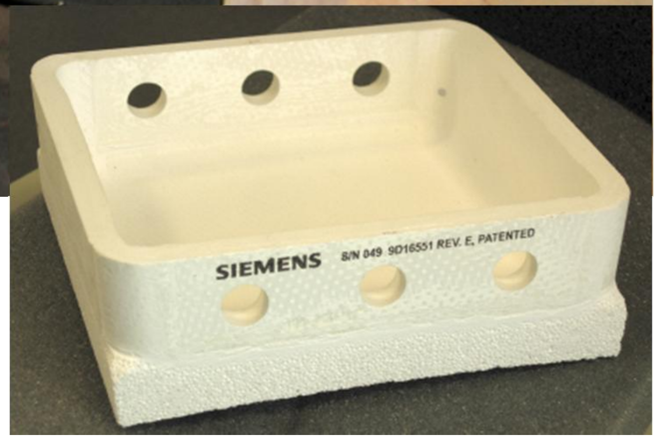
Features:

Reduced Cooling from metal baseline design

Tip seal improvement features

Retrofittable design

High temperature sealing



Full engine set: Tested successfully for > 50 hours

Siemens Project Team

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Integrated Project Team

Principal Investigator

Contract Management / Master Engineer

Materials & Technology
CMC & TBC

High Pressure Combustion Testing
Siemens AG – Clean Energy Center

Combustion Design
Advance transition design & testing

CMC Behavior
Siemens Corporate Technology

Manufacturing Development & Industrialization
Advanced manufacturing development

CMC Manufacturing Vendor
COI Ceramics, Inc.

Advanced Seal Design
CMC – Metal interface

Design & Analysis Contracting
FTT - Florida Turbine Technologies

Design Tools
Mechanical integrity & lifing methods

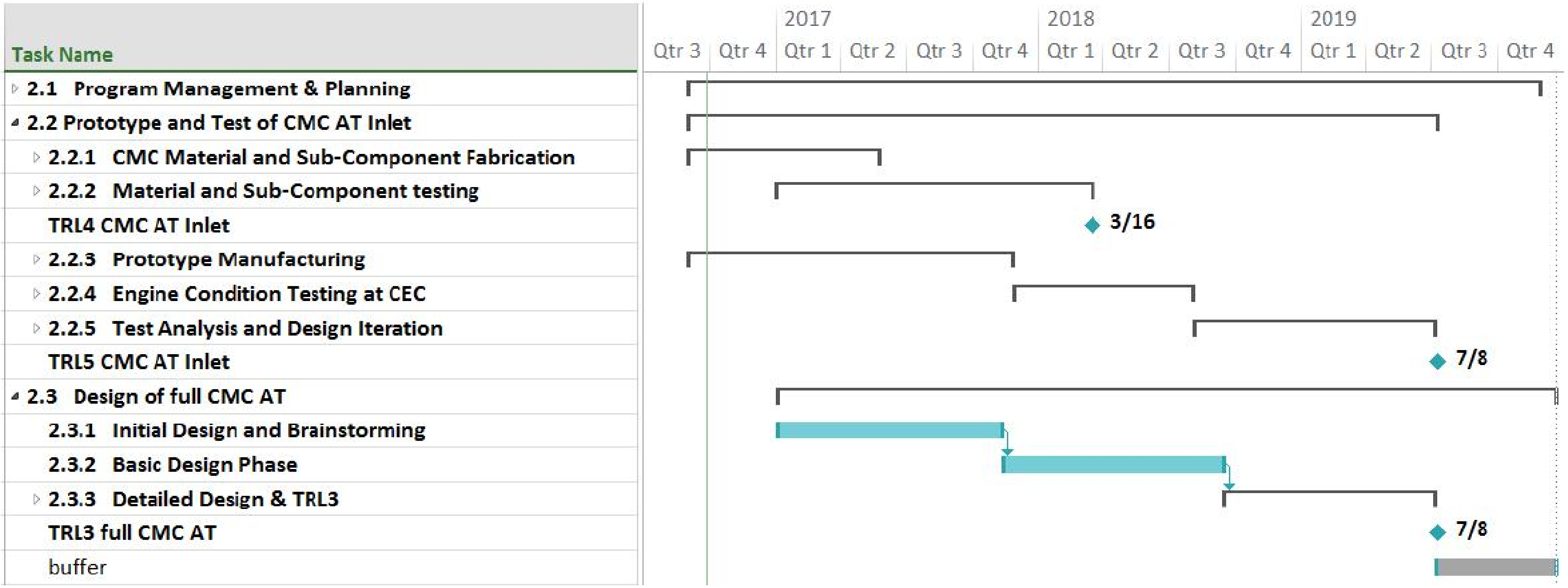
Material Testing
Cincinnati Test Labs

Advanced Transition Manufacturing
SEI – Charlotte

Siemens
Vendor

Siemens has assembled a multi-disciplinary team of internal experts and external vendors and partners to successfully execute this program.

Schedule & Major Milestones



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Technology Development

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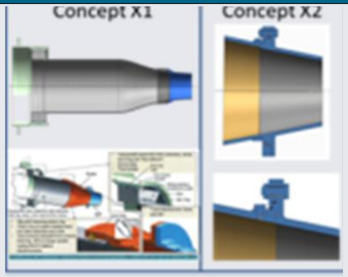
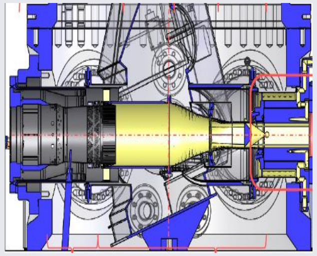
PHASE 1
Concept Feasibility



Conceptual Design

PHASE 2
Technology Development & Testing



Manufacture & Combustor Rig Testing

PHASE 3
Technology Demonstration

Engine Testing

Technology Progression for Future Phases identified

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CMC AT Concept Down-selection Process

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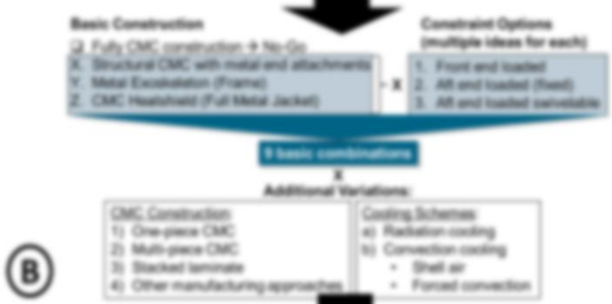

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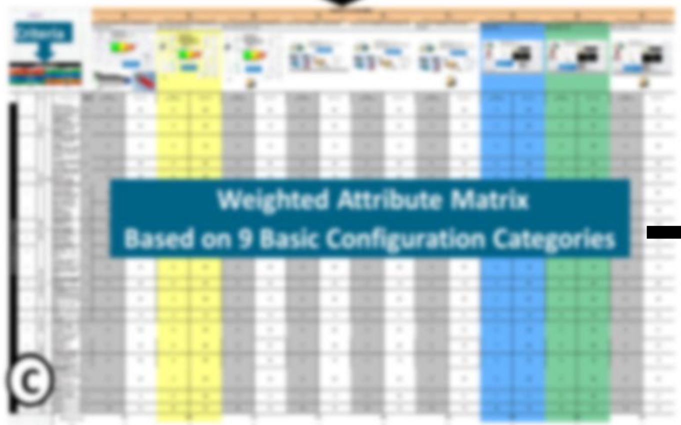

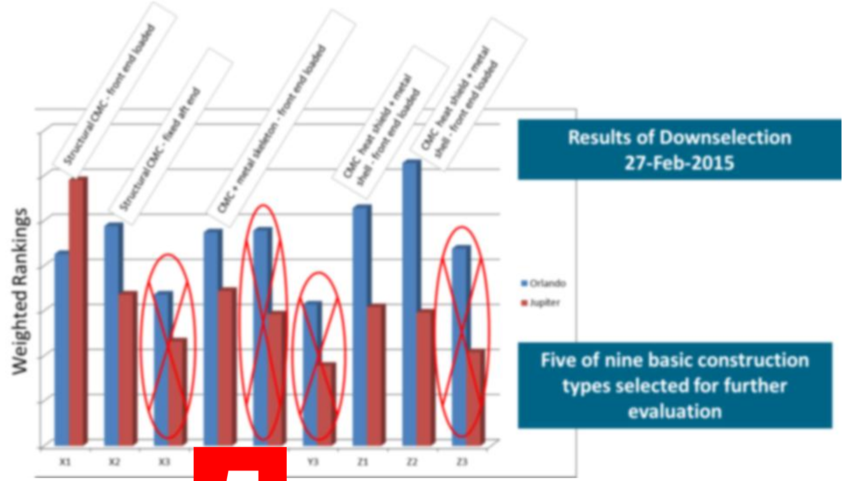

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Structural CMC's → Heat Shields

Milestone Sept 2015 → Two Concepts

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Heat Transfer → CMC with backside cooling

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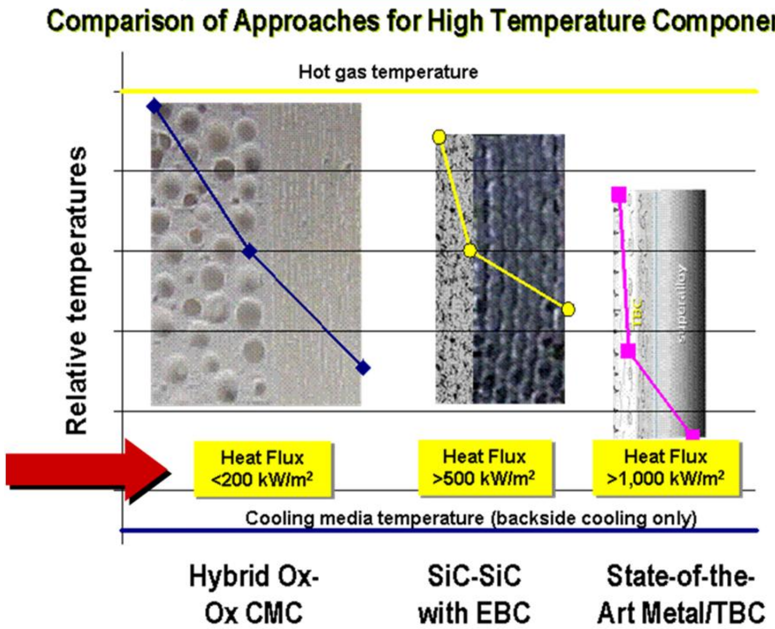
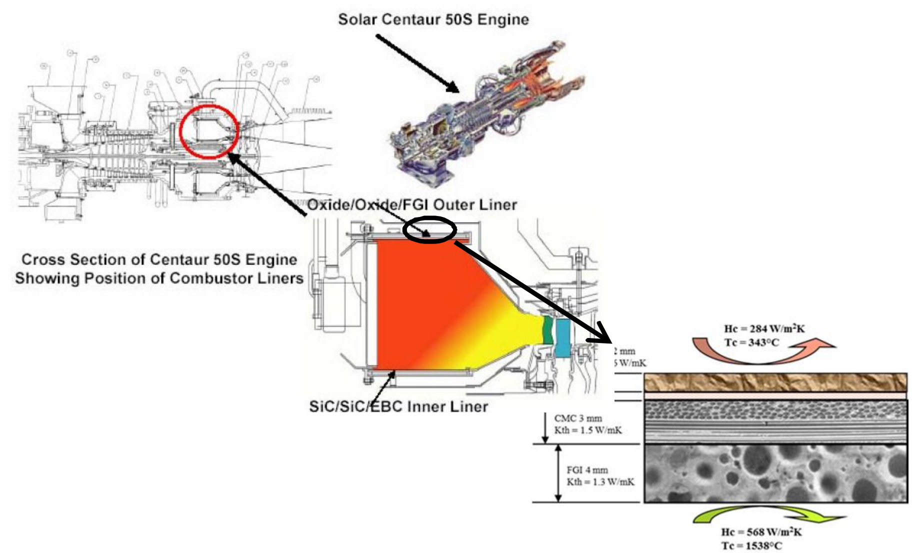
Shell Air Circulation



Insulating characteristic of Hybrid Oxide CMC enables use of low cooling coefficients (similar to levels in engine midframe)

Radiation Cooling



Radiation cooling method proven effective in previous combustion tests

Two Cooling Options:

1. **Shell air circulation → feasibility shown with 1D heat transfer**
2. **Radiation cooling → used on Solar combustor liner design**

Both eliminate active (chargable) cooling

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Supporting CMC Data & Remaining Challenges

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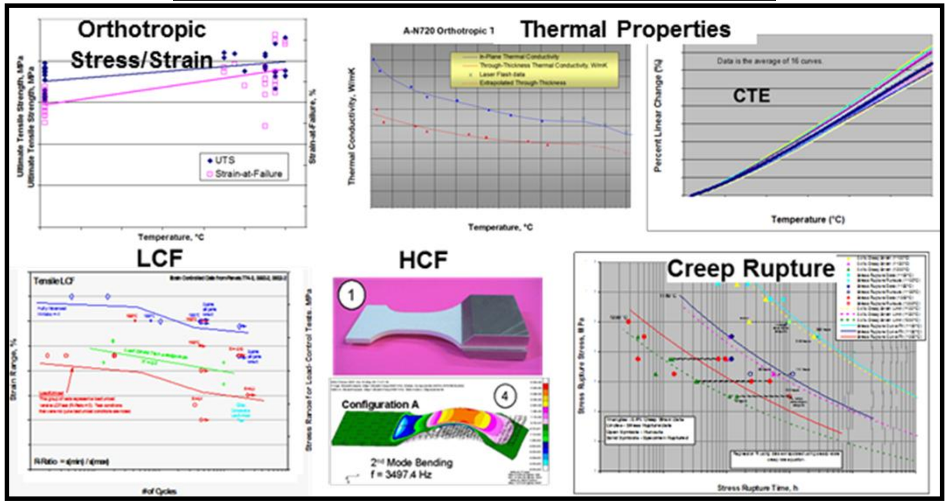
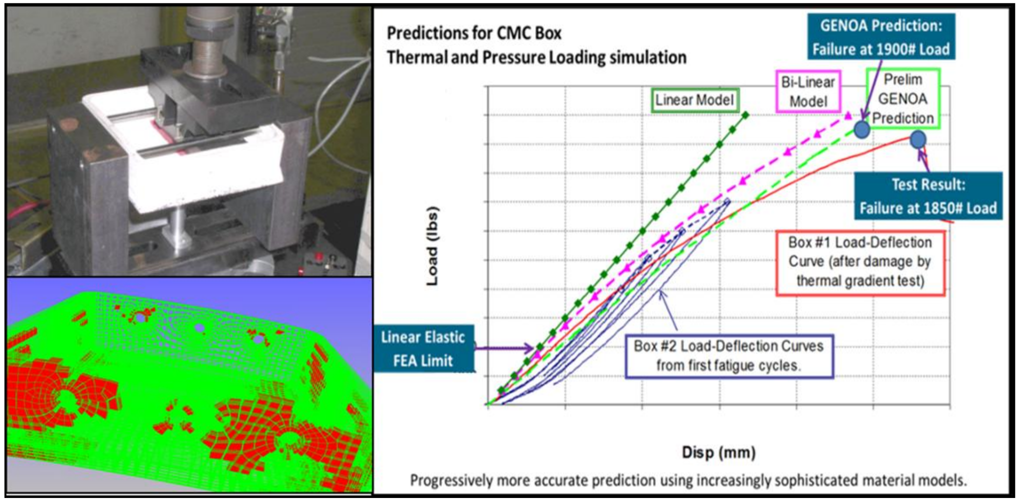
Coupon Test Data



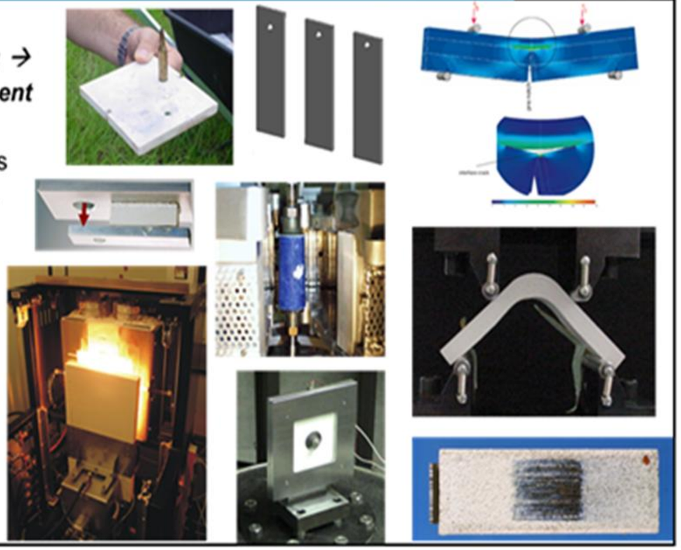
Damage Accumulation & Life Prediction Tools



Subelement & Component test data

Sub-Element Testing → System and Attachment Behavior

- Attachment features
- Geometric features
- Coating adhesion
- Wear
- Thermal stress
- Abradability
- Impact
- Sealing
- Etc.



Remaining Design / Materials Challenges

- Sealing methods for high temperature
- Metal-to-CMC Interfaces:
  - Wear resistance (anti-wear coatings)
  - Contact stresses / inserts / compliant layers

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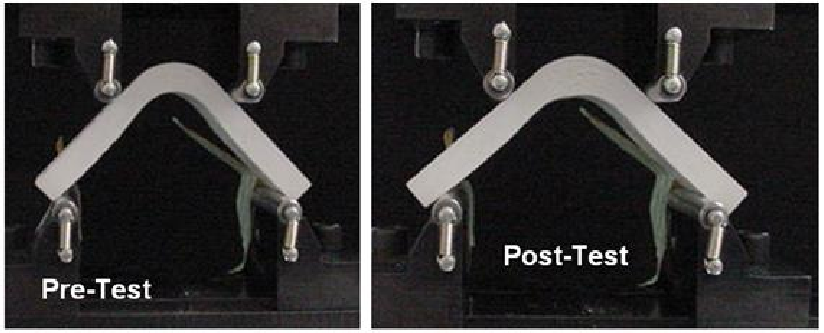
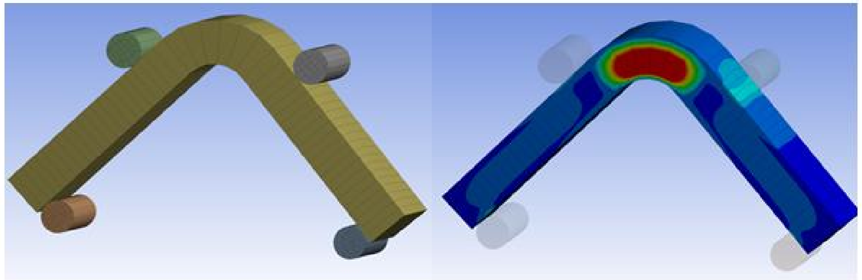
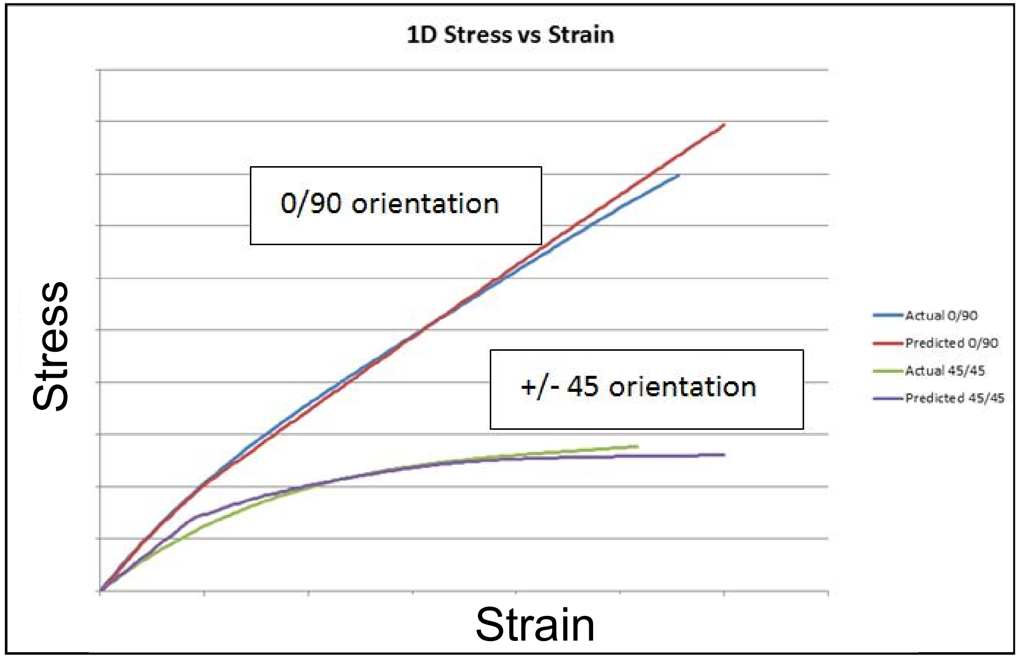
Micromechanics Modeling (MAC/GMC)







- Constitutive model (fiber & matrix properties)
- Iteratively best-fit to a series of test data (different geometries)
- Matches stress-strain behavior of simple (uniaxial) and complex shape (multiaxial stress) test data

- **Model calibrated and matches test data**
- **Works interactively with FEA**

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CMC Structures and Numerical Modeling

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Bi-Directional Design Optimization

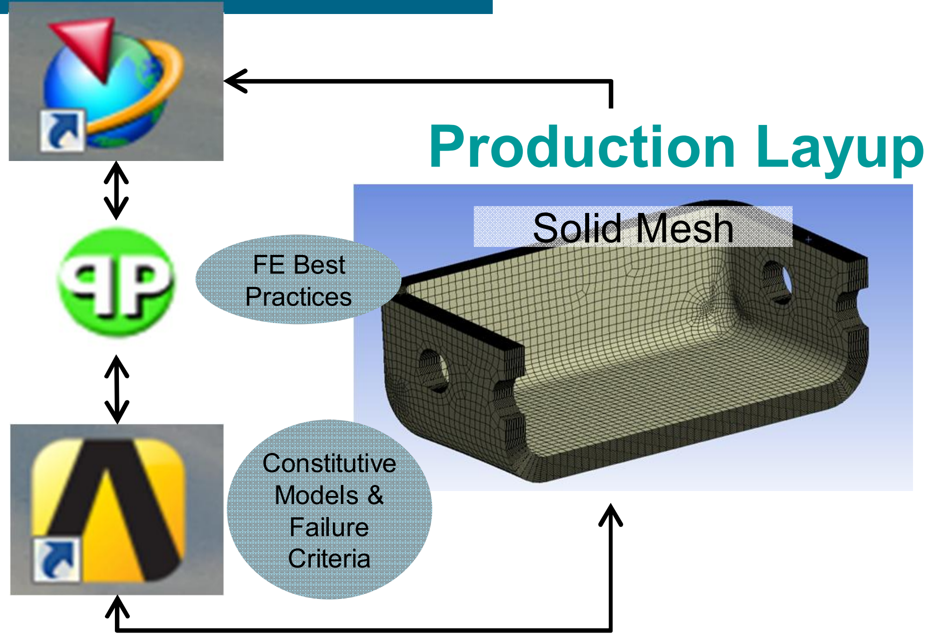
Hi-Fidelity Damage Simulation

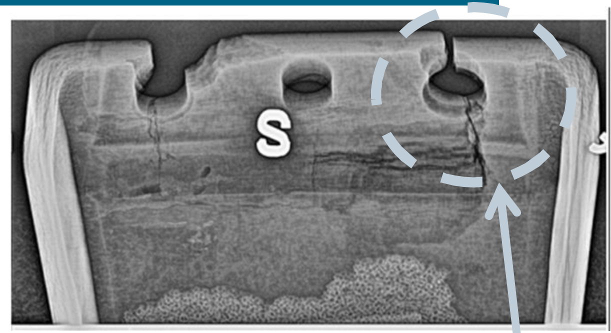
NXR CAD

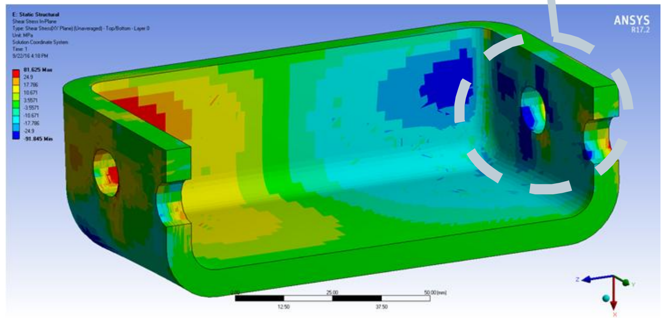
ANSYS ACP

Workbench

Production Layup





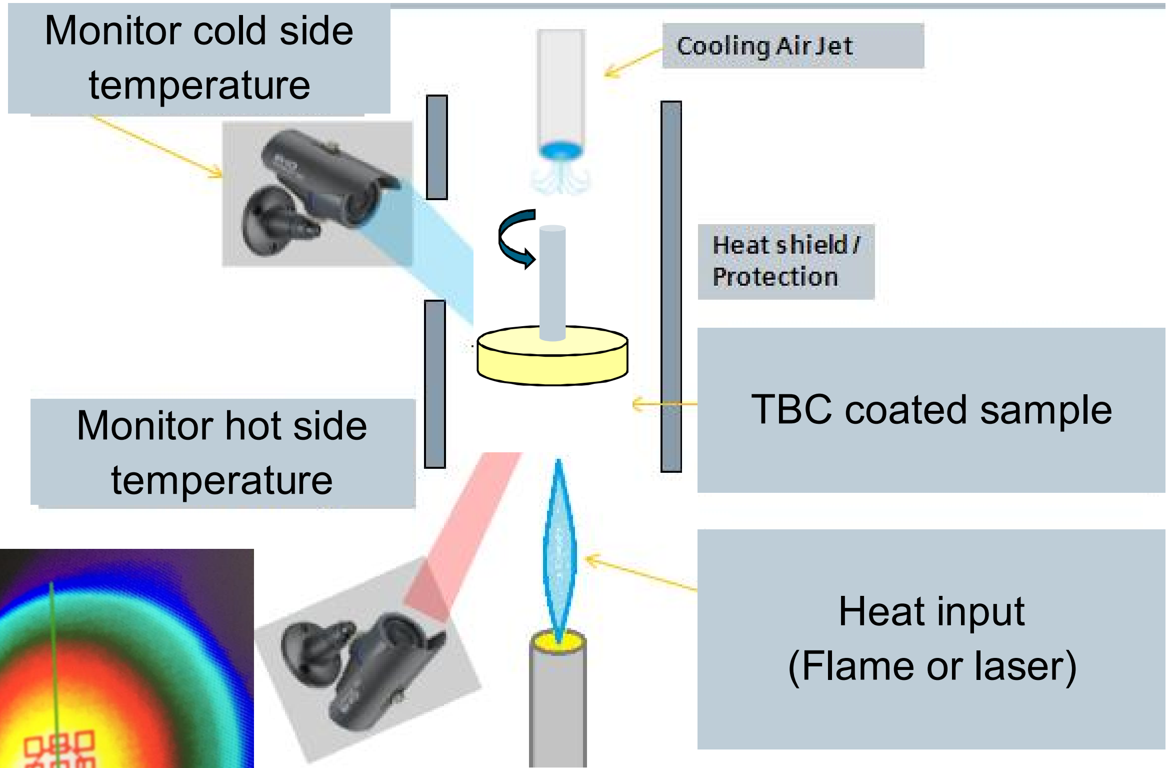


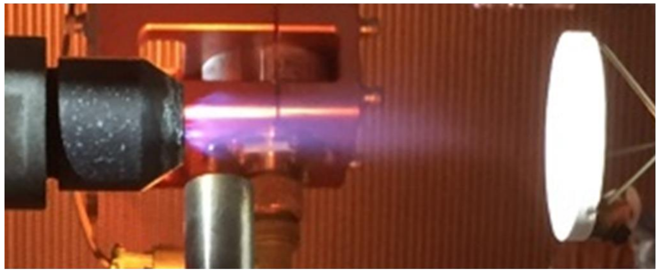
- **Advanced Simulation Methods Calibrated to Lab and Sub Component Testing to Provide Accurate and Robust Design Rules.**

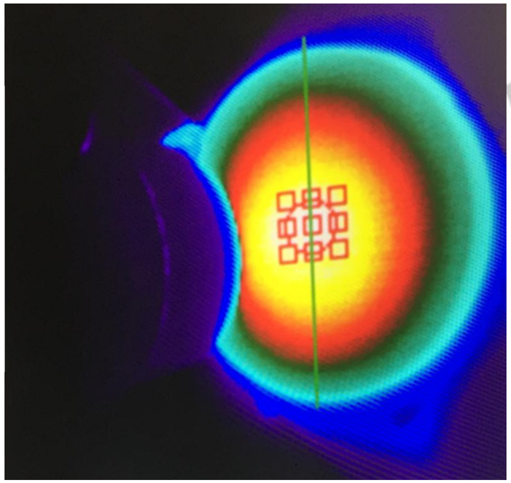
TBC Testing

Objective:
Simulate TBC failure under pseudo engine condition (high heat flux, backside cooling)

Application of HHFT:
- Down select coating
- Characterize CMC/Coating system behavior

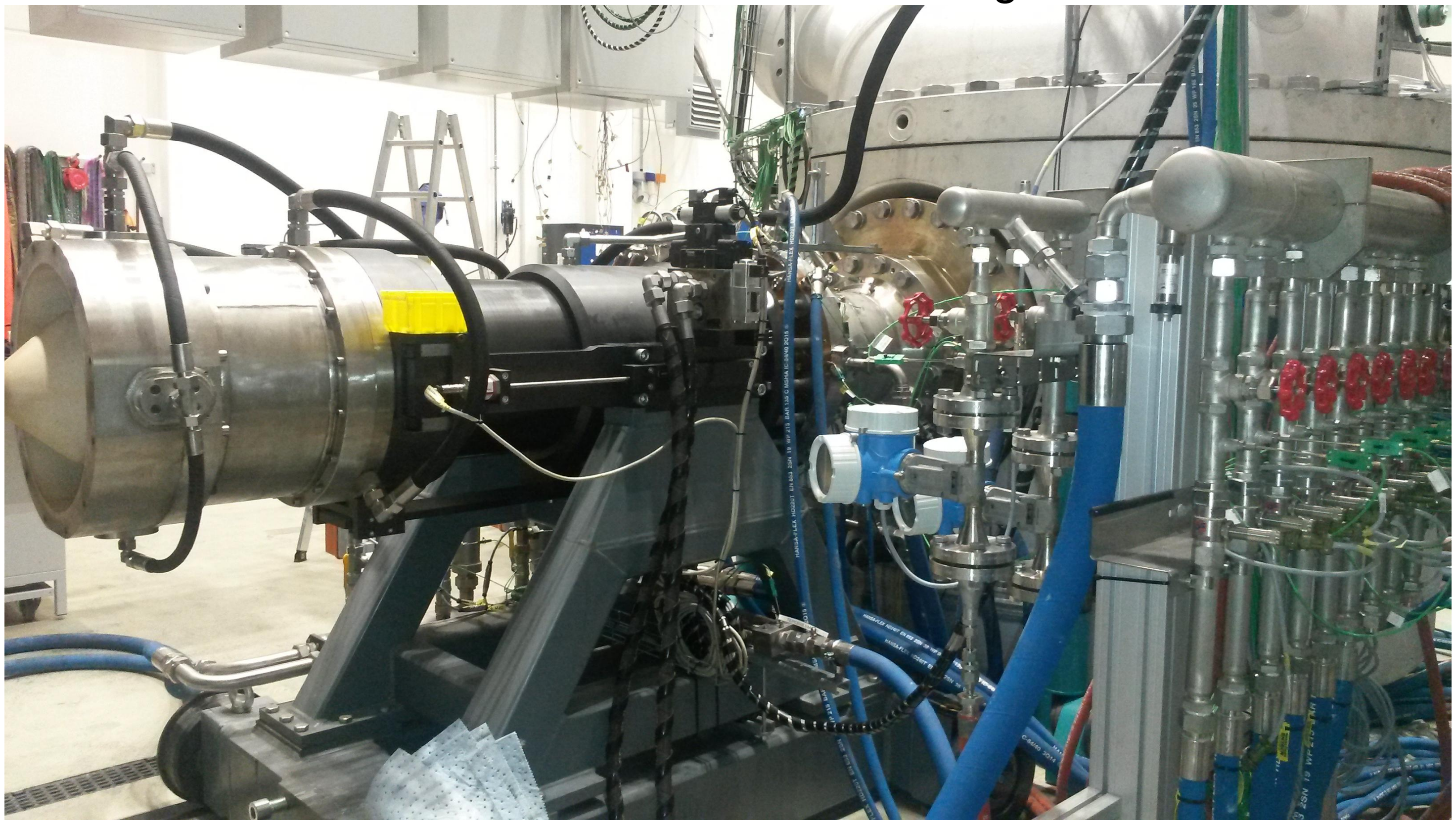






Combustor Rig Testing

Siemens Clean Energy Centre
Advanced Transition test rig



CMC Advanced Transition Inlet section will be tested in this dedicated rig facility (full scale; full pressure; full flow; full temperature)

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Acknowledgements

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- This program is based upon prior work supported by the US Department of Energy, under Award Number DE-FC26-05NT42644.

- The Siemens team wishes to thank Dr. Seth Lawson, NETL Project Manager and Mr. Rich Dennis, NETL Turbine Technology Manager for the opportunity to collaborate on the development of these novel technologies.

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U.S. DEPARTMENT OF ENERGY

Answers for Energy.

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Thank You. Questions?

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Hybrid Ox-Ox CMC Rationale

Reference ASME GT 2007-27532