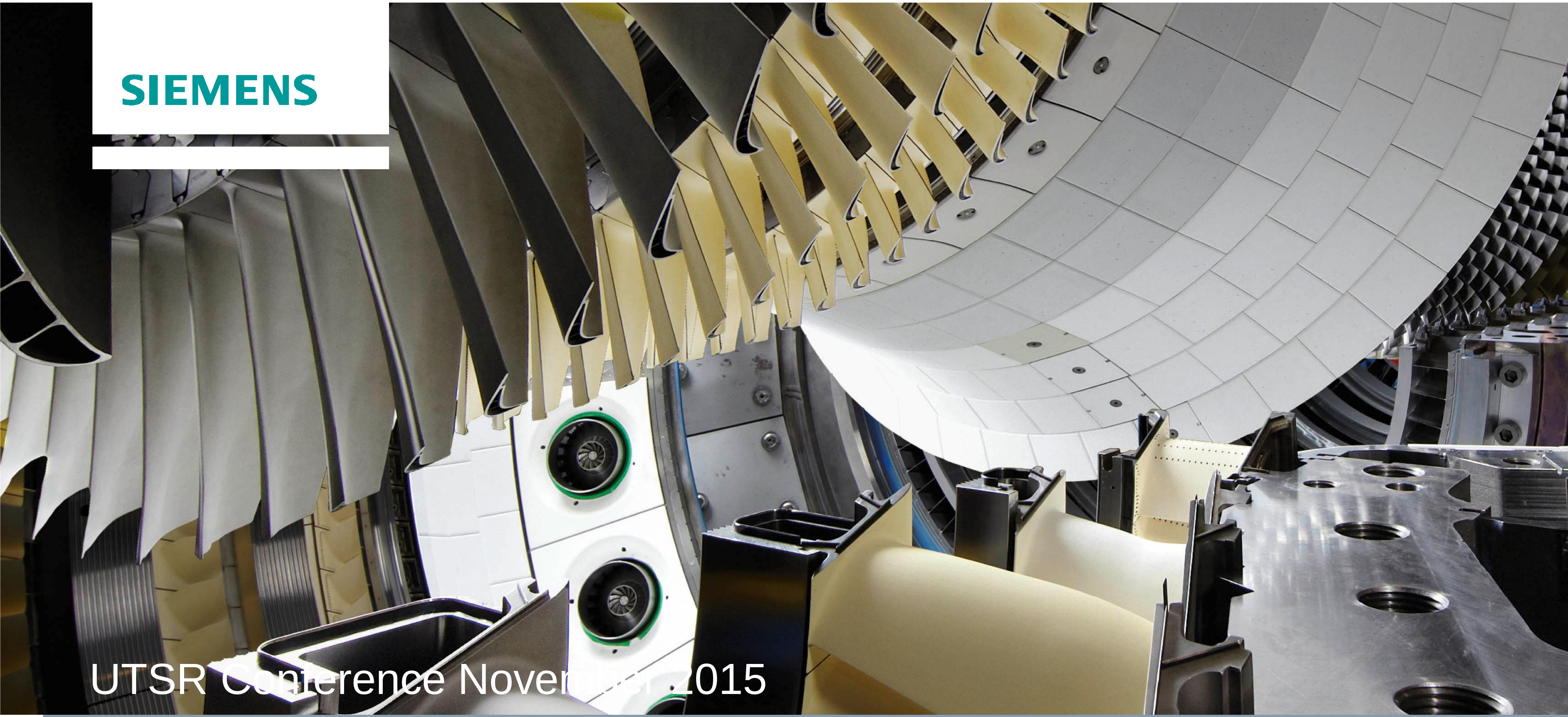
SIEMENS



UTSR Conference November 2015

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

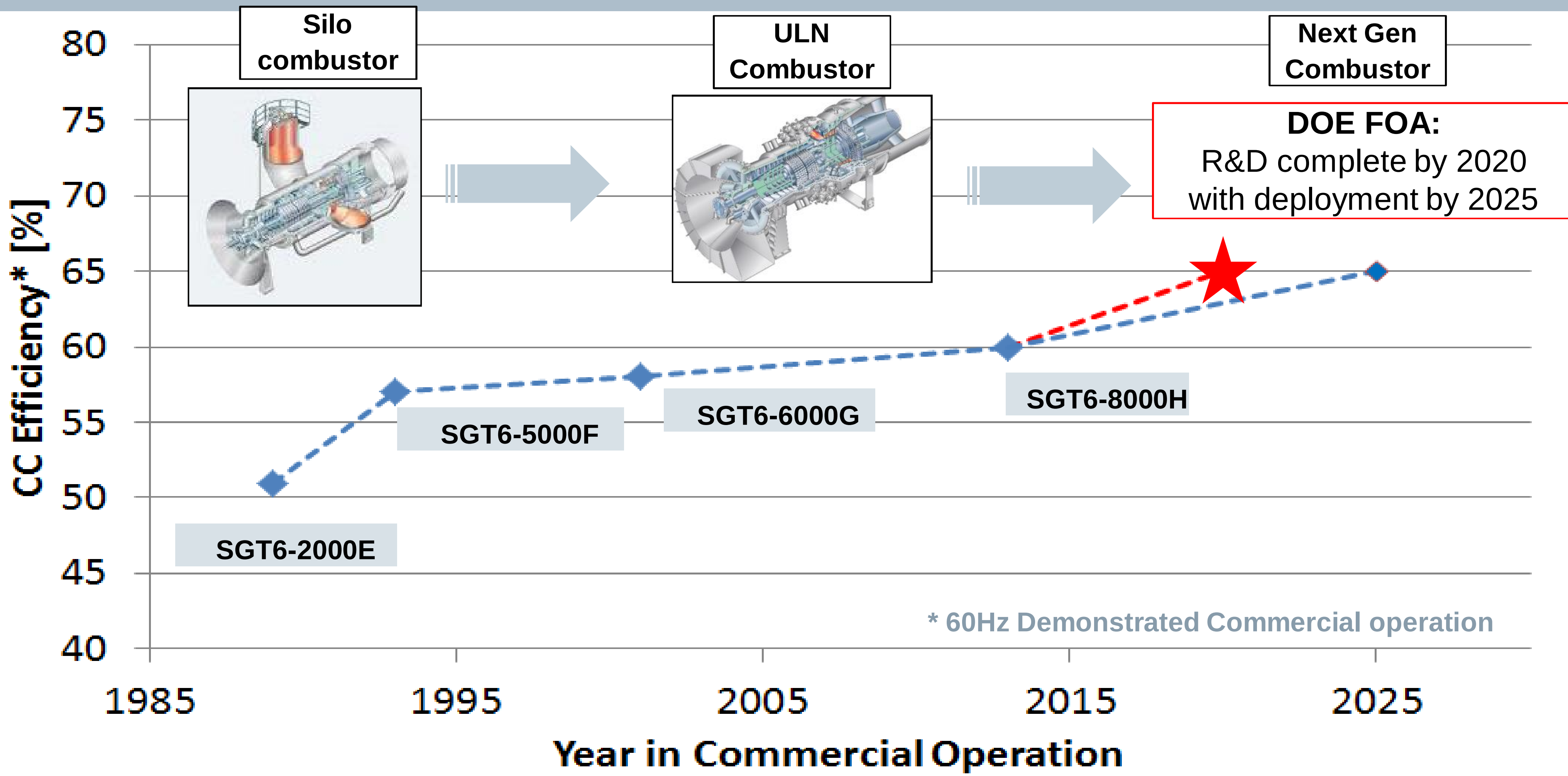
http://siemens.com/energy/power-generation/gas-turbines

CMC Advanced Transition for η > 65% CC
Program Overview

SIEMENS

Content of Today's Presentation

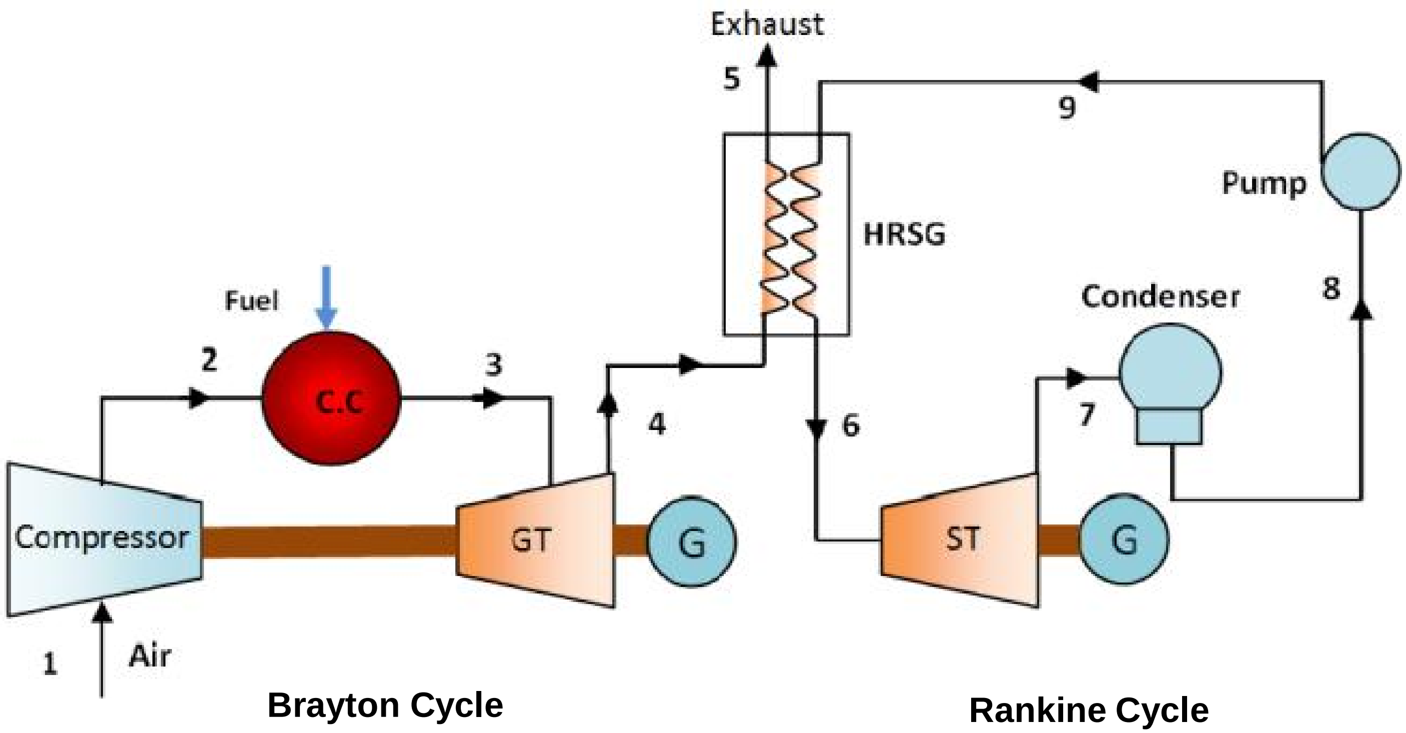
Towards a 65% CC system



DOE targets are driving a step change in GT combustion technology

Towards a 65% CC system

SIEMENS



Source: Ibrahim et. al (2012)

Brayton Cycle

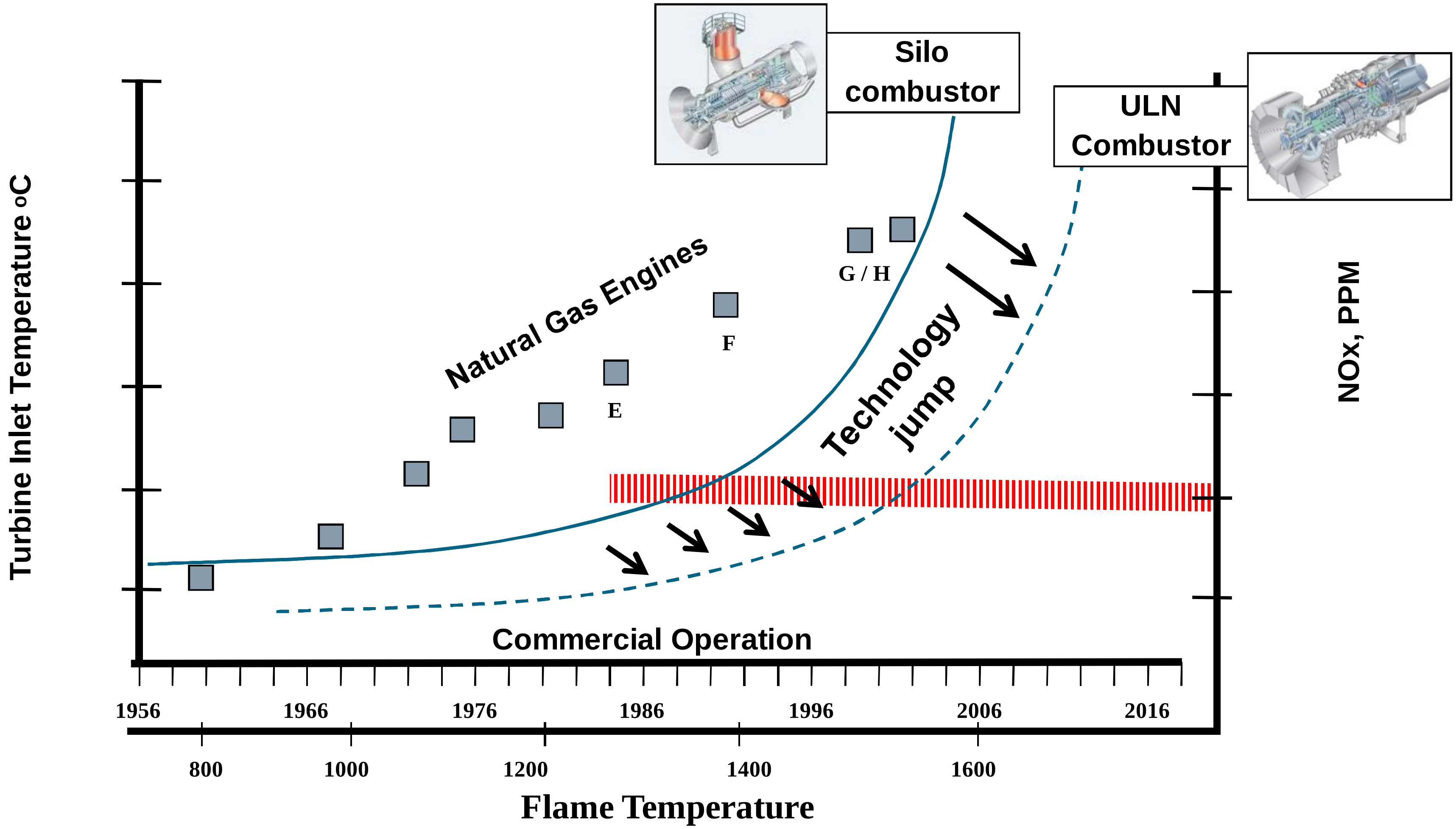
- Plant output and efficiency improved by raising the top of the cycle
- i.e. **Higher firing temperature** and **pressure**.

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

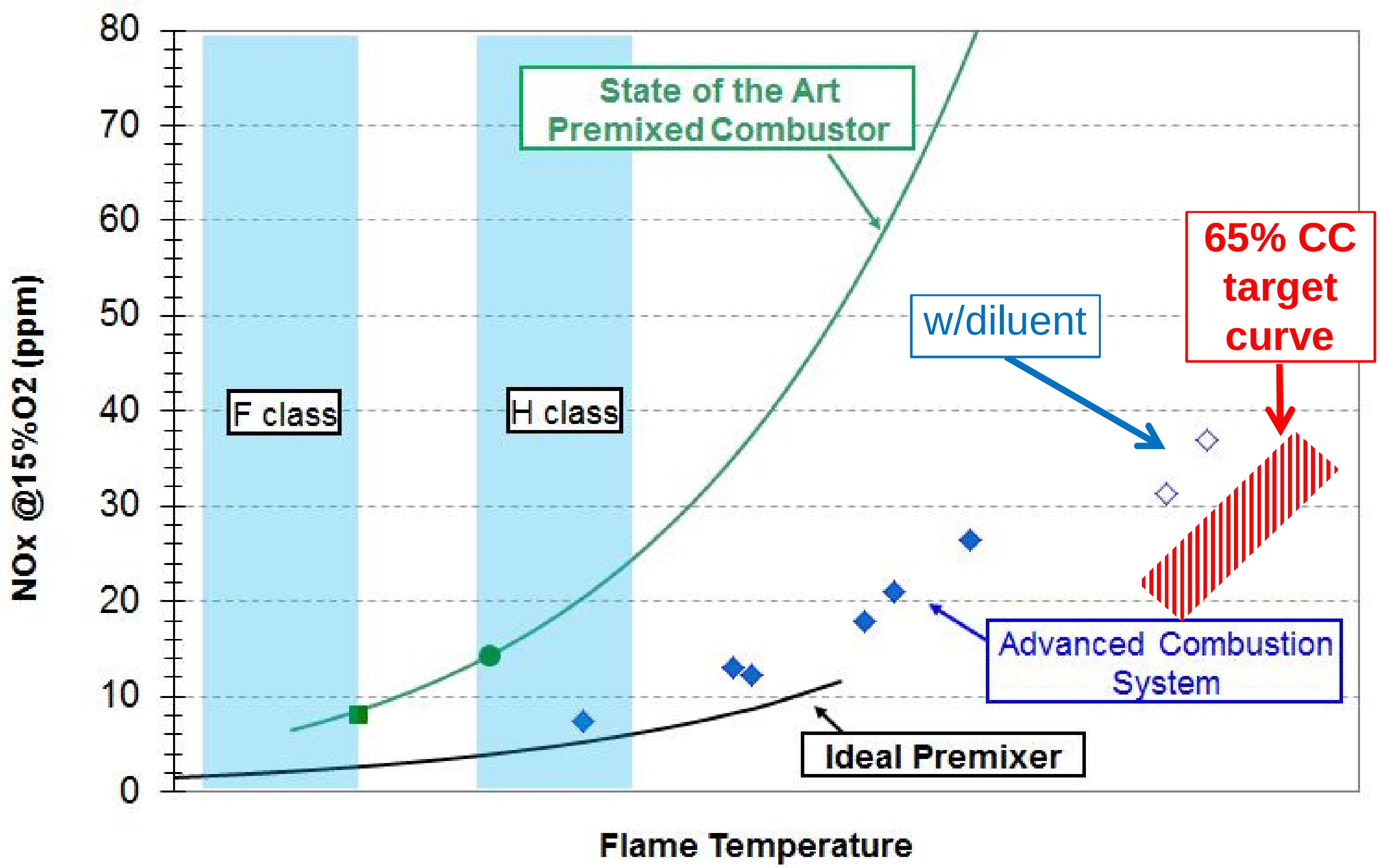
Towards a 65% CC system



GT technology jumps required to enable low NOx

Siemens Solution to Program Challenge: Combustion Development

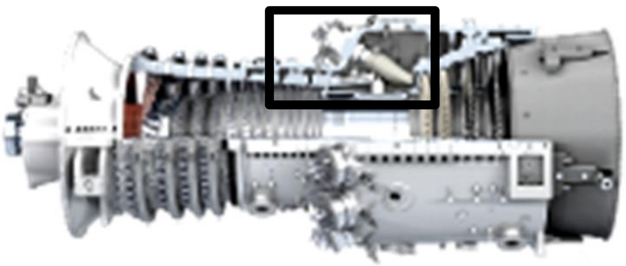
SIEMENS

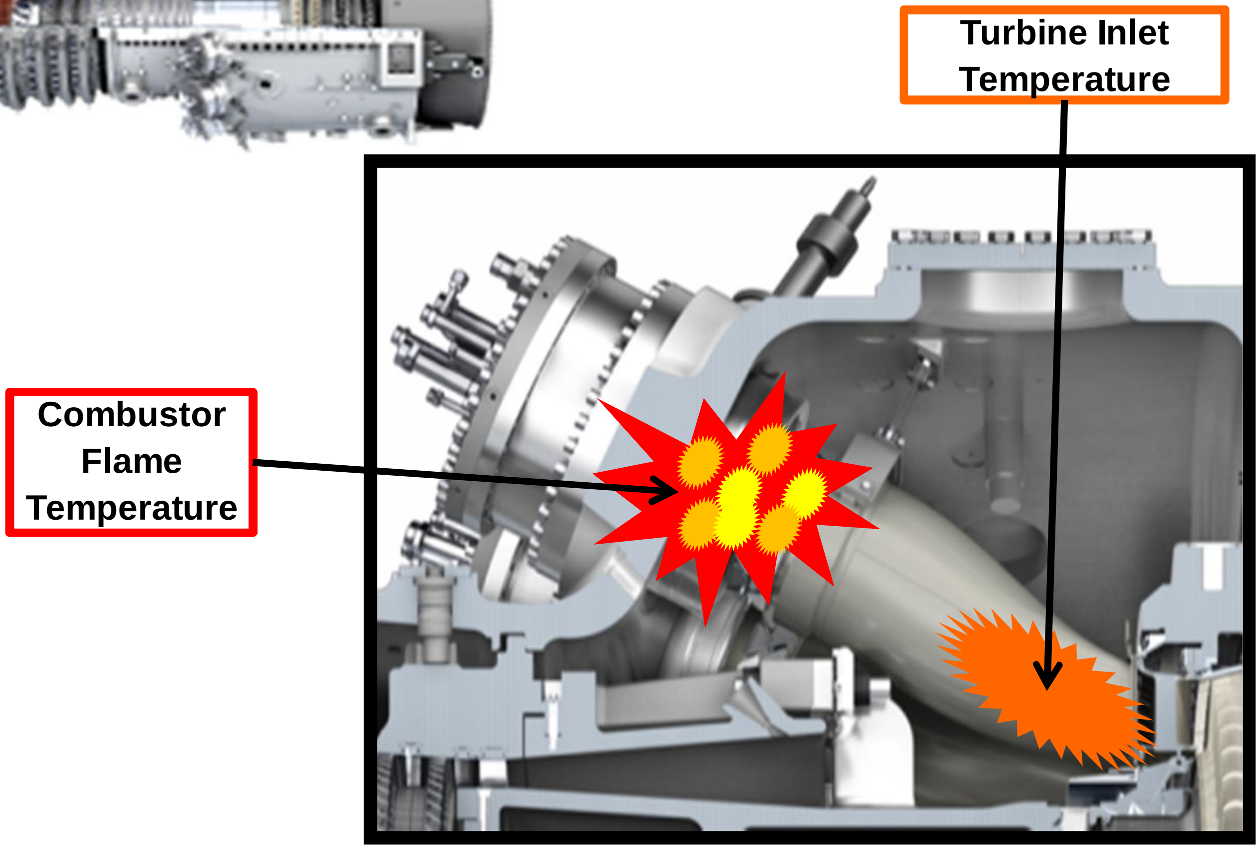


Combustion Technology “jumps” are required to shift NOx curve right

Enablers: Increase Premixing Quality

SIEMENS





How it works

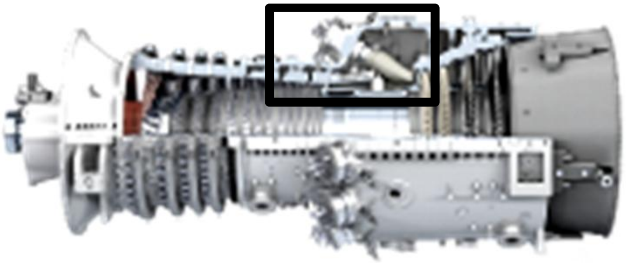
- Uniform mixing in combustion process
- Avoid local “hot spots” in the combustion process
- No local flames at high equivalence ratios
- Lower NOx

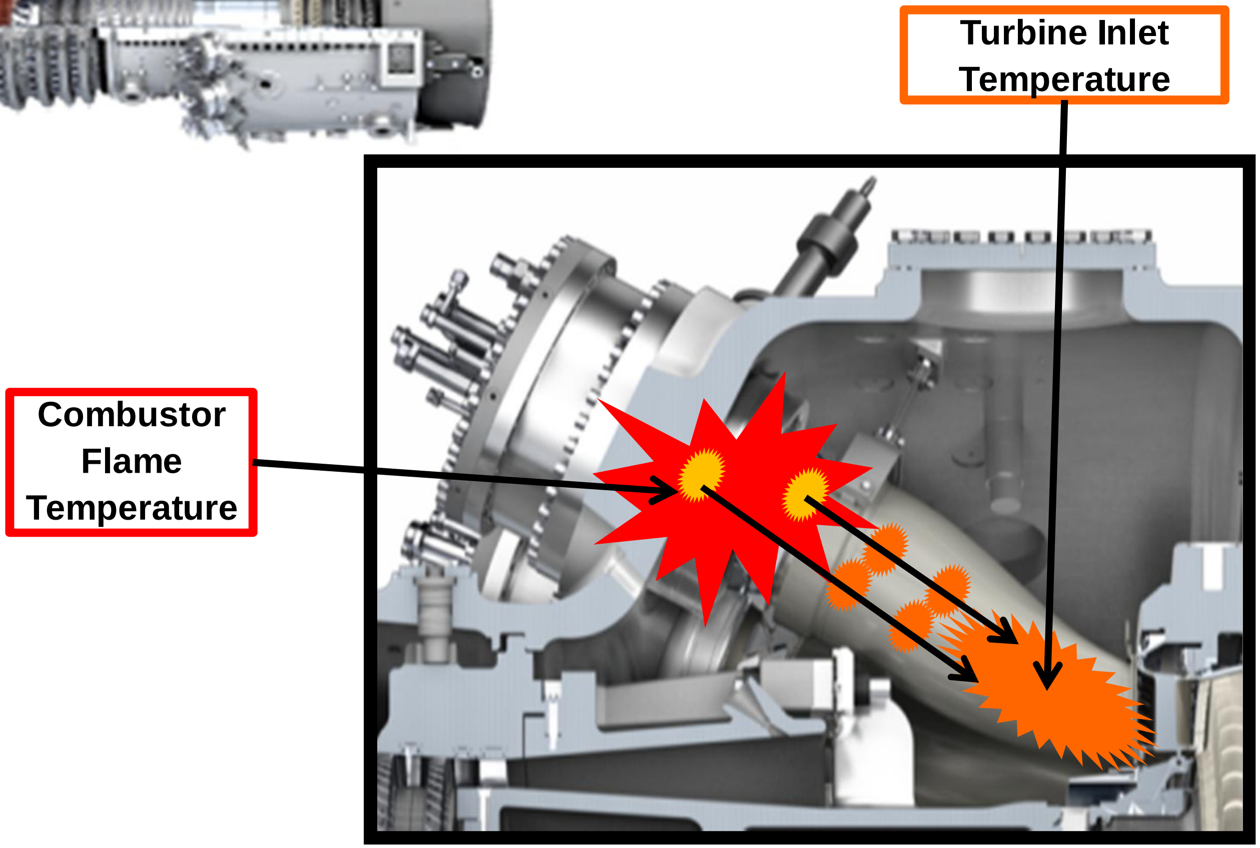
→ downside is combustion dynamics

Increase premixing → Avoid Hot Spots → Better emissions

Enablers: Decrease Residence Time

SIEMENS





How it works

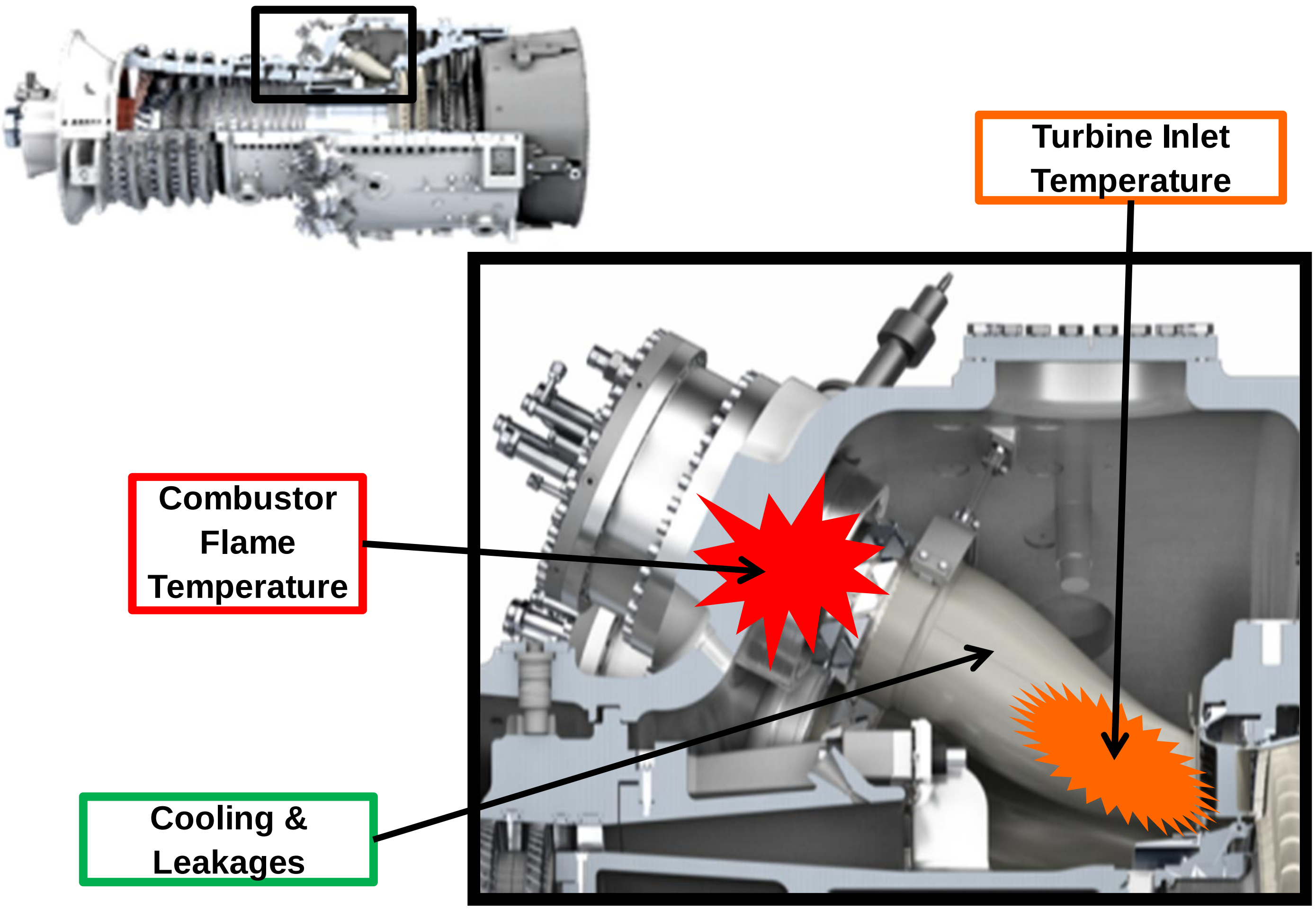
- Decrease time of hot gases in the combustion chamber
- Hot gases are producing NOx
- Lower NOx

→ Limit set by time needed for complete combustion

Decrease residence time → finish reactions quickly → Better emissions

Enablers: Decrease CCLA
Combustion Cooling & Leakage Air

SIEMENS



How it works

- TIT needs to be fixed to meet performance
- Air used for cooling is used in combustion instead
- Lower equivalence ratio
- Lower NOx

→ Limited by material temperatures

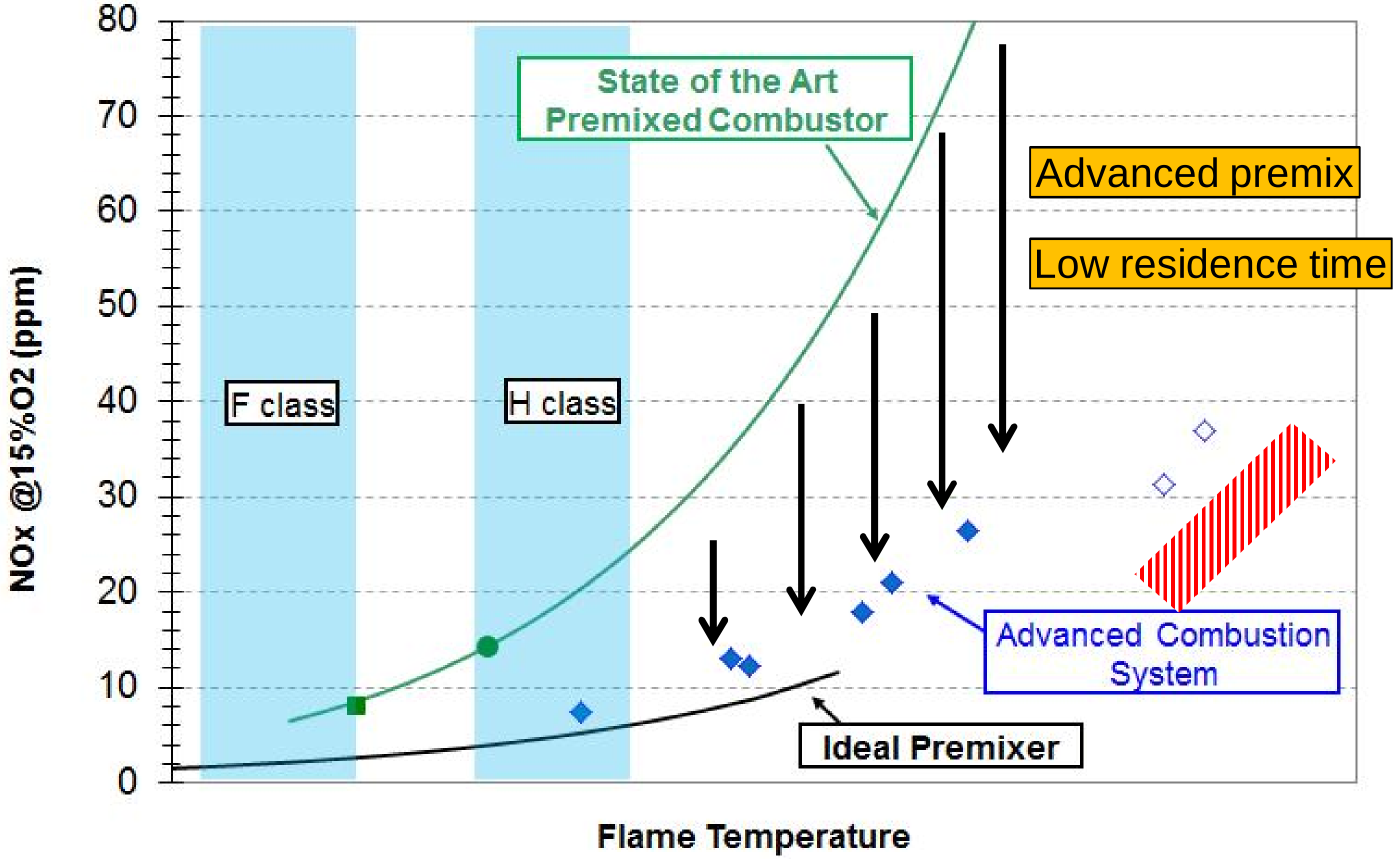
Decrease CCLA → Lower Flame Temperature → Better emissions

Siemens Solution to Program Challenge: Combustion Development

SIEMENS

Enablers

- Lower CCLA
- Increase premixing quality
- Decrease residence time
- Diluents



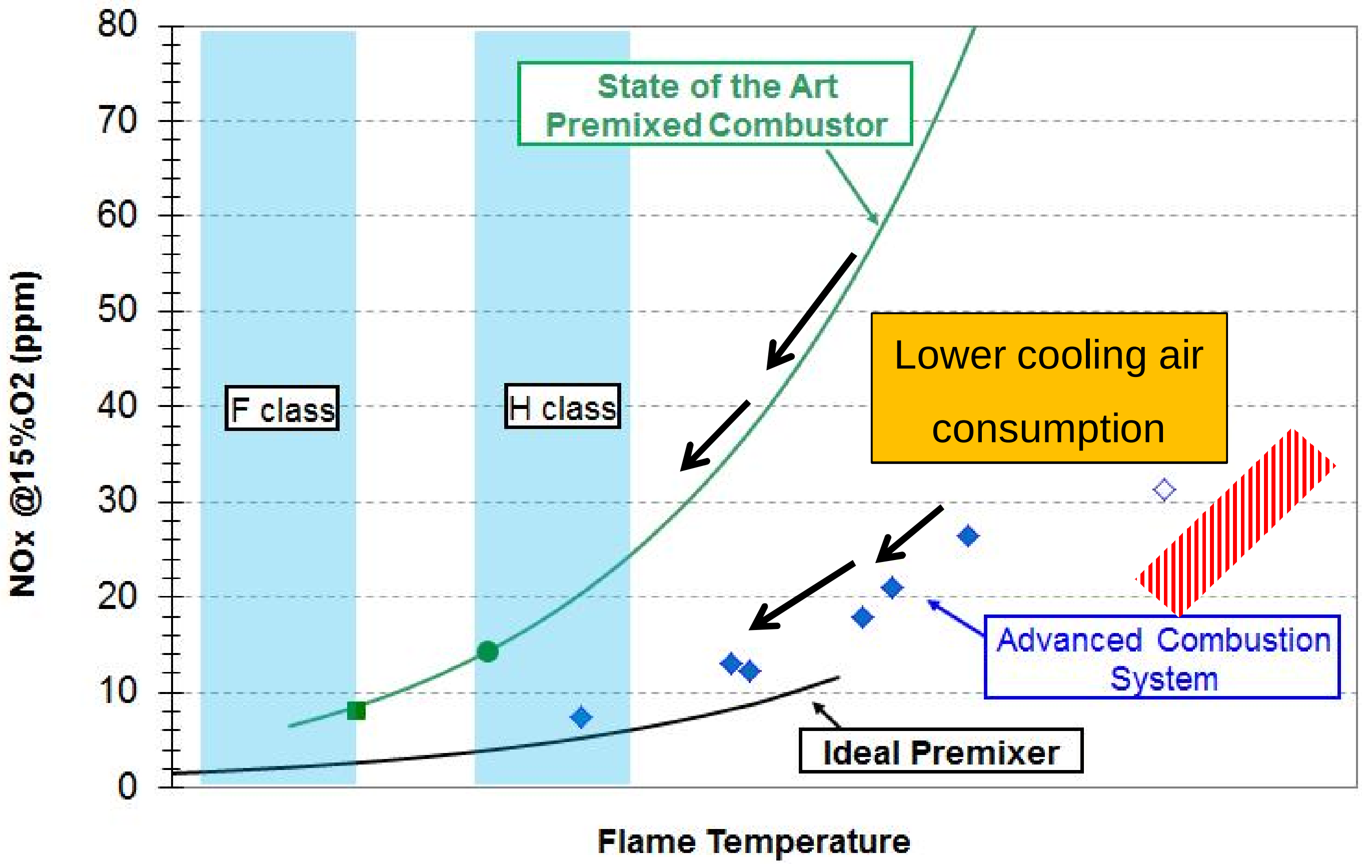
Residence time reduction & premixing allow lower NOx at flame temperature

Siemens Solution to Program Challenge: Combustion Development

SIEMENS

Enablers

- Lower CCLA



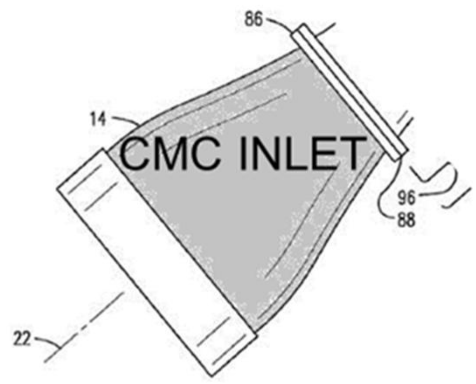
Lower cooling air consumption allows lower flame temps for fixed TIT

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Introduction

- **Objective:**
  - Phase 1: 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

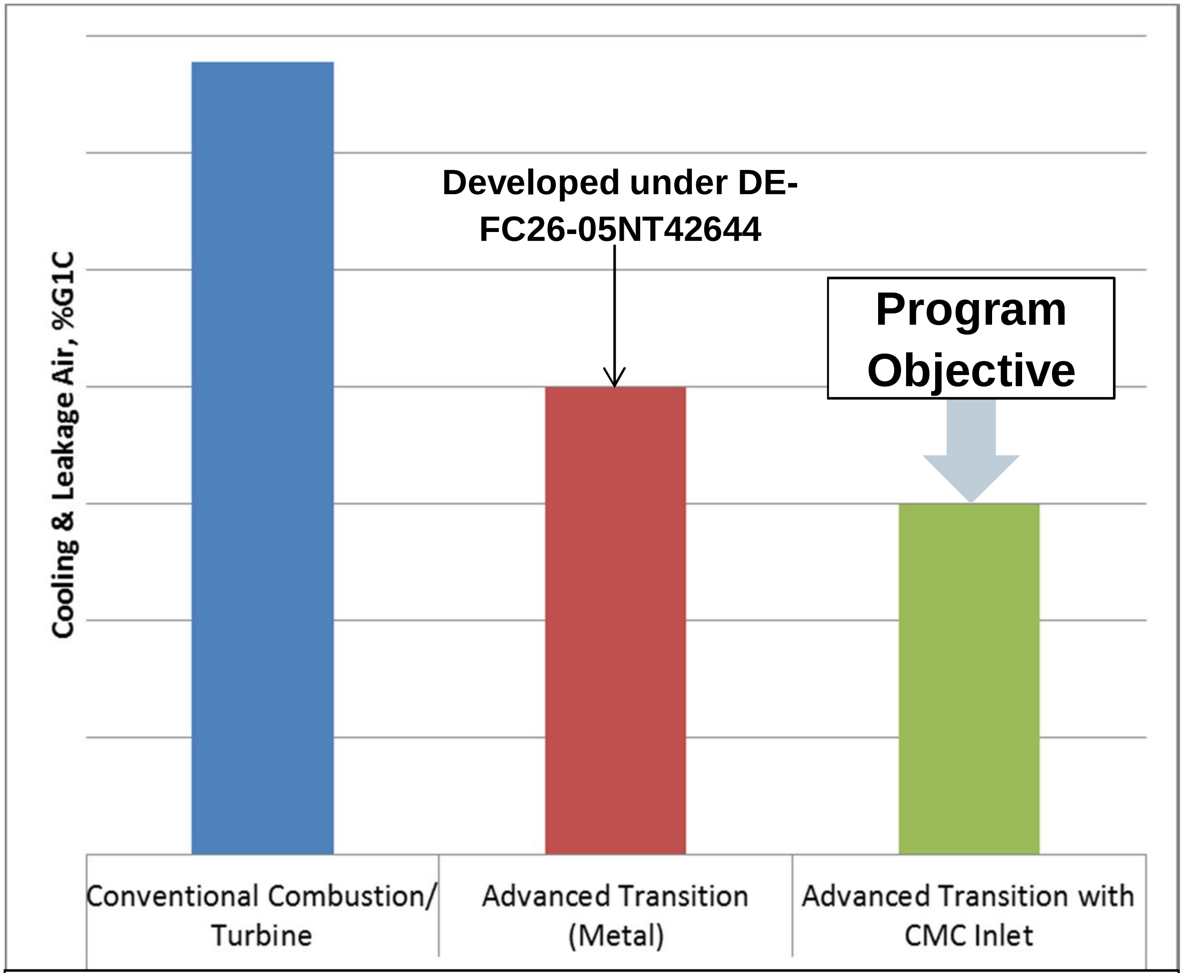


Experience base

- 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

SIEMENS

Benefits: Cooling Air Reduction



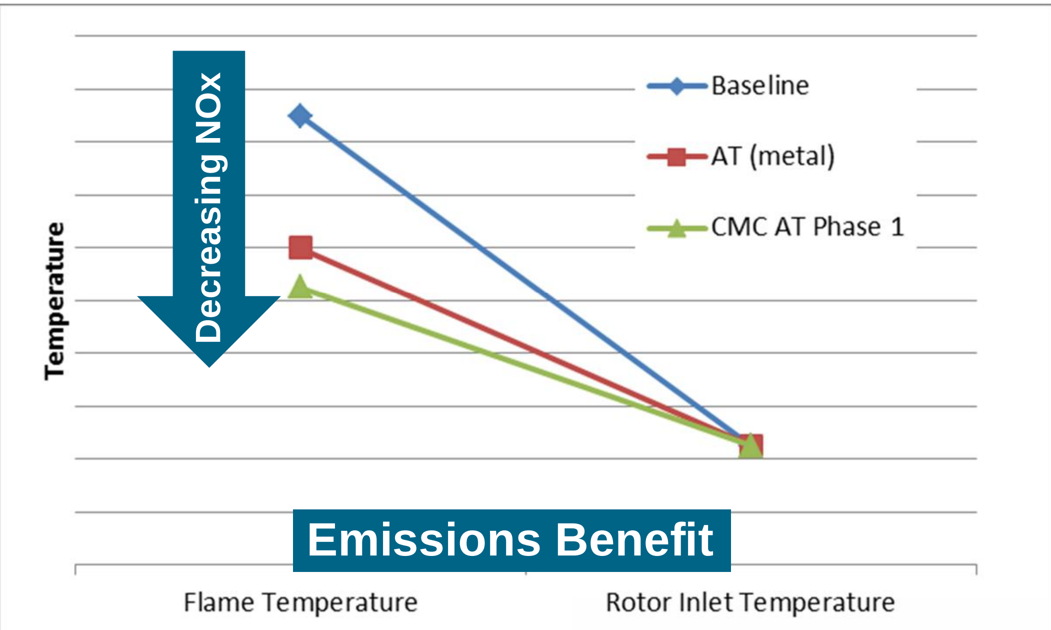
65% Efficiency GT – Technology Projections

NOx emissions reduction at High Firing Temperatures

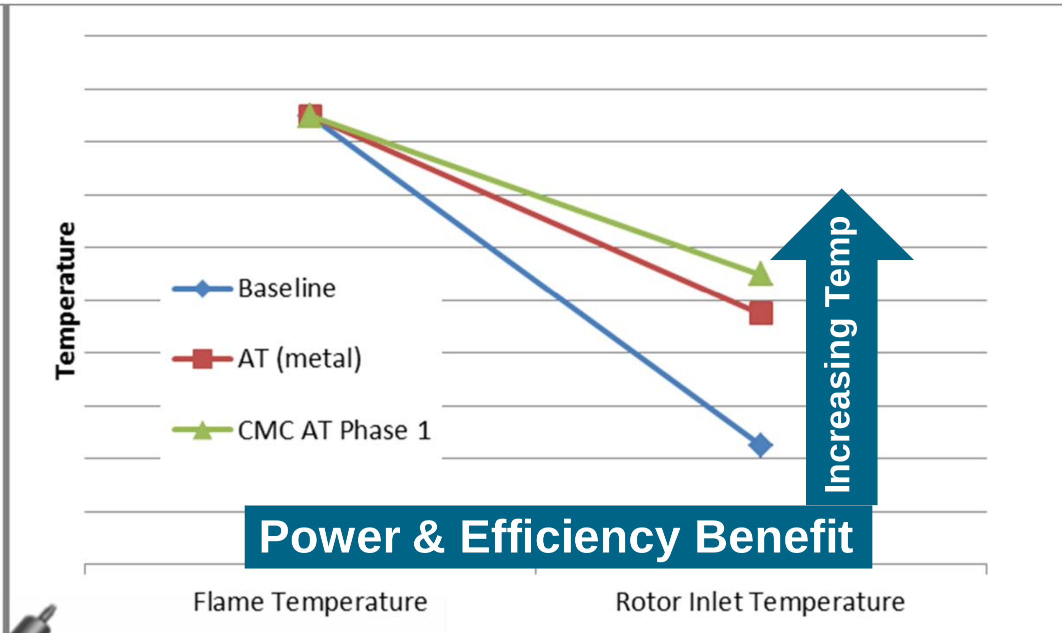
SIEMENS

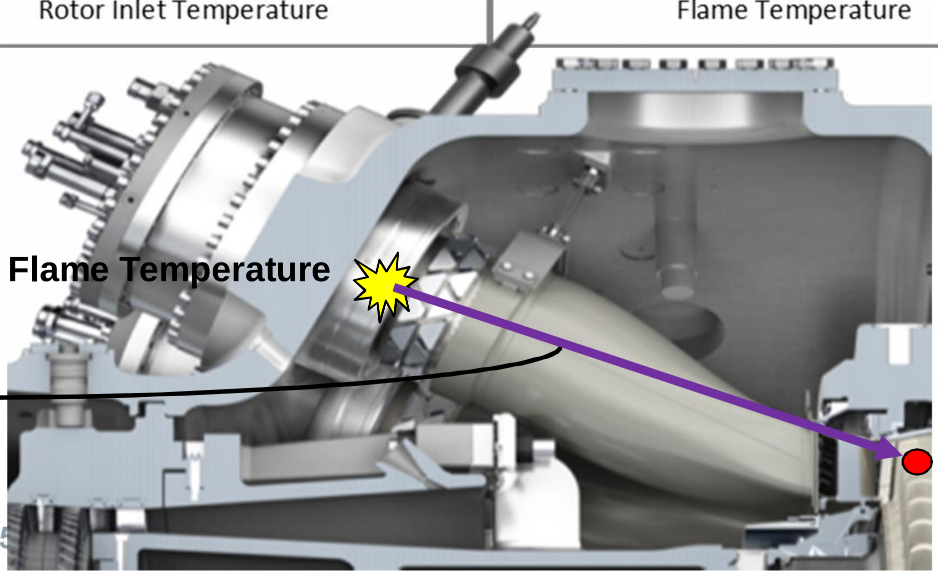
Benefits: NOx Decrease vs. RIT Increase

1) Constant Rotor Inlet Temperature



2) Constant NOx





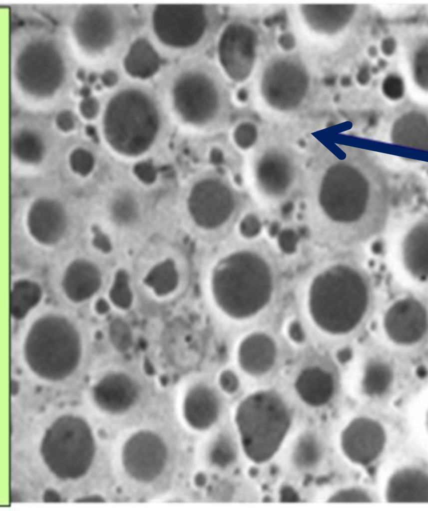
Reduced cooling & leakage air between flame and turbine rotor

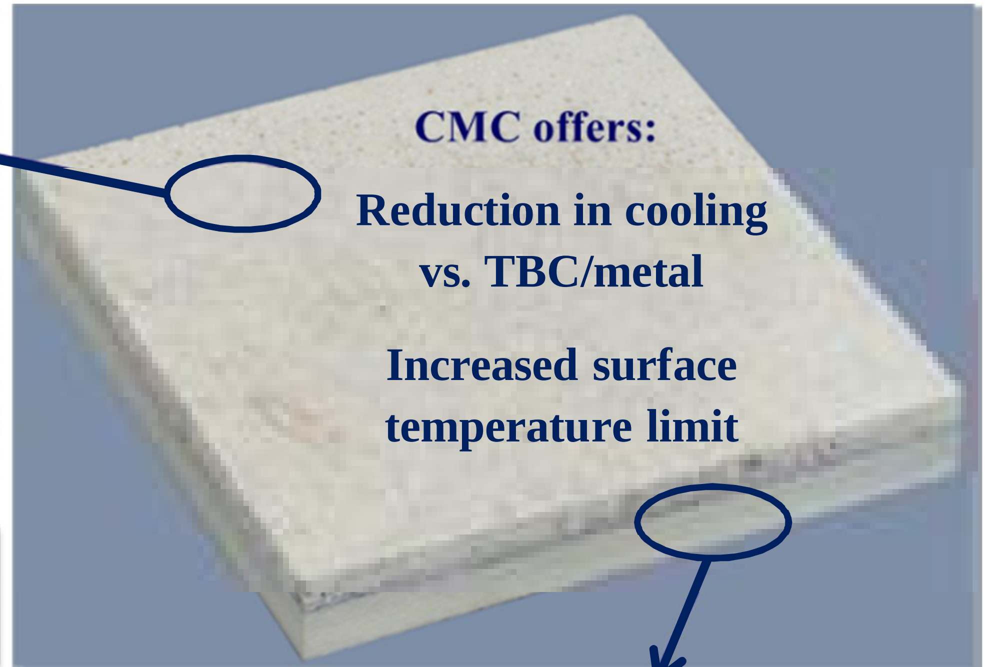
Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Siemens' Hybrid CMC Technology

SIEMENS

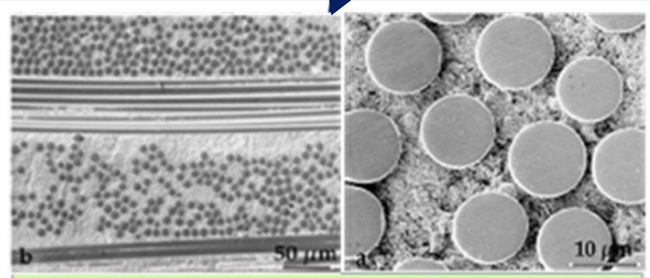
Coating: FGI (Friable Graded Insulation) – Siemens patented material consisting of thermally stable hollow ceramic spheres closely packed in a ceramic matrix binder.





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

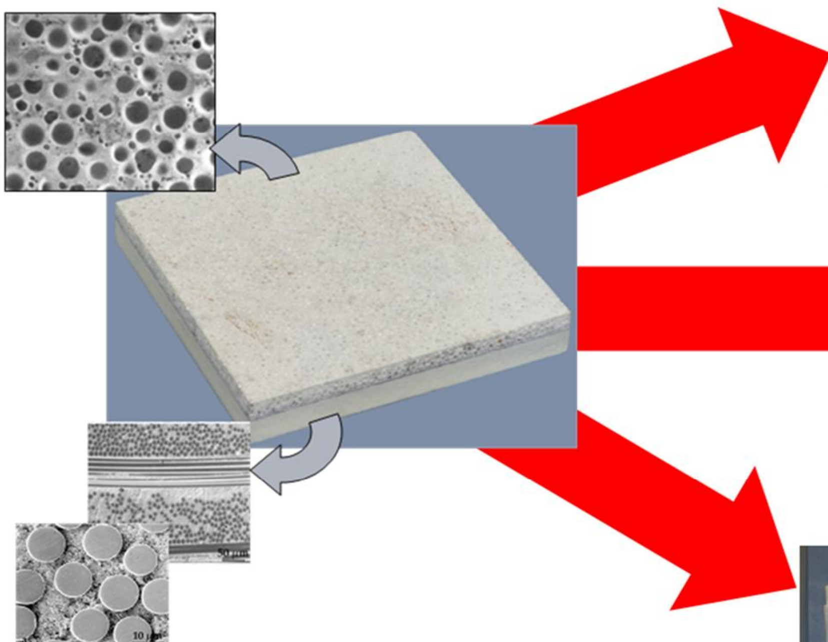
Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

CMC Technology Status

Benefits:

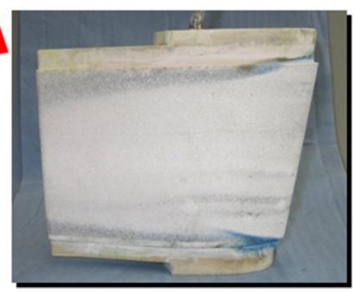
- *Ultra-low cooling requirements*
- *Oxidatively stable constituents*

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**

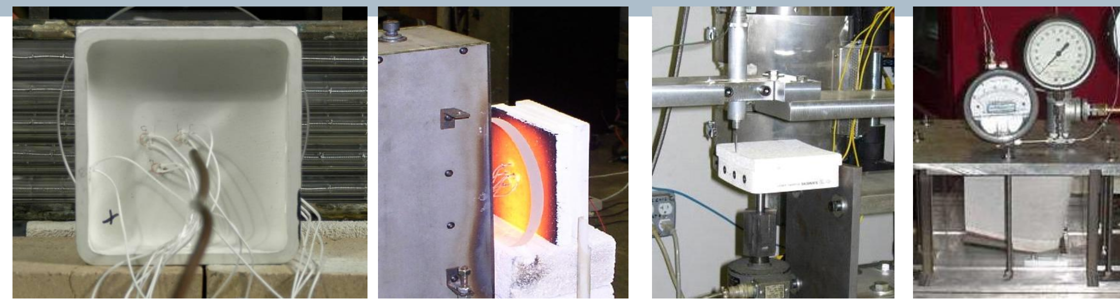
Combining two high pay-off technologies individually developed & tested

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

CMC Component Testing Summary

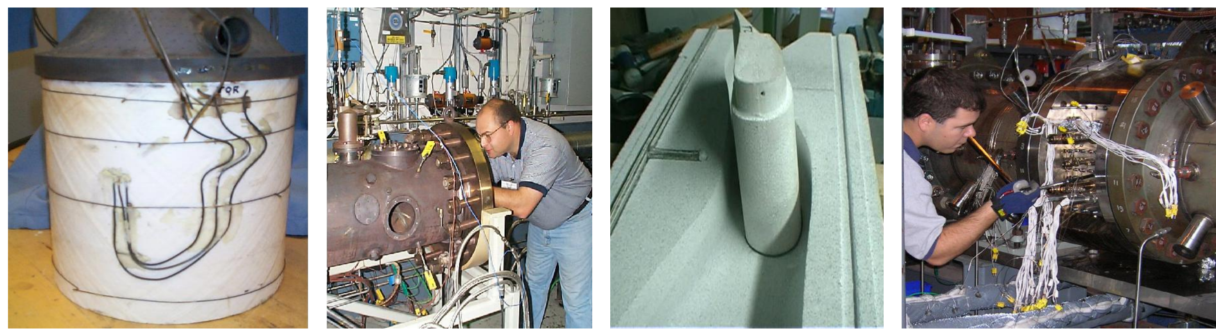
SIEMENS

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



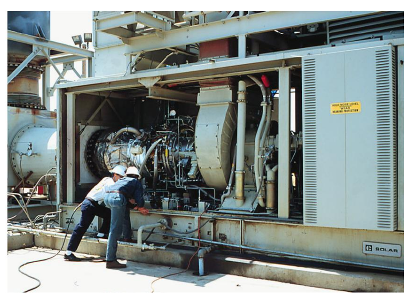
Ring segments (4 types), airfoils, subelements

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

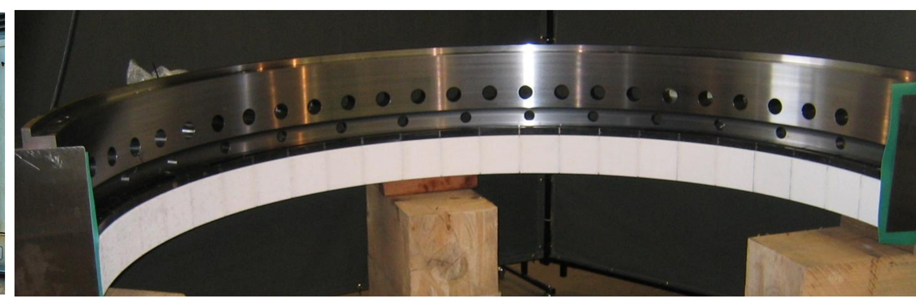


Combustors, Airfoils, Ring segments (4 types)

- Engine testing
  - Customer site / durability
  - BTF engine



Combustor



Ring Segment

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Hybrid Oxide CMC Combustor Liner

SIEMENS

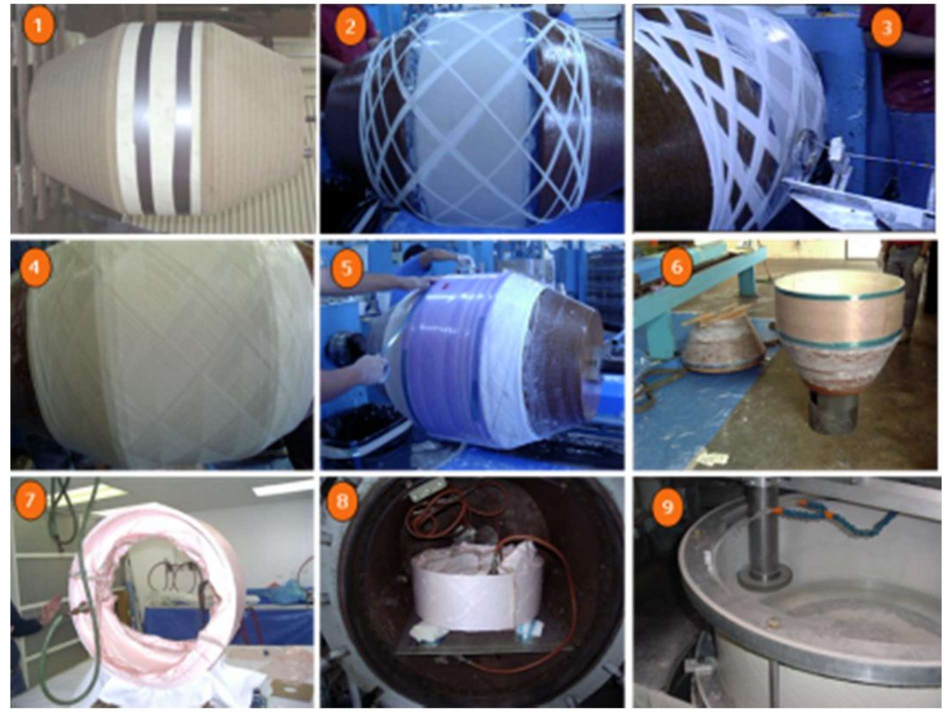
- Siemens Hybrid Oxide CMC system (FGI thermal barrier)
- Filament wound combustor outer liner (made by COIC)
- Operated in Solar Centaur 50™ engine.
  - 25,404 hours / 109 cycles;
  - Bakersfield, CA
  - Still serviceable
- Surface & CMC temperatures representative of AT inlet

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

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

CMC Manufacturing Options

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

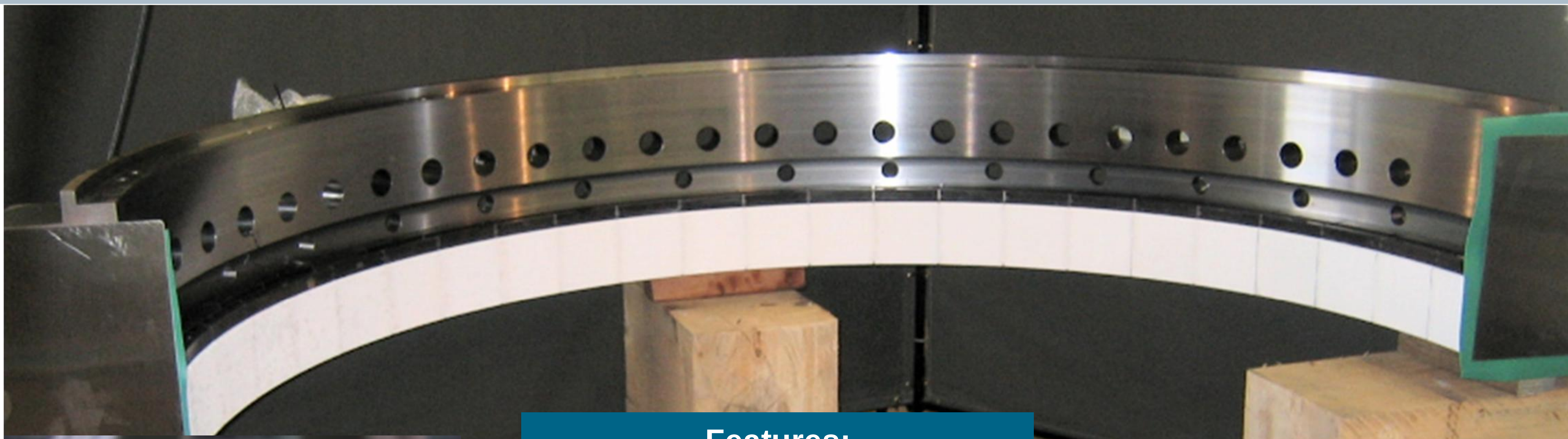


- **Both manufacturing approaches are feasible for most AT inlet concepts**
- **Concepts with out-of-plane features more conducive to fabric lay-up**

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

CMC Ring Segment Engine Test

SIEMENS



Features:

Reduced Cooling from metal baseline design

Tip seal improvement features

Retrofittable design

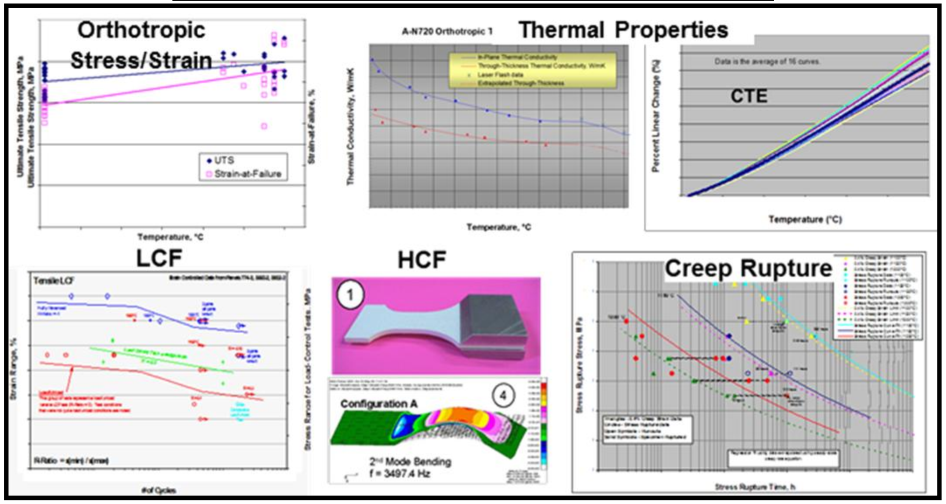
High temperature sealing

Full engine set: Tested successfully for > 50 hours

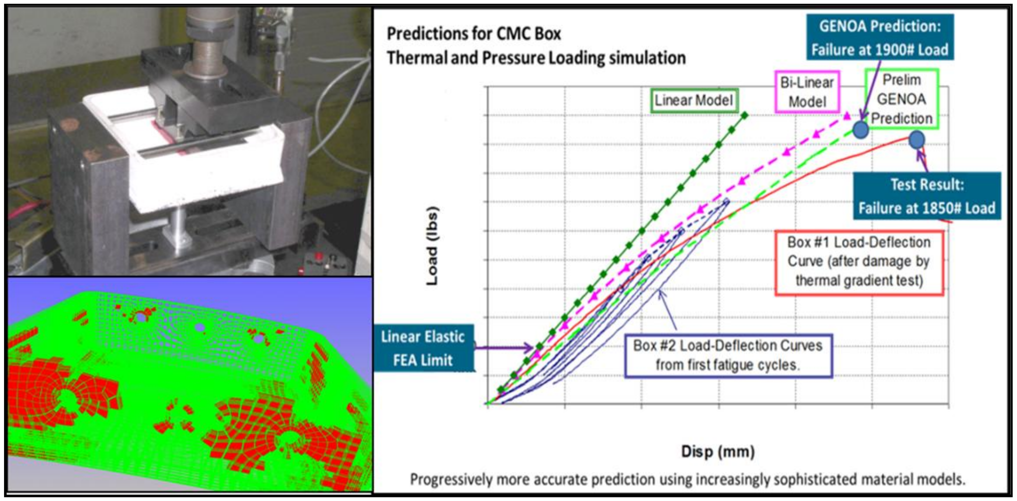
Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Supporting CMC Data & Remaining Challenges

Coupon Test Data



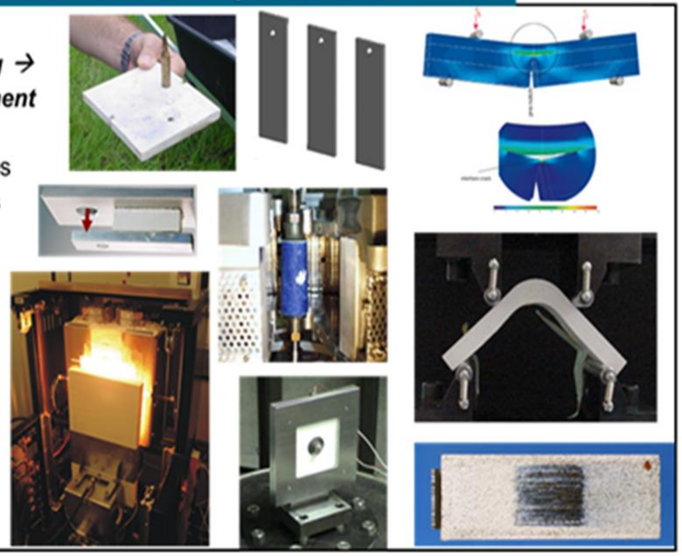
Damage Accumulation & Life Prediction Tools



Subelement & Component test data

Sub-Element Testing → System and Attachment Behavior

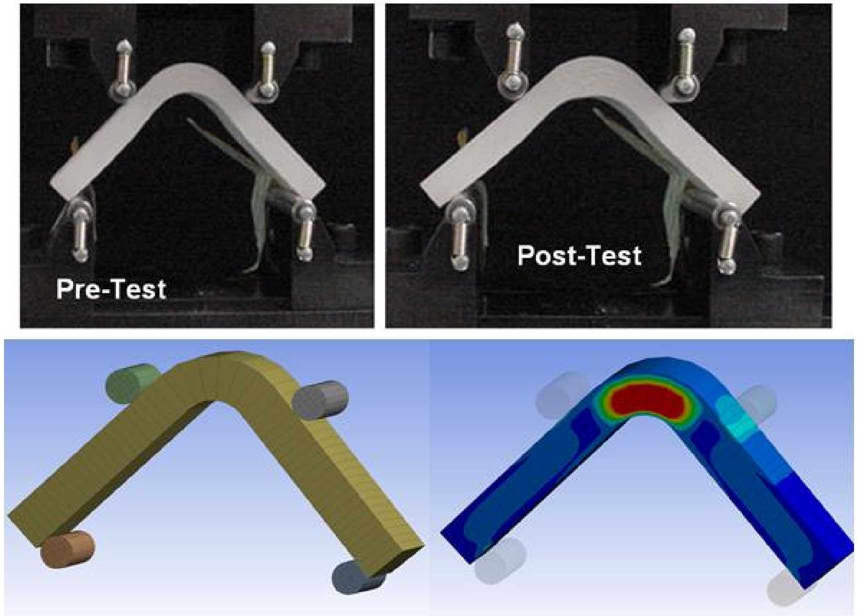
- Attachment features
- Geometric features
- Coating adhesion
- Wear
- Thermal stress
- Abradability
- Impact
- Sealing
- Etc.

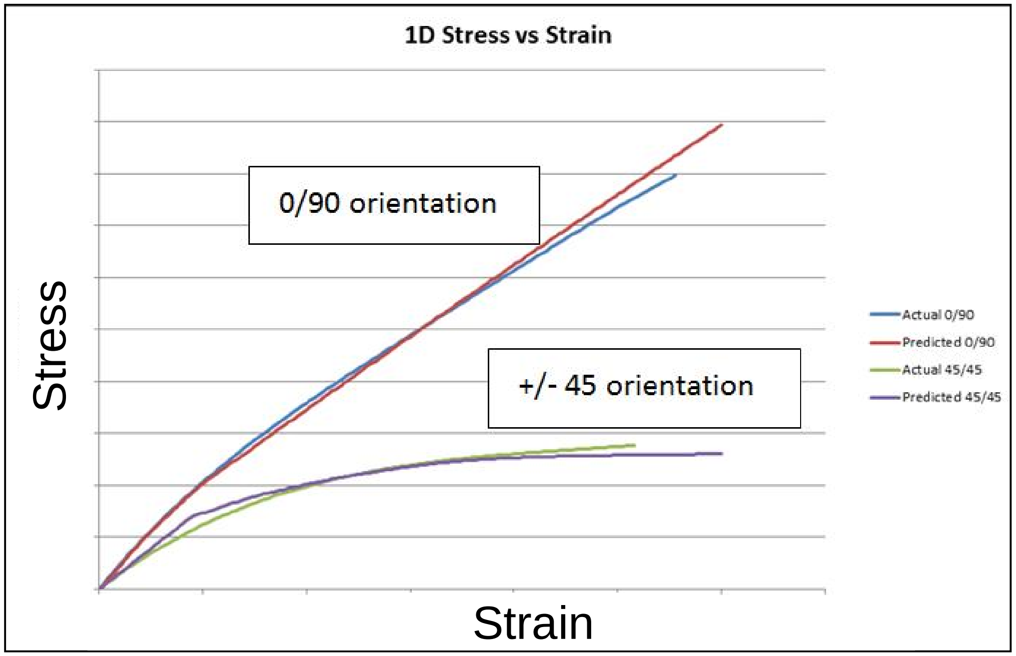


Remaining Design / Materials Challenges

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

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**

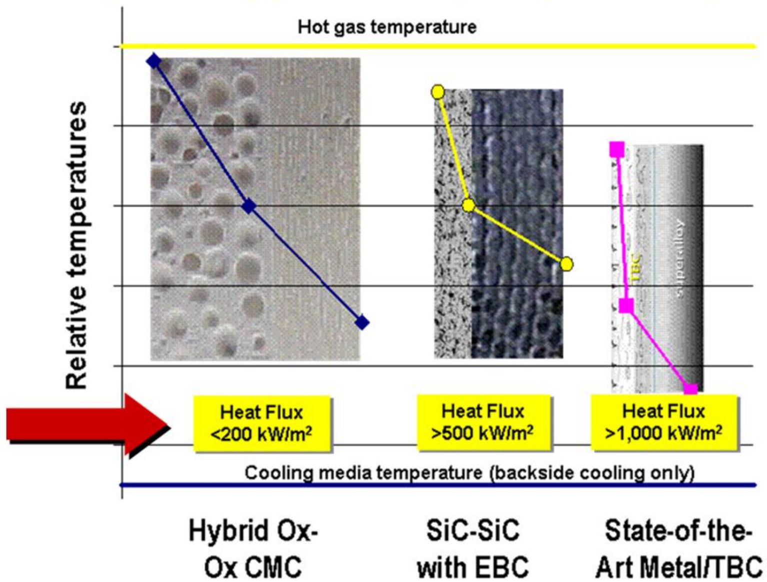
Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Heat Transfer → CMC with backside cooling

SIEMENS

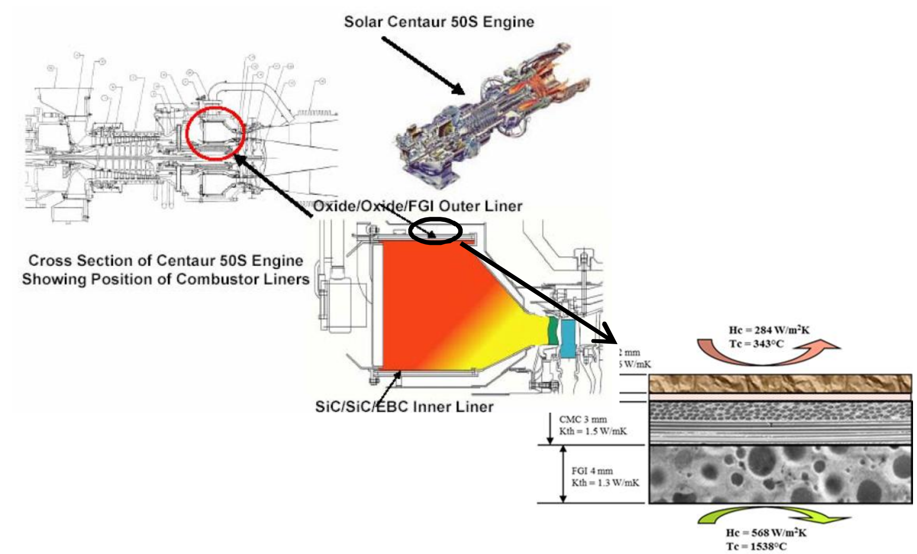
Shell Air Circulation

Comparison of Approaches for High Temperature Components



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

<u>Two Cooling Options</u>:

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

Both eliminate active (chargable) cooling

Acknowledgements

- This work is performed under US Department of Energy Award Number DE-FE0023955.
- 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.

SIEMENS

&

U.S. DEPARTMENT OF ENERGY

Answers for Energy.

Jay Morrison
Program Manager - Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

Siemens Energy Inc.
4400 Alafaya Trail
Orlando, FL 32826
Phone: +1 (407) 736-2000

E-mail:
jay.morrison@siemens.com

Thank You. Questions?