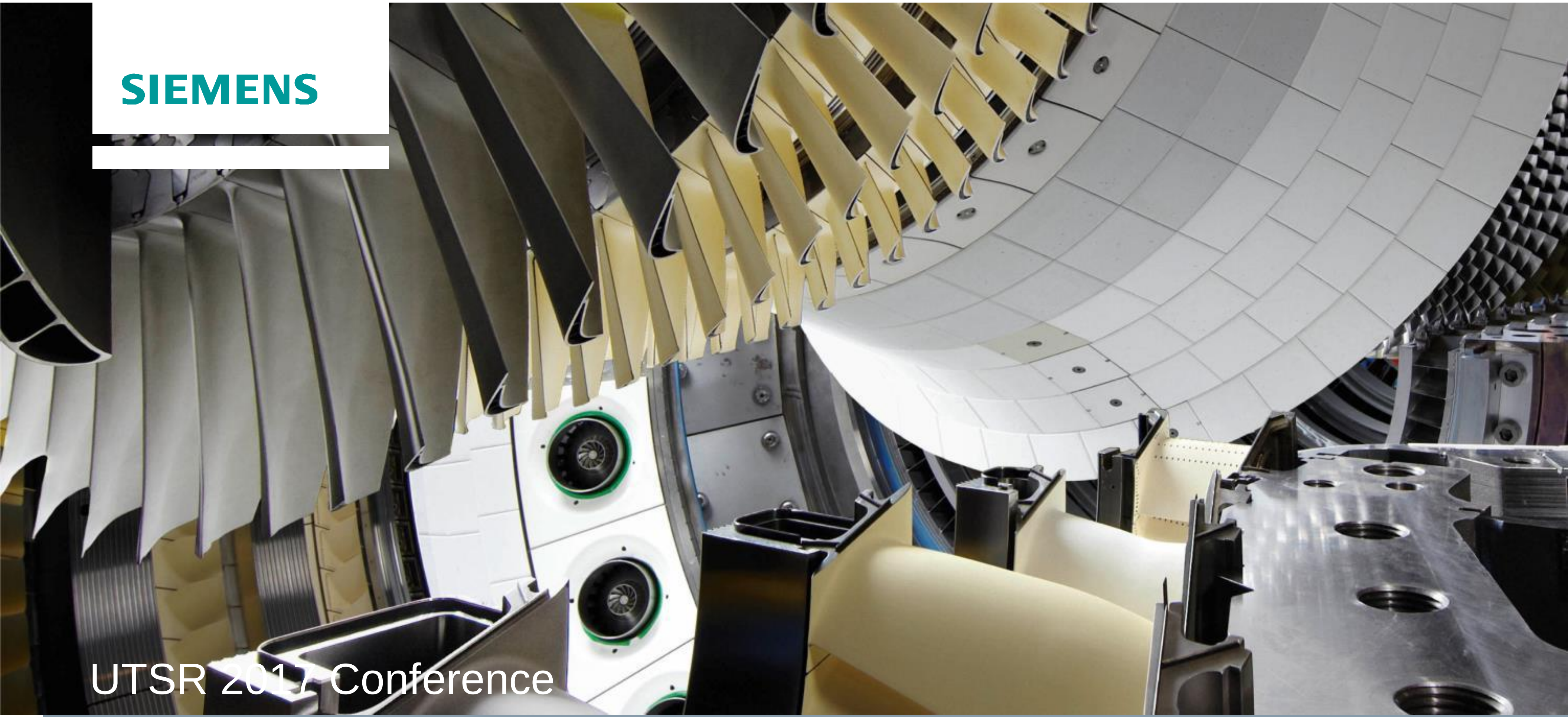

UTSR 2017 Conference

# "Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency" DE-FE0023955

DPREF-60987040

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

# CMC Advanced Transition for η > 65% CC
# Program Overview

## Content of Today's Presentation



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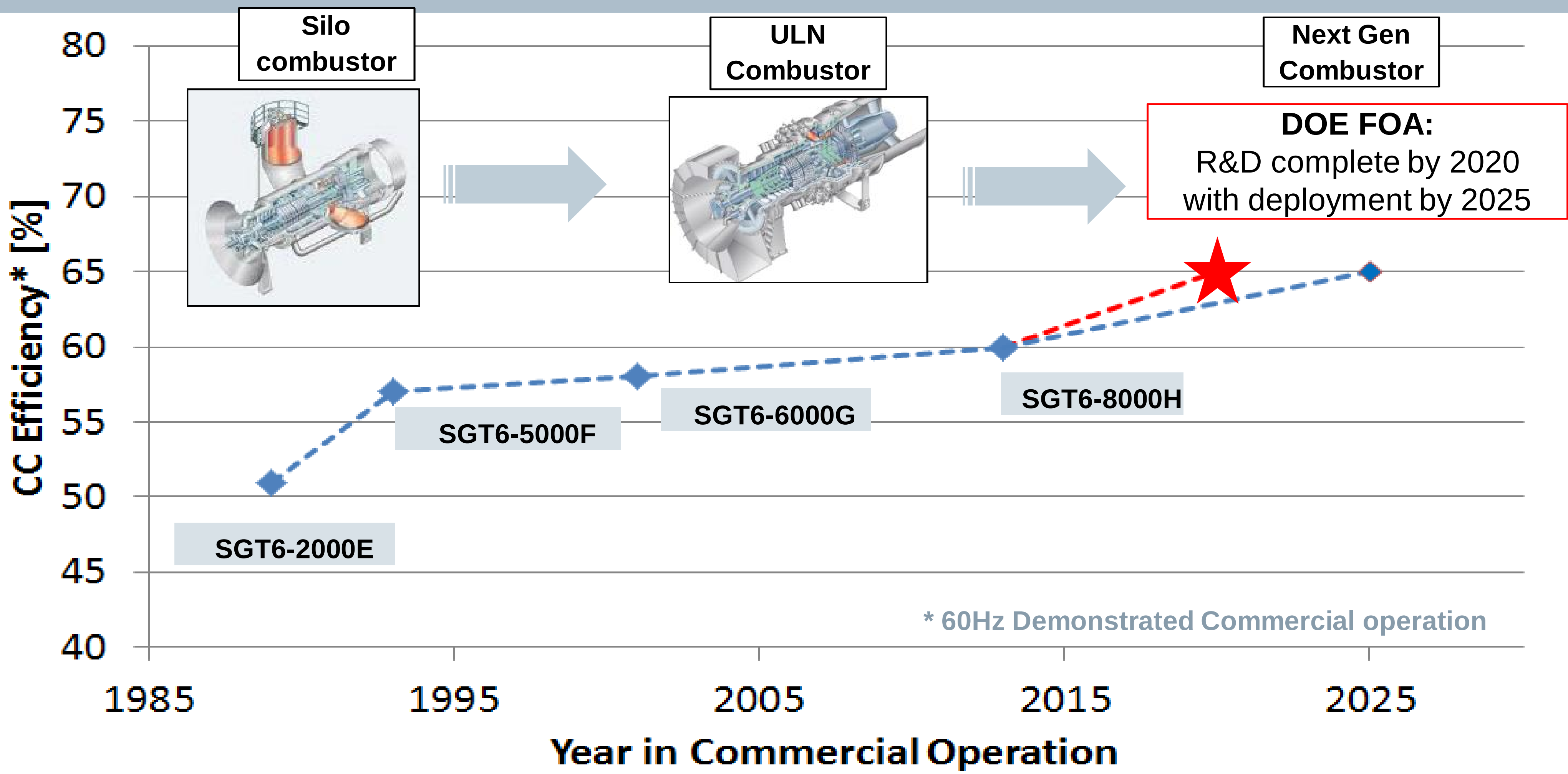
# Towards a 65% CC system




**DOE targets are driving a step change in GT combustion technology**

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# Towards a 65% CC system

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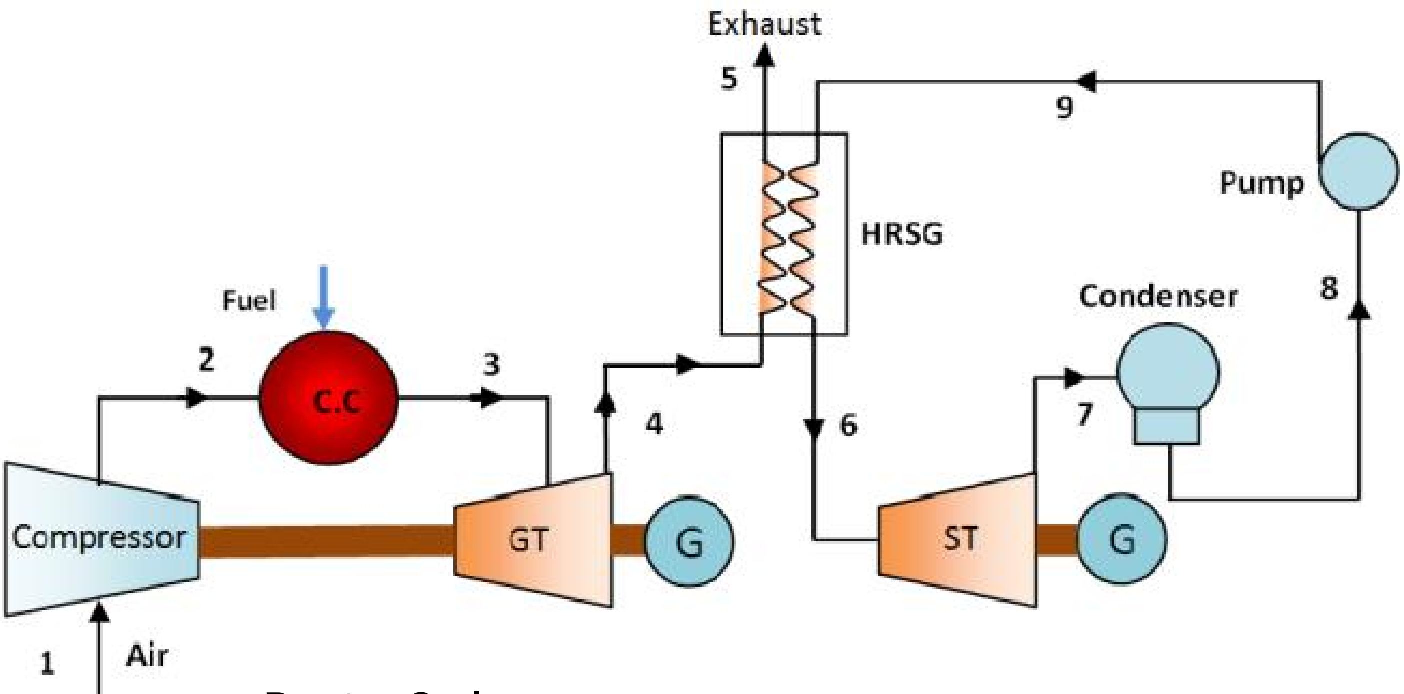


## Brayton Cycle

- 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.

Source: Ibrahim et. al (2012)

**65% CC efficiency targets Firing Temperature > 1700ºC**
**NOx emissions become limiting**



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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *NOx Reduction Approaches*

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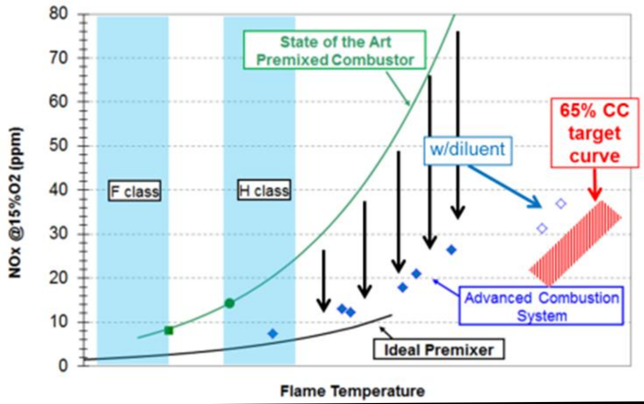
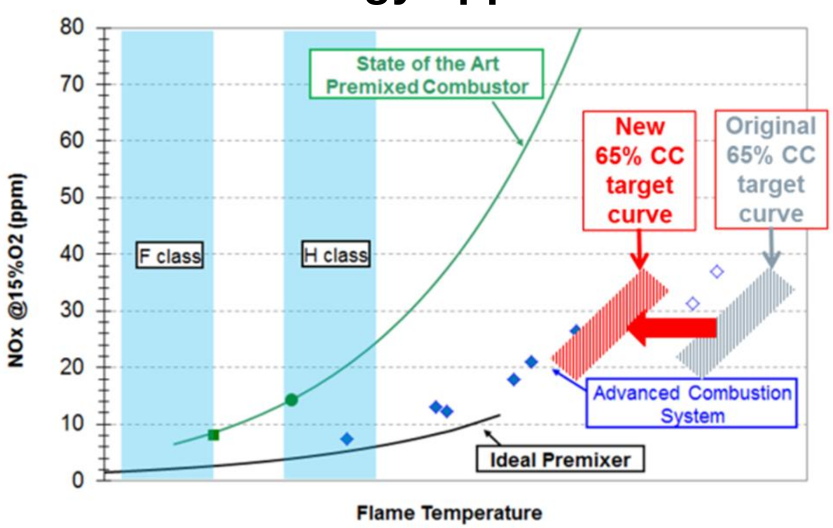
### Combustion technology approach



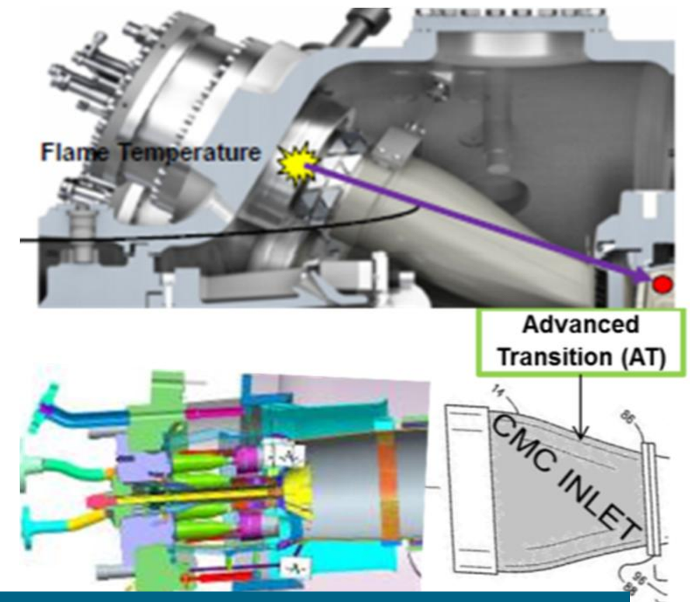

**Enablers:**
- Increase premixing quality
- Decrease residence time
- Diluents

***Focus of this program***

### CMC technology approach




**Enablers:**
- Reduced Cooling & Leakage Air (between flame and rotor inlet)




**CMC Technology approach to NOx reduction is additive to conventional approaches**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Introduction*

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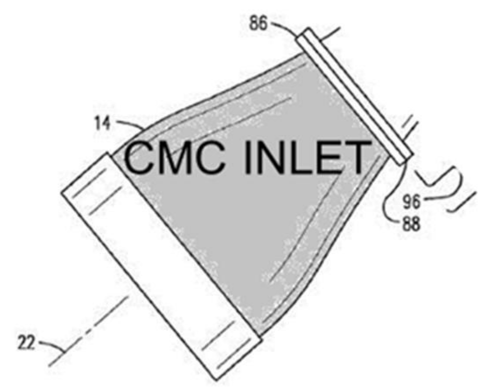
- **Objectives (Phase 2):**
  - Manufacture & test CMC inlet for Siemens Advanced Transition (TRL5)
  - Design CMC exit for AT (TRL3)
- **Benefits:**
  - Reduction in Cooling Air → NOx reduction or RIT increase
  - CO reduction (eliminate wall quenching)
  - Reduced aero losses
    - Due to cooling air 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

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

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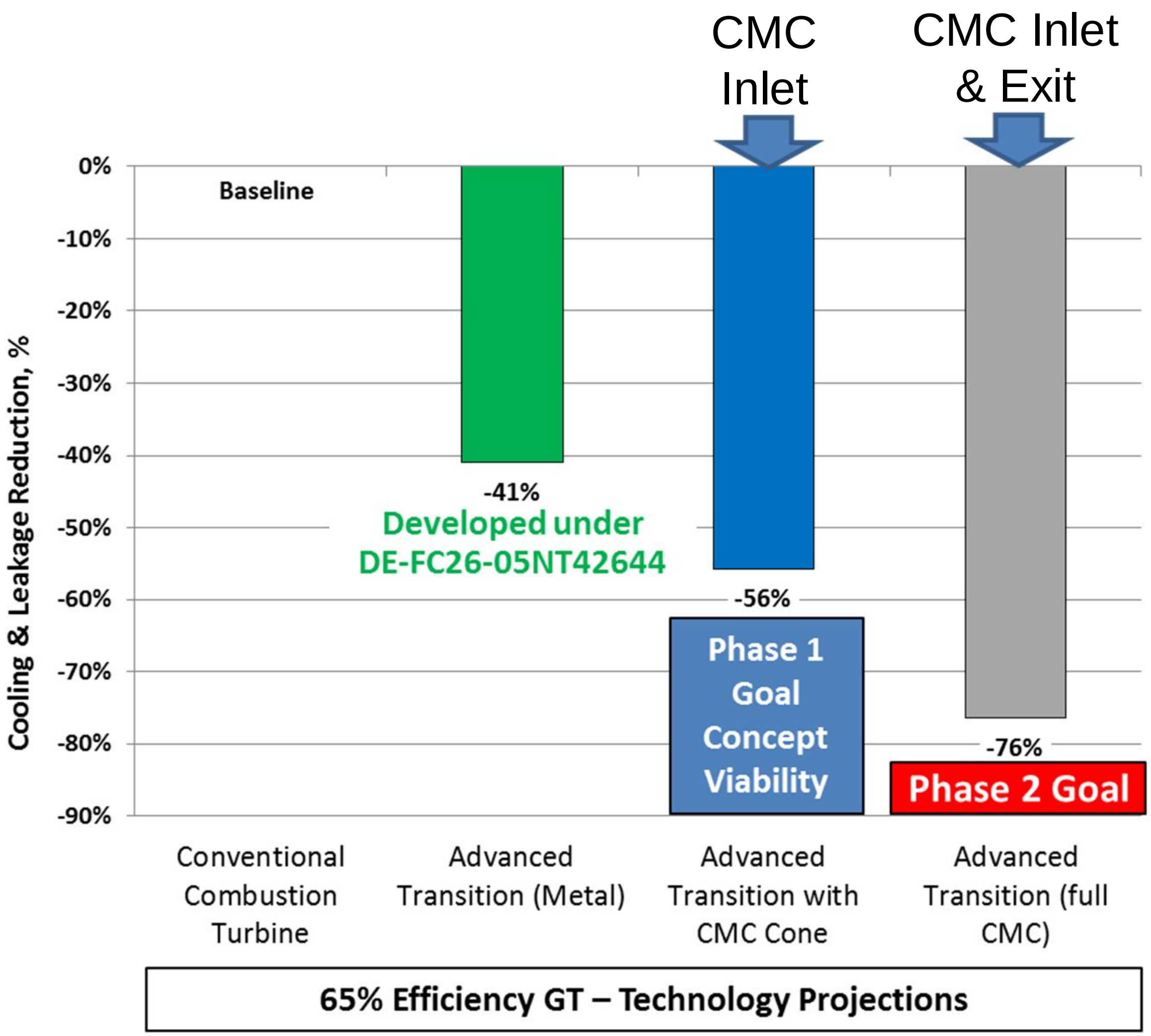
## *Benefits: Cooling Air Reduction*




**Phase 2 objectives:**

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

**→ NOx emissions reduction at High Firing Temperatures**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

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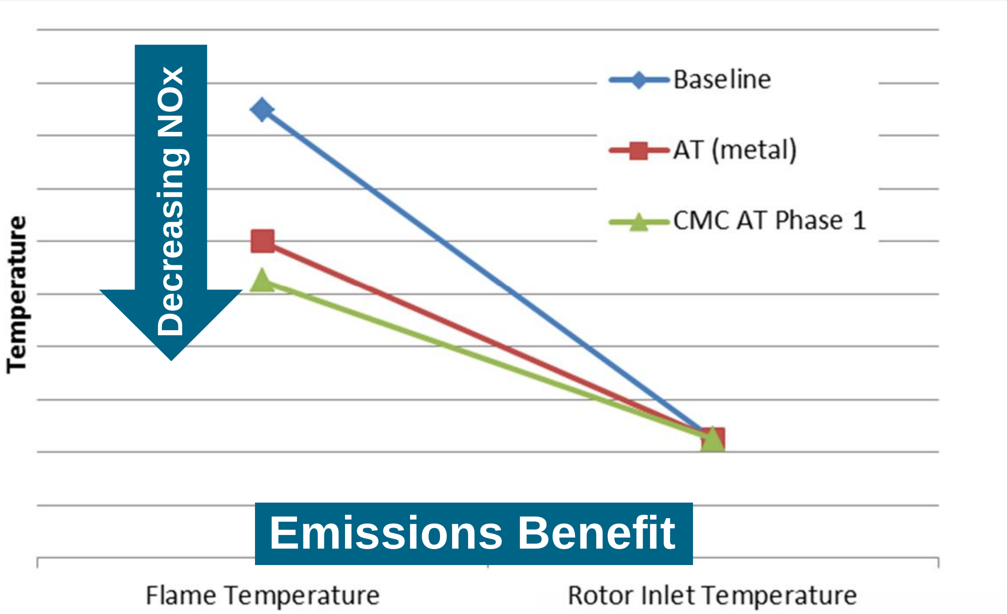
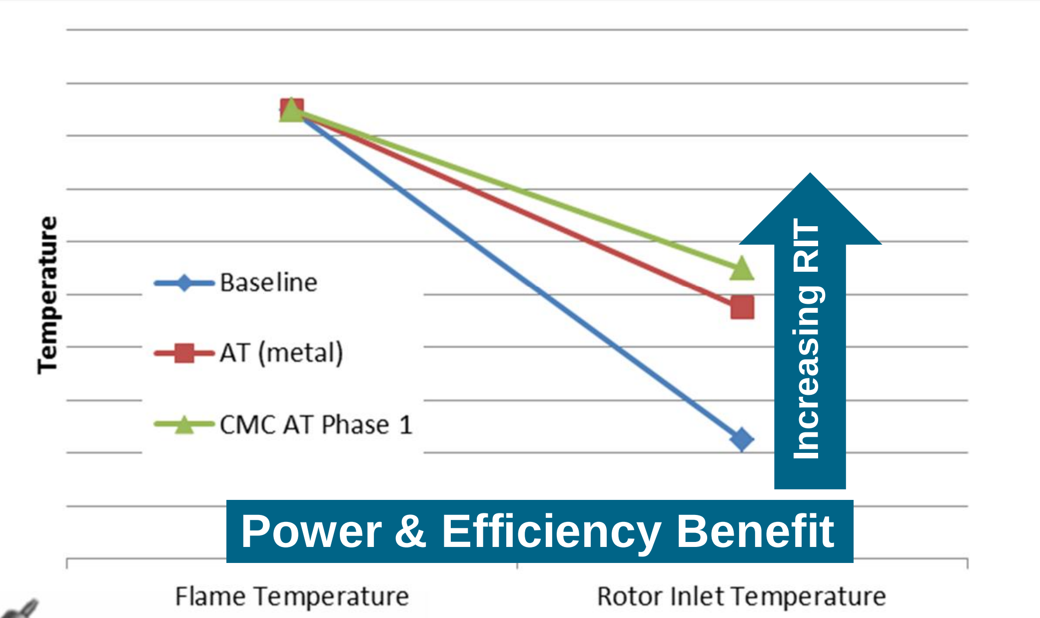
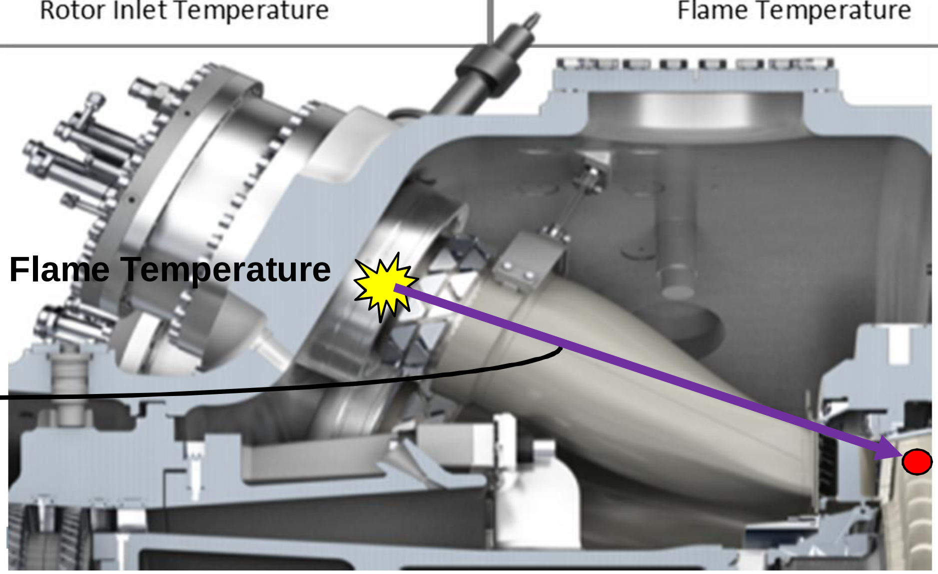
## *Benefits: NOx Decrease vs. RIT Increase*

### 1) Constant Rotor Inlet Temperature




### 2) Constant NOx




**Reduced cooling & leakage air between flame and turbine rotor**

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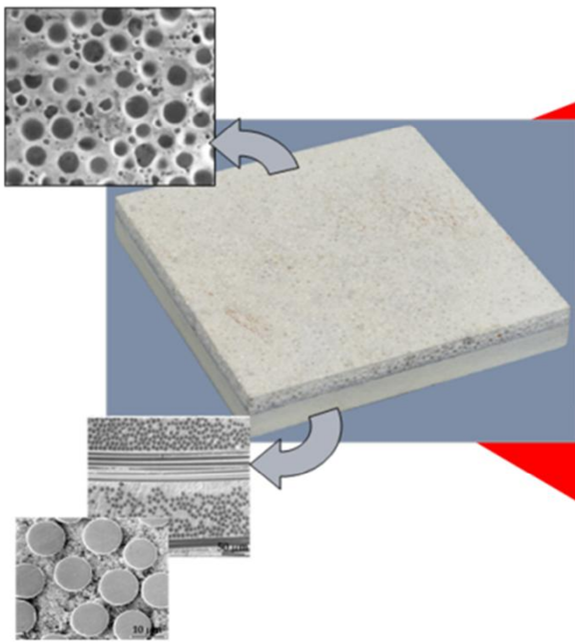
# CMC Technology Status

**Benefits:**

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

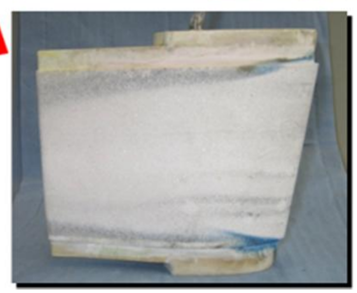


- *Low cost*
- *Millions of engine operating hours (tiles)*
- *>25,000 hours proven in combustors*

## 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

\+ **Siemens' Advanced Transition**

**Combining two high pay-off technologies individually developed & tested**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *CMC Component Testing Summary*

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

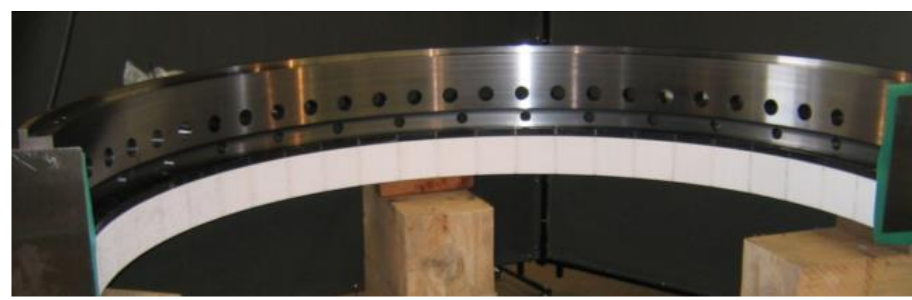
**Ring segments (4 types), airfoils, subelements**

- 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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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Program Overview*

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *CMC AT Concept Down-selection Process*

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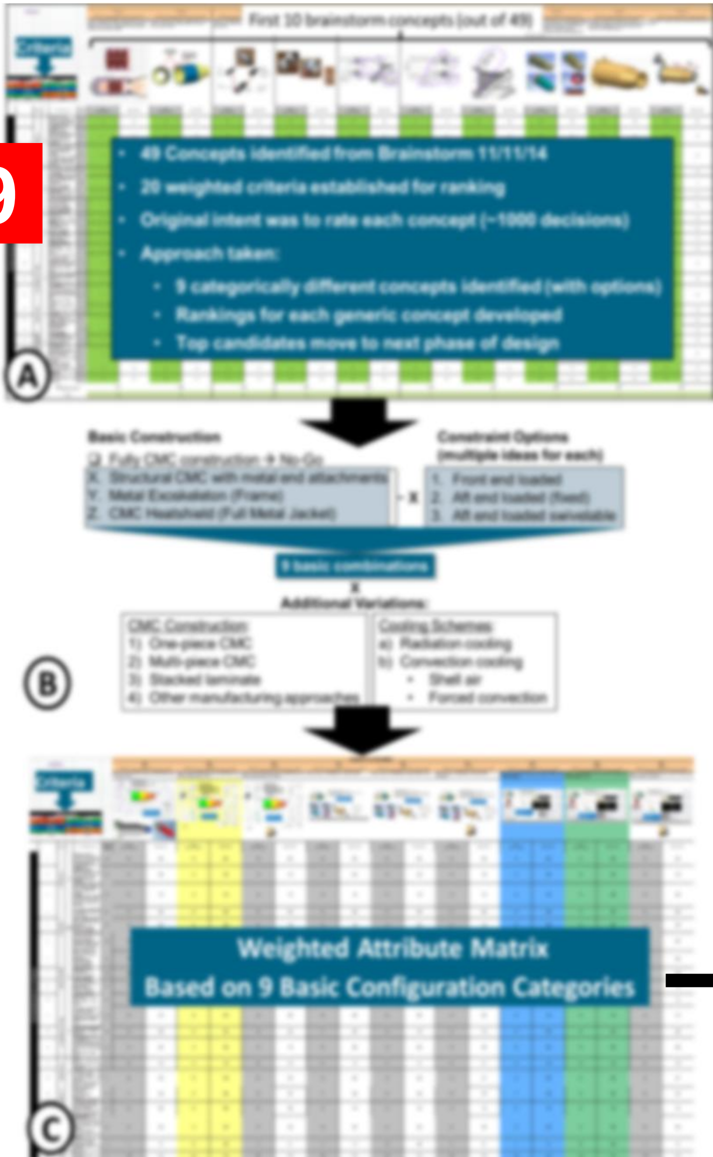


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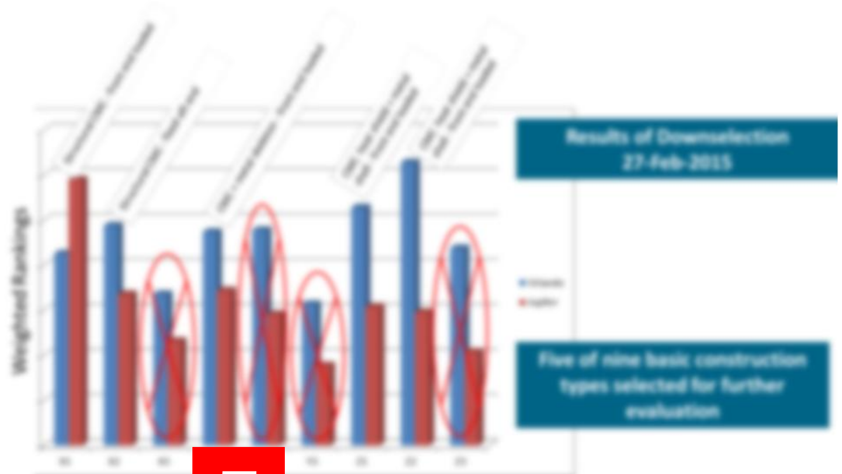


**5**

Structural CMC's ⟶ Heat Shields

**Milestone Sept 2015 → Two Concepts**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Advance Transition Concepts*

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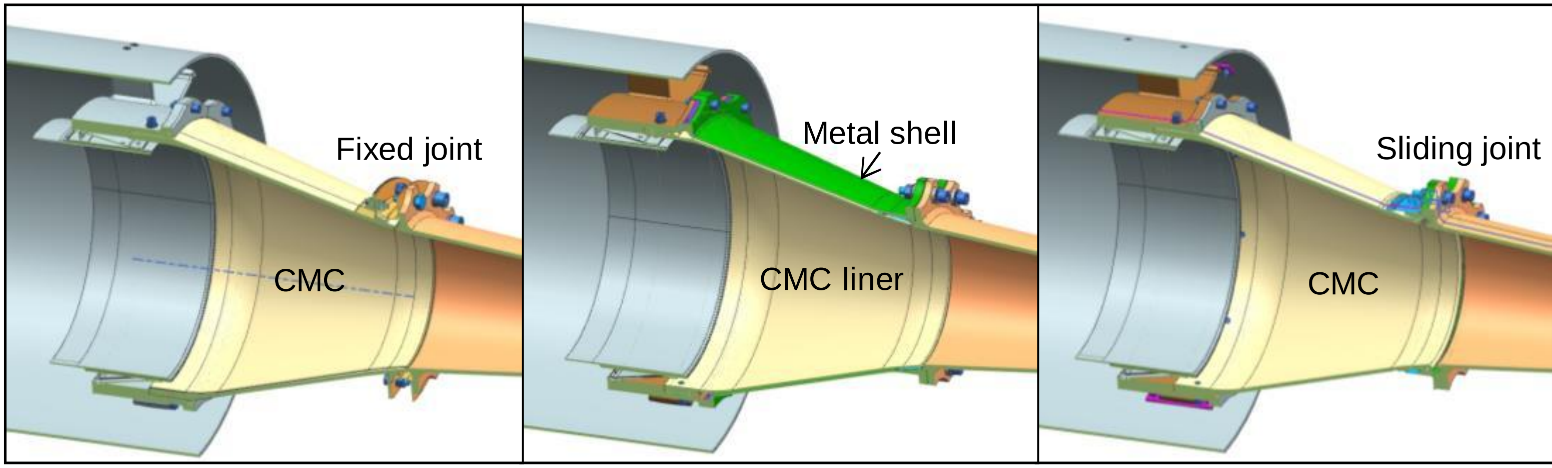
| Feature | Concept 1 | Concept 2 | Concept 3 |
|---|---|---|---|
| CMC duty | Thermal + Structural | Thermal-only | Thermal + Structural |
| Flow sleeve attachment | Sliding | Sliding | Fixed (axially) |
| Inlet ring attachment | Pinned | Pinned | Pinned |
| Aft Attachment (Exit Piece) | Fixed | Fixed | Sliding |
| Cooling scheme | Shell air (regenerative) | Radiation + convection | Shell air (regenerative) |
| Sealing difficulty | Moderate | Easy | Difficult |

Three uniquely different concepts were selected to offer complementary design challenges, learning experiences, and engine benefits. (performance / first cost / life-cycle-cost).




**Set-based-design approach increases chances of success**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Advance Transition Manufacturing Status (COIC)*

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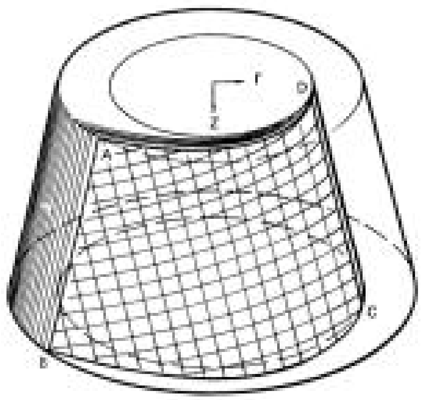
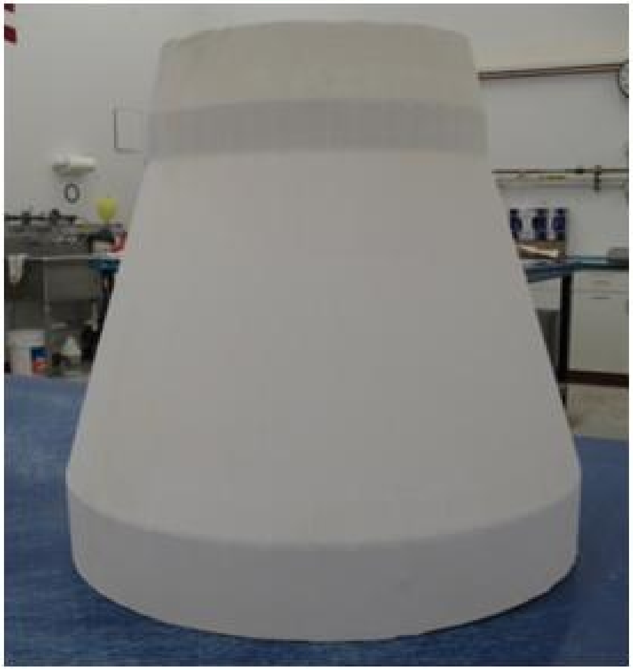


All parts made via involute wrap

**Concept 1**

As-Fabricated Condition



**Concept 2**

Thinner (heatshield) version

**Cones being manufactured by COIC**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Additive Manufacturing*

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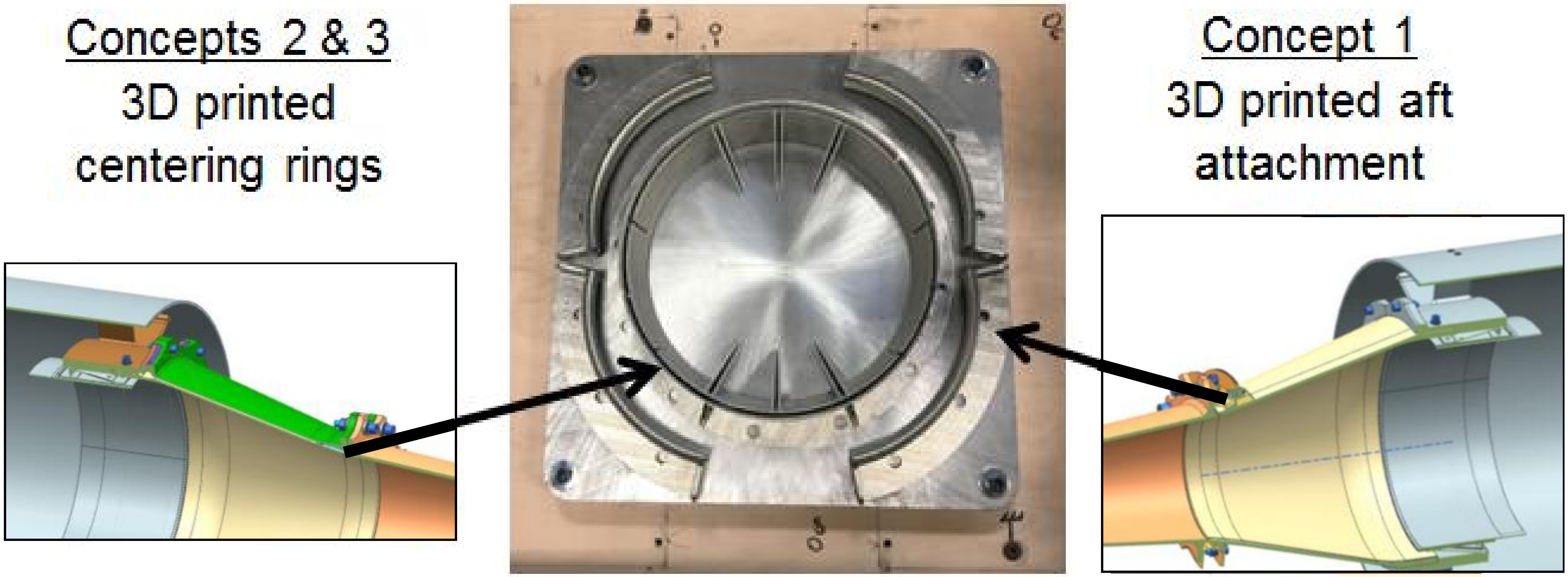
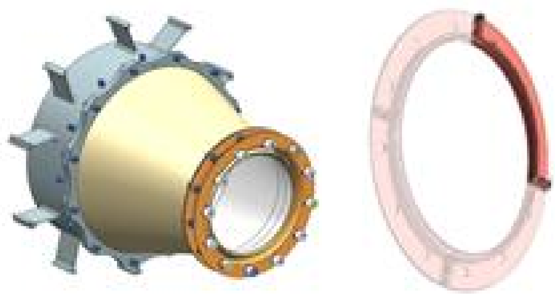
Concepts 2 & 3
3D printed centering rings

Concept 1
3D printed aft attachment





**Additive Manufacturing plays key role in AT components**

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# CMC Advanced Transition for η > 65% CC
# Program Overview

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# *CMC Mechanics – Current Status*

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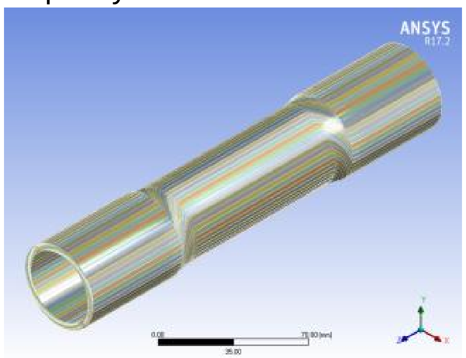
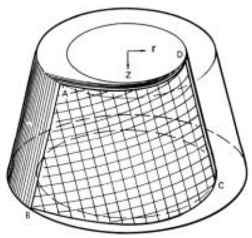
**Core Topics:**

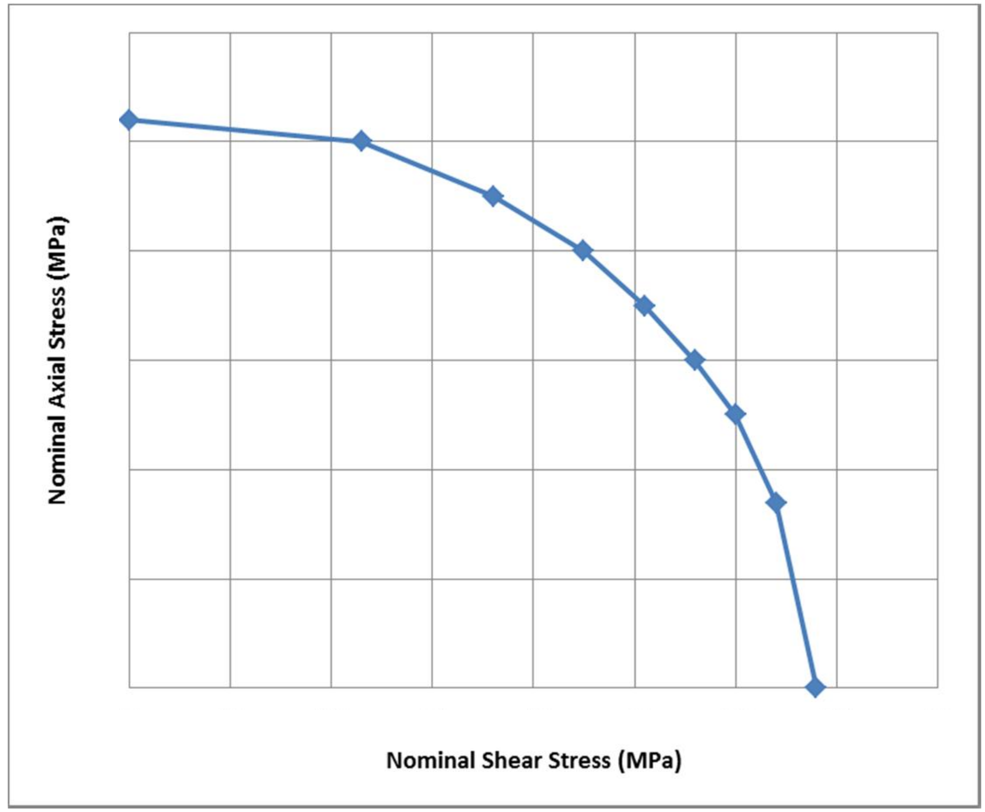
- **Deformation & Strength**
- **Dynamics**
- **CMC/TBC Modeling**

Involute Layup modeled explicitly in FEM

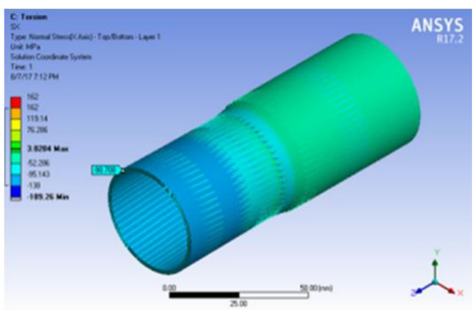


Bi-Axial Failure Model




Predicted Stress & Failure




- Bi-axial failure model allows the interaction of different stress states to interact with one another, debiting or augmenting the design allowables.

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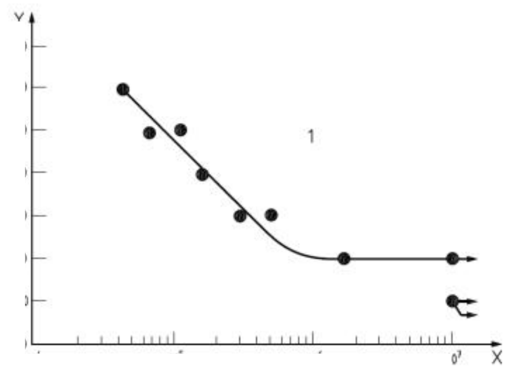
## *CMC Mechanics – Current Status*

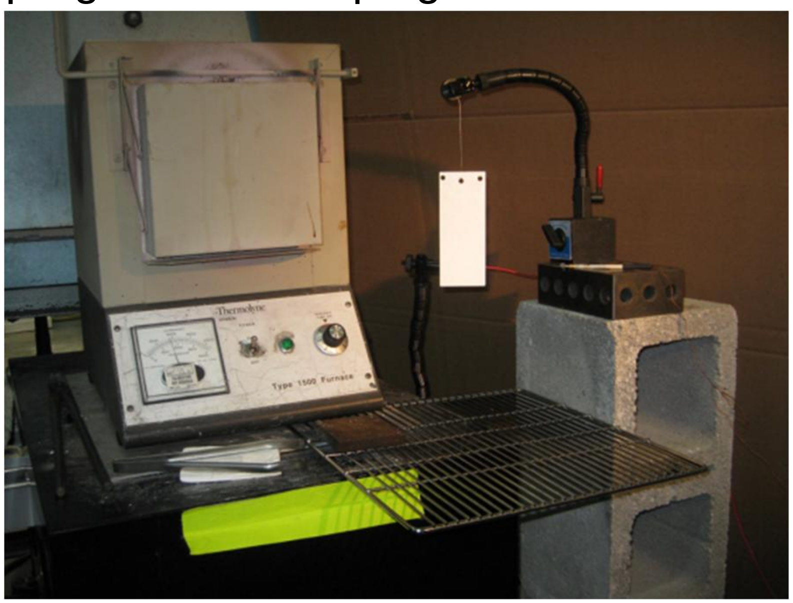
**Core Topics:**

- **Deformation & Strength**
- **Dynamics**
- **CMC/TBC Modeling**

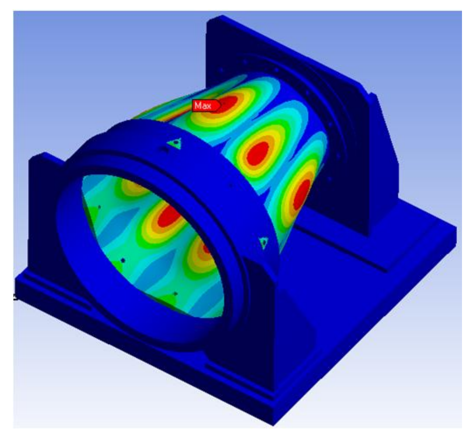
- Test Matrix Finalized - Specimens ordered (currently in machining)
- Goal is to fill out Woehler curve (Life defined by vibratory stress) for lifing components for HCF



Standardized Method Devloped in this program for damping measurement



Applied to initial cone dynamics analyses



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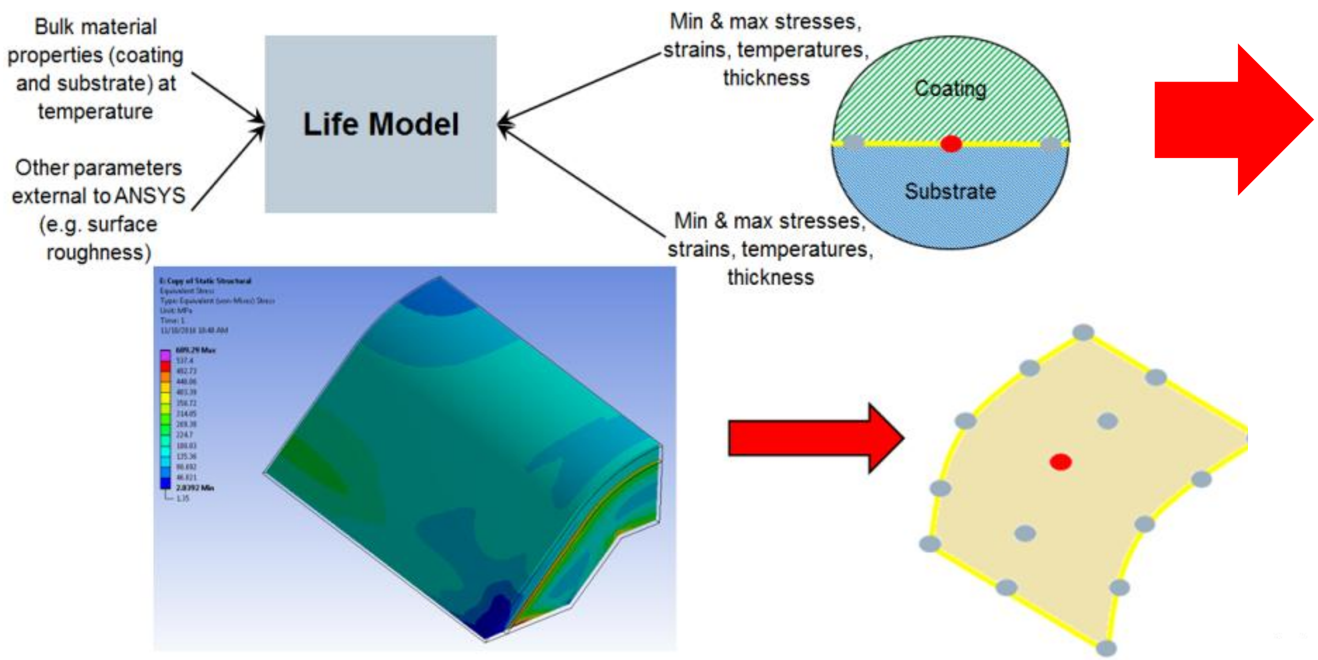
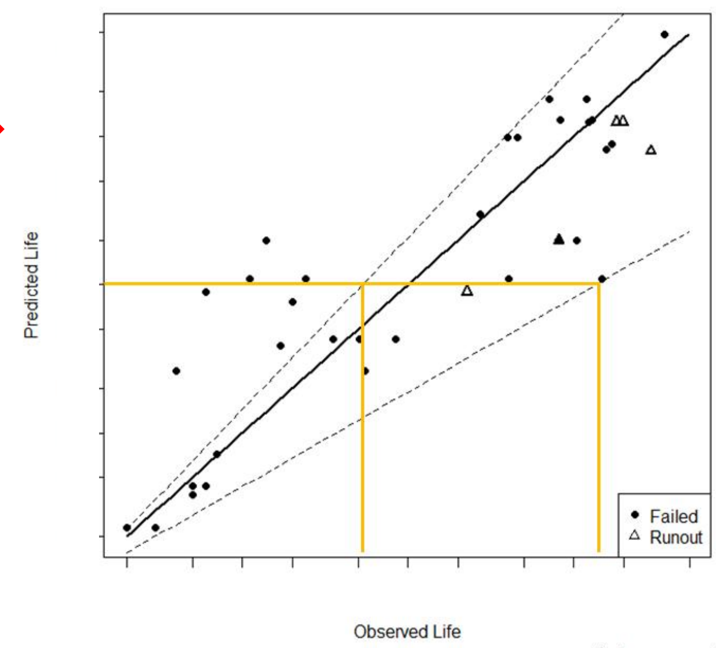
# *CMC Mechanics – Current Status*

**Core Topics:**

- **Deformation & Strength**
- **Dynamics**
- **CMC/TBC Modeling**

- Similar approach as in fluid dynamics
- Output many outputs from FEM model, determine which are significant
- Construct life prediction based on a function of significant non-dimensionalized parameters.
- Ideas is “leave the black box” not “understand everything.”

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

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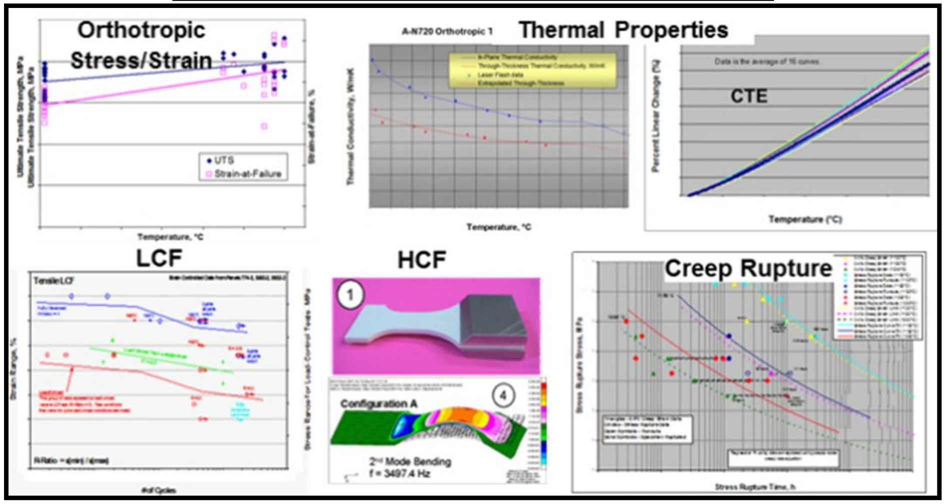
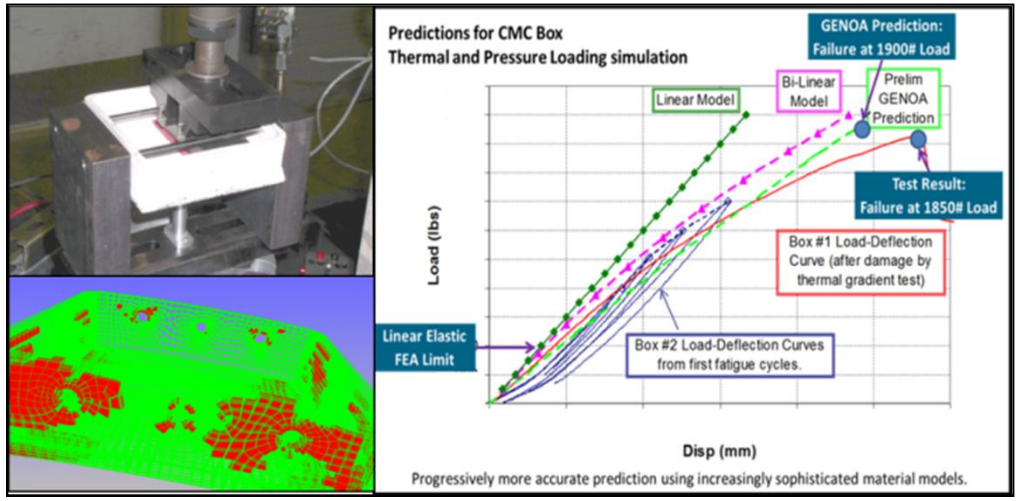
## *Supporting CMC Data & Remaining Challenges*

### Coupon Test Data



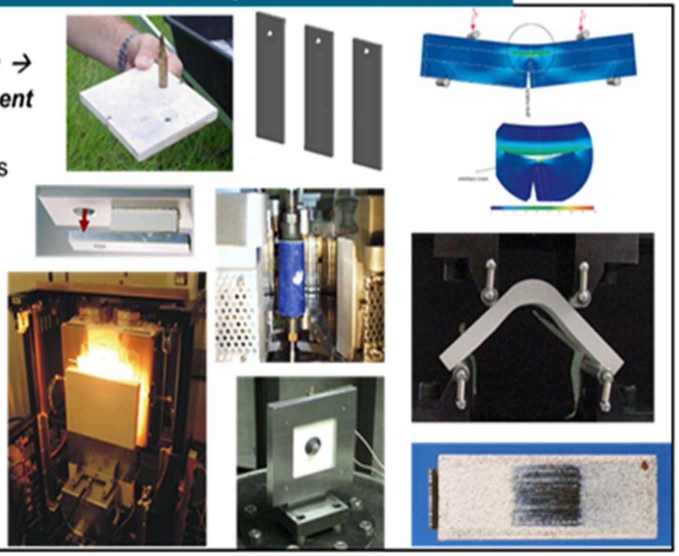

### Damage Accumulation & Life Prediction Tools




### 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

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency
## *Test Activity Summary*

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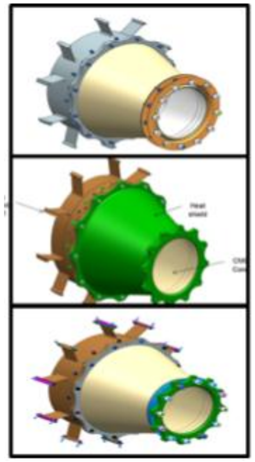
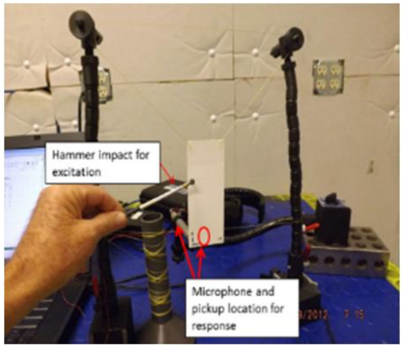
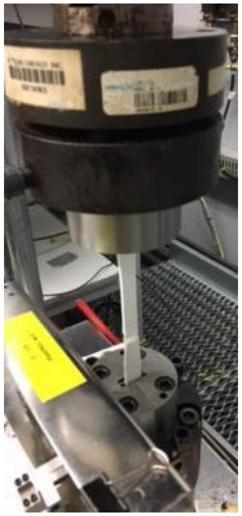
- **Casselberry Labs** (CLAB)
    - Flow & Leakages (test samples + full cone)
    - Material Strength & attachment
    - TBC
    - HHFT
    - wear
- **Cincinnati Test Labs** (CTL )
    - Material (involute wrap)
- **Florida Turbine Tech.** (FTT)
    - Ping Testing (coupons & full cones)
    - Shaker Table (full cone, concept #1)
- **Clean Energy Center** (CEC)
    - Cone (full, pressure, combustion tests, 4 concepts)





**Manufacturing peer review held as workshop in April 2017**

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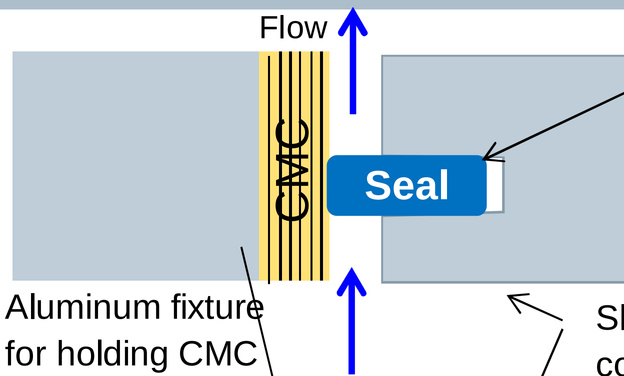
# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Seal Testing for CMC Cone: On-going Seal Tests*

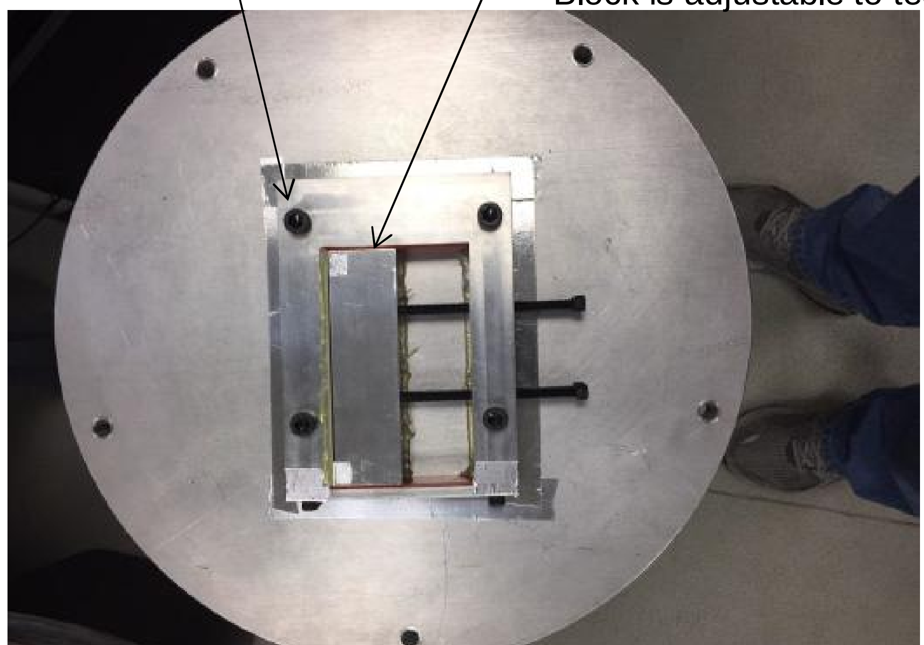

**Seal types:**

- **Rope seals (several types)**
- **E-seals**
- **Piston rings**

Aluminum fixture for holding CMC

Slotted blocks can be interchanged to fit component application

Block is adjustable to test different gaps



**Test plan:**

- Pressure ratios: 1.2, 1.4, 1.6, 1.8, 2.0
- Seal gaps: 0mm, 0.13mm, 0.64mm, 1.016mm and 1.27mm
- Pre-compression

**Seal flow testing has identified several options to reduce leakage and improve cooling & leakage air useage further**

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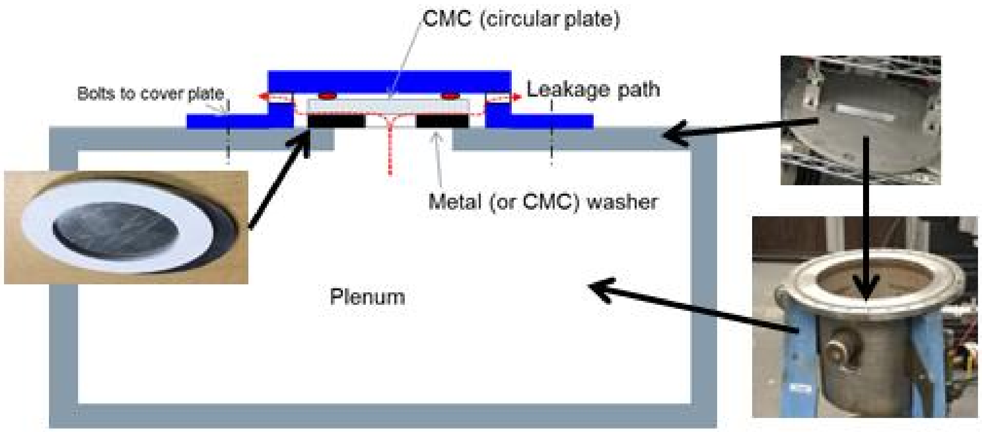
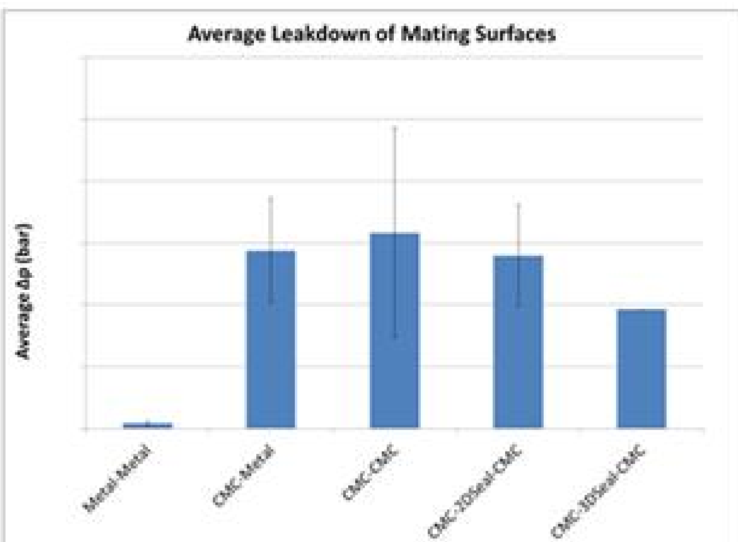
# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Seal Testing for CMC Cone: Subelements for Test*

Setup for CLAB flow testing




**Results**

- CMC-CMC joint was as fabricated, and showed the highest leakage, but still well within targeted values.

**Next steps:**

- Testing various seal configurations
- E-seal testing
- Full assembly cone leakage tests

**CMC-Metal leakage is less than predicted.**
**Anticipated benefits exceeding targets.**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Full scale leakage testing*


**Full scale component assembly (attachments & seals) leakage testing conducted. Performance as expected based on coupon testing.**

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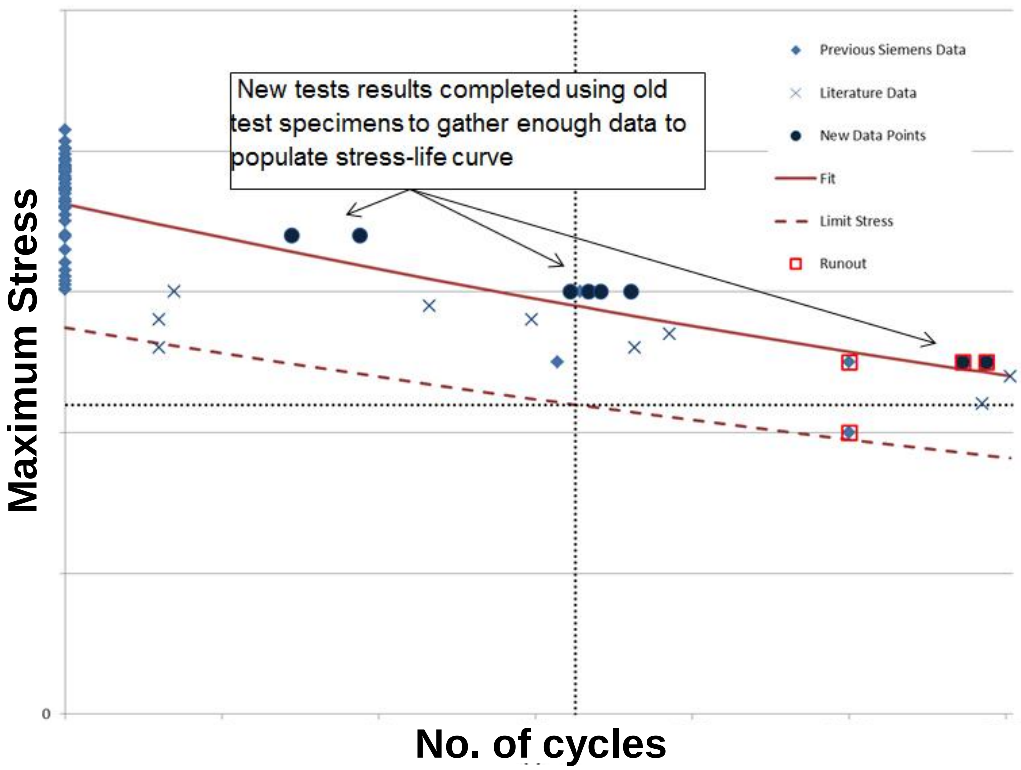
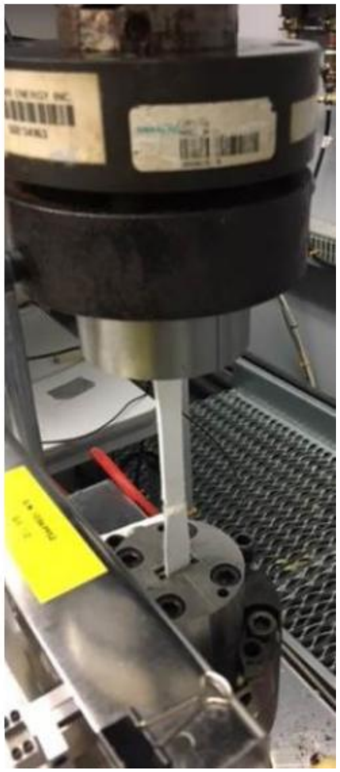
# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Material Strength Testing*



**Comparison of current CMC to ca 2005 database shows good agreement**
**(Lower cost 3000 denier fabric used in current design)**
**Testing of involute layup specimens in progress**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Attachment testing for Concept 1*

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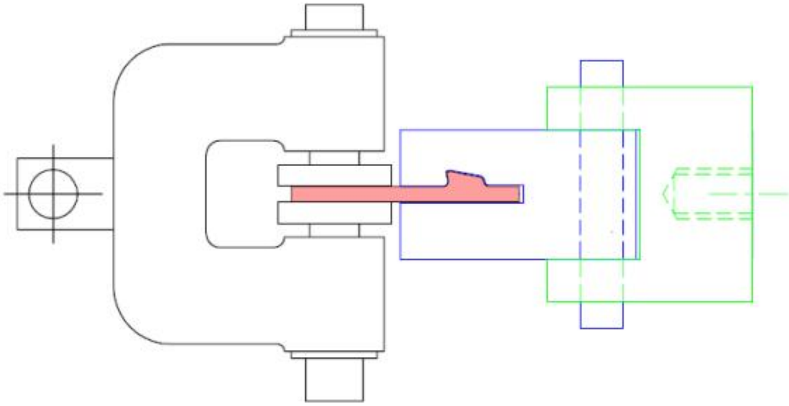

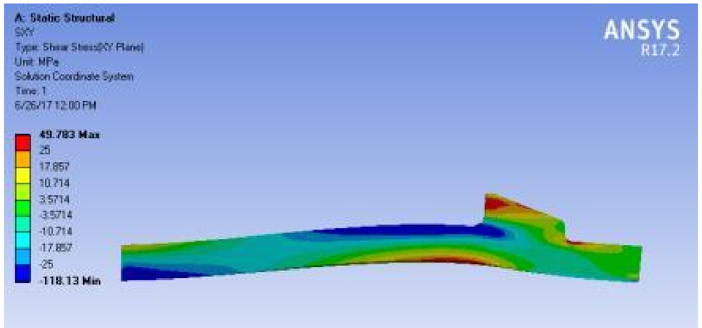


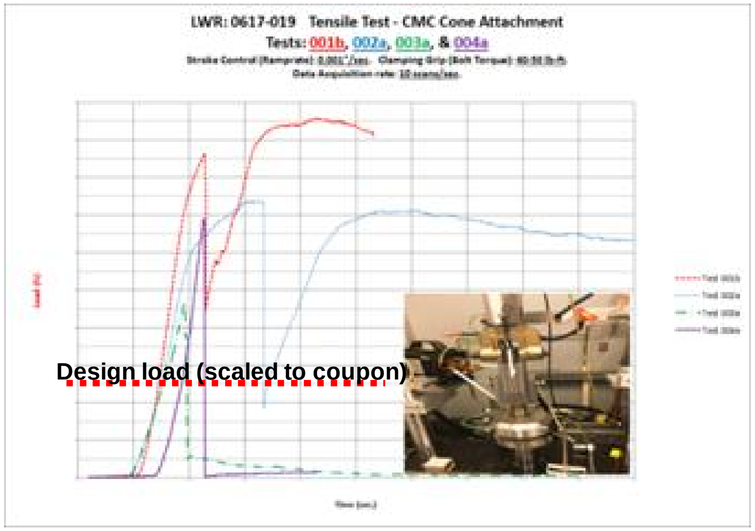


**3X Static design load capability – Fatigue testing in progress**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *CMC Material & TBC Testing*

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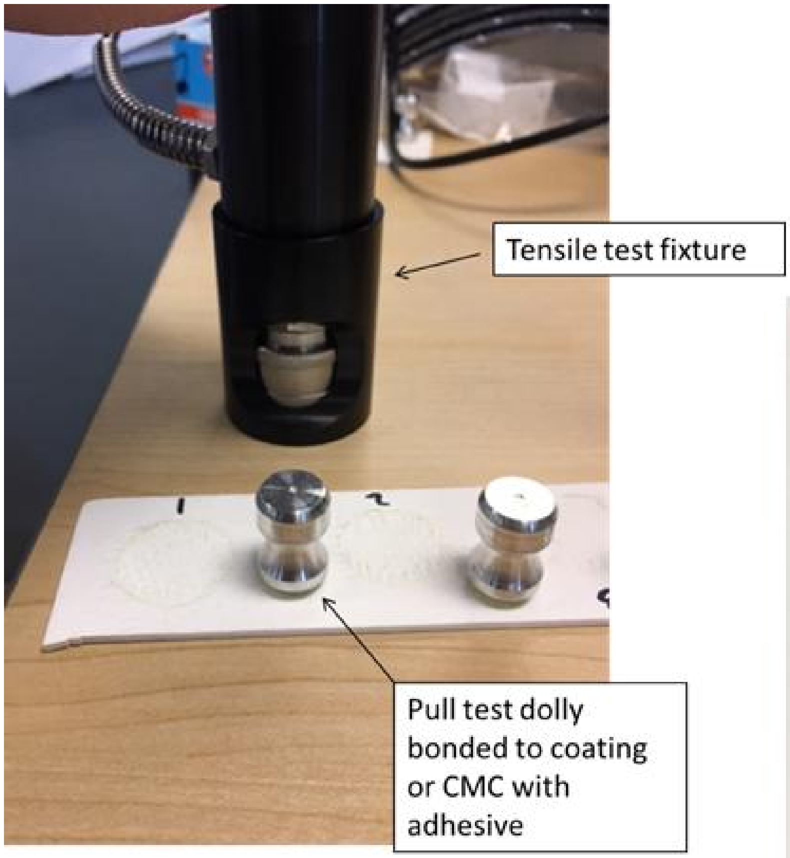
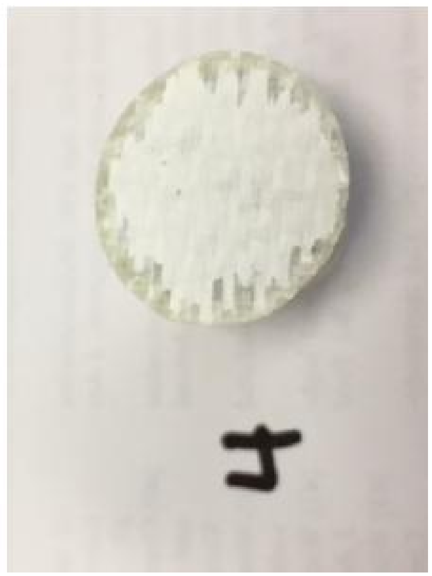



Sample testing



CMC-TBC bond test : 1-day procedure established at CLAB

**Steps**:

- Coating,
- Adhesive Preparation,
- Curation,
- Testing

**Method used for rapid screening & semi-quantitative ranking of CMC-TBC bonding concepts**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *CMC + TBC Testing*

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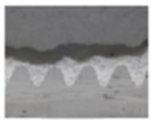
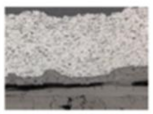
## The Challenge:


strong inter-connection



**Challenge 1: TBC adhesion**
- Interface from TBC to Matrix/Fibre/BC
- target: chemical bonding + improved mechanical bonding (incr. roughness)

**Challenge 2: Bondcoat / CTE missmatch**
- mitigate CTE missmatch using bondcoat



**Challenge 3: Weak matrix**
- spallation usually occurs in top matrix, 1st fibre or 2nd matrix layer
- target: strengthening matrix or bring failure down into 2nd/3rd ply

**# of options target each challenge**

4+4 Chemical approaches
- 4 options + 4 feasibility

4+7 Mechanical approaches
- 4 options + 7 feasibility

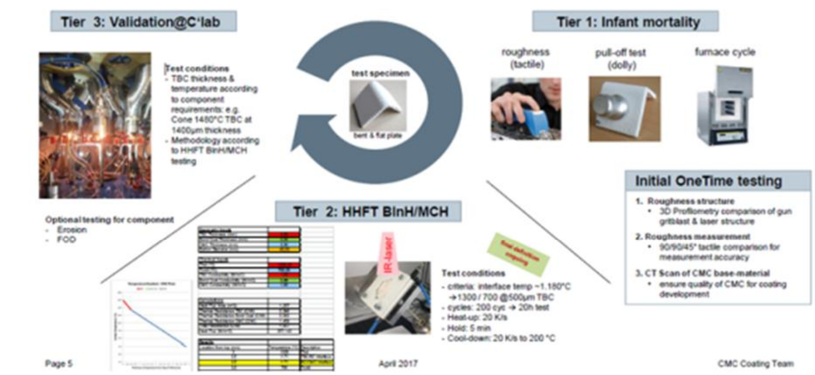
4 approaches

4 approaches

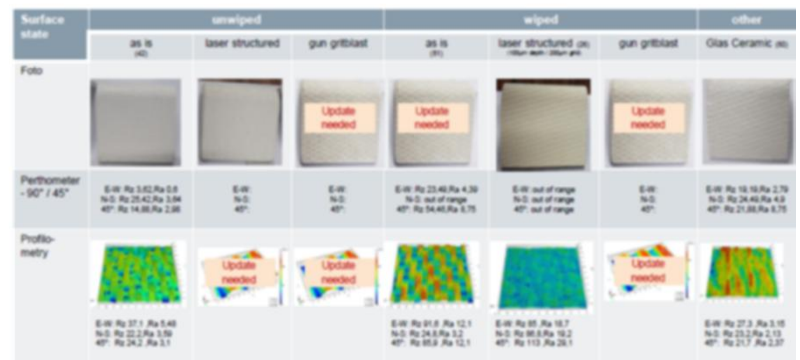
## The Approach:

| Option | | Baseline | | Surface texturing (pre-sint.) | | Top ply engineering | | | | | | Bonding layers (post-sint.) | | Topcoat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Baseline 1 gun gritblast #13 | Baseline 2 laser structure #14 | Glas Ceramic w gun gritblast #15a | Glas Ceramic w laser structure #15b | (2) Hard tool texturing (mesh) #27 | Ply cut-out #35 | (1) Top ply chemistry Zirconia #38 | Top ply chemistry Silica #39 | Wiping + thick matrix #41 | Wiping laser structure #42 | (3) Silicon wiped #50 | Aluminum (thin) #54 | Topcoat variations |
| configuration | Roughening | gun gritblast | laser | gun gritblast | laser | no | gun gritblast | gun gritblast | gun gritblast | tbd | laser | no | no | laser |
| | Bondcoat | no | no | (yes) | (yes) | no | no | no | no | no | no | yes | yes | no |
| | TBC | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | 500µm 8YSZ | various |
| | Laser engr. | no | no | no | no | no | no | no | no | no | no | No | no | various |
| Target / hypothesis statement | | baseline: required for comparison | | chemical adhesion to CMC matrix and TBC expected | | improved adhesion and mechanical ply-strengthening | | matrix strengthening by using a stronger matrix composition for prepreg | | improved bonding by increased surface & wiping approach | | chemical adhesion using an additional bondcoat | | comparison of different TBCs |
| Est. bonding / strengthening mechanism | | mech | mech | mech + chem | mech + chem | mech + top ply strength | mech | CMC strength | CMC strength | mech | mech | chem | chem | • 8YSZ LE<br>• 8YSZ Segm.<br>• 8YSZ Std |
| Feasibility trials to identify further options | | | | #20 Surface stitching<br>#21 Laser surface remelt | | #44 Oxy Chloride Infiltration<br>#28 Laser texture at bisque state<br>#28 + alter top ply chemistry<br>#29 Large Particle infiltration | | #43 Release layer structure<br>#30/31 3.000 + 10.000 denier<br>#33 Hard tool macro<br>#40 TBC at bisque state + cosinter | | | | #51 Silicon Metal in Al [illegible]<br>#52 SPS [illegible] | | |

## Test Plan:




## Example Results (surface roughness):




**Method used for rapid screening & semi-quantitative ranking of CMC-TBC bonding concepts**

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# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Ping Testing*

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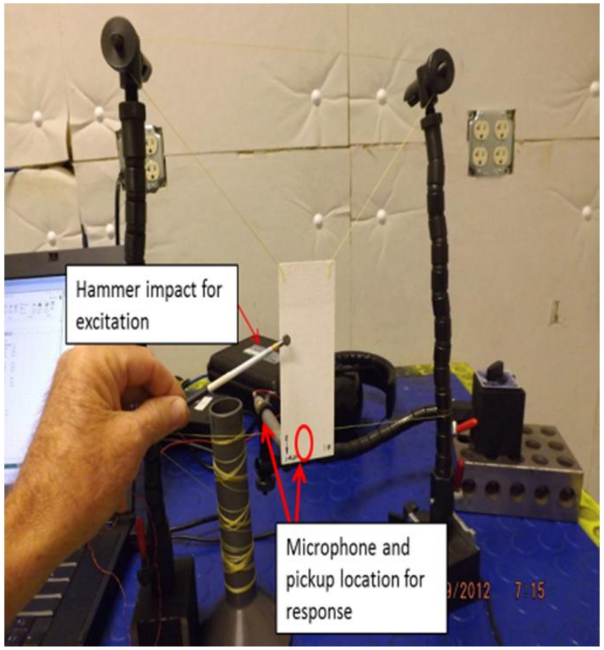
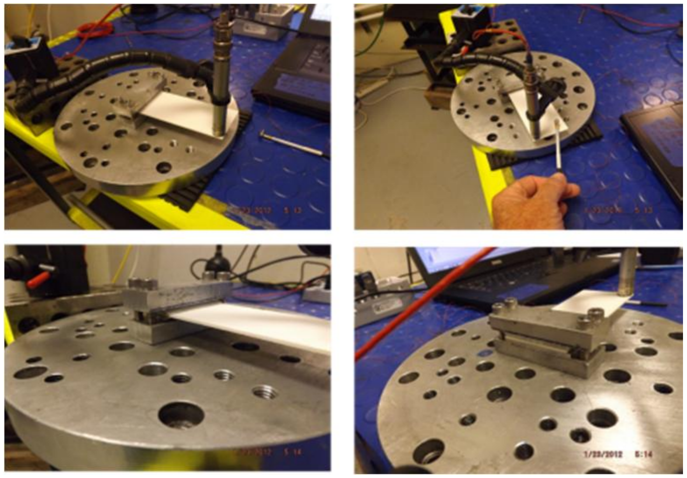
### Free – Free setup




### Fixed – Free setup



### Cone setup

**Validation data being gathered for calibration of CMC modal analysis**

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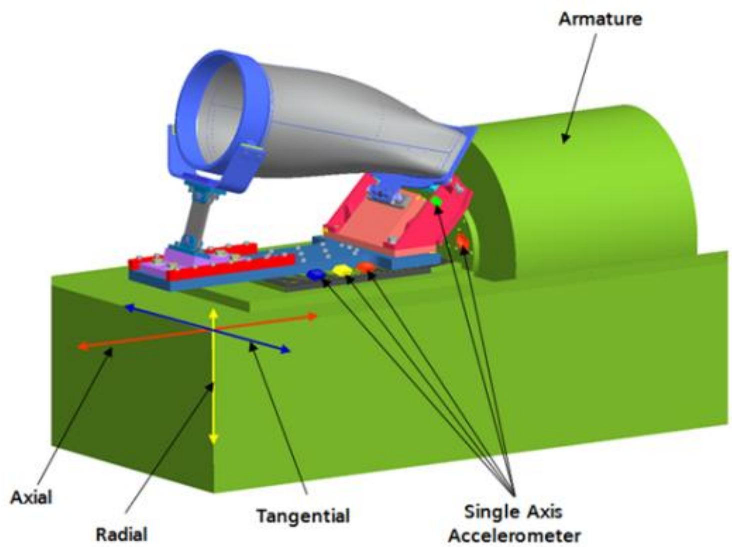
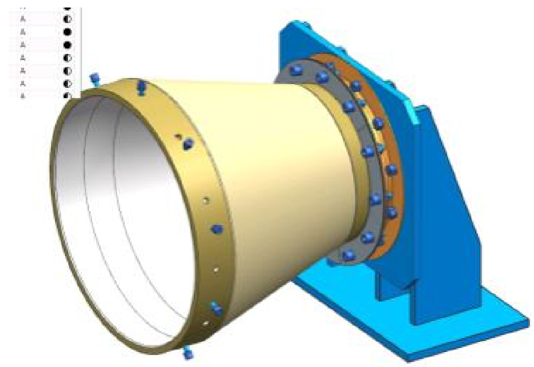
# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

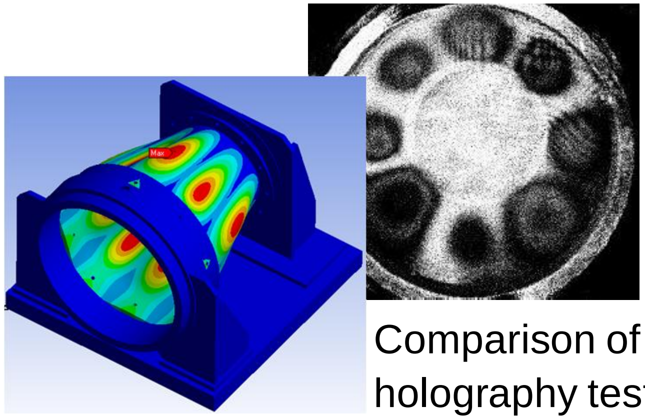
## *Shaker table test (FTT)*




Fixed - Free



Fixed – Free(axial) / Fixed (radial)



Comparison of predicted and holography testing is ongoing

**FTT shaker table used to validate modal analysis method.**
**Apply validated method for CEC testing of cones.**

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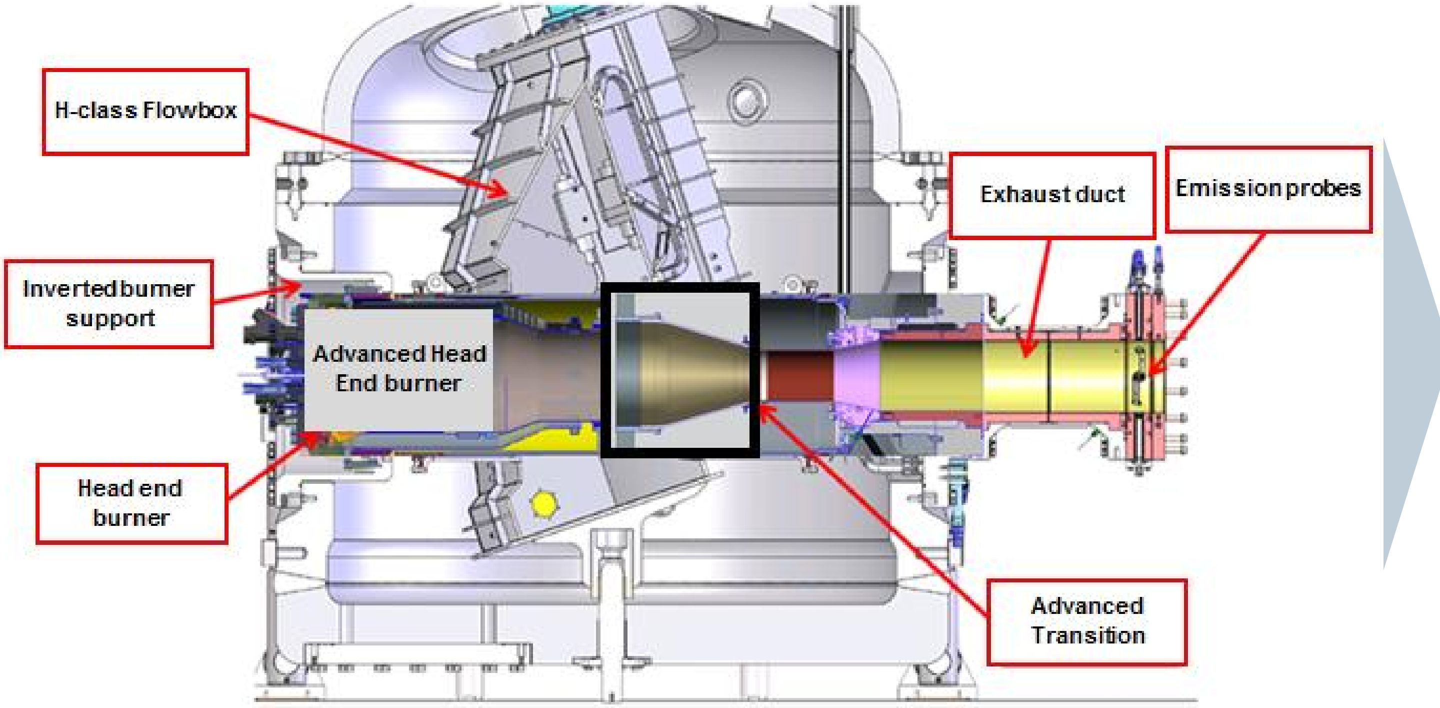
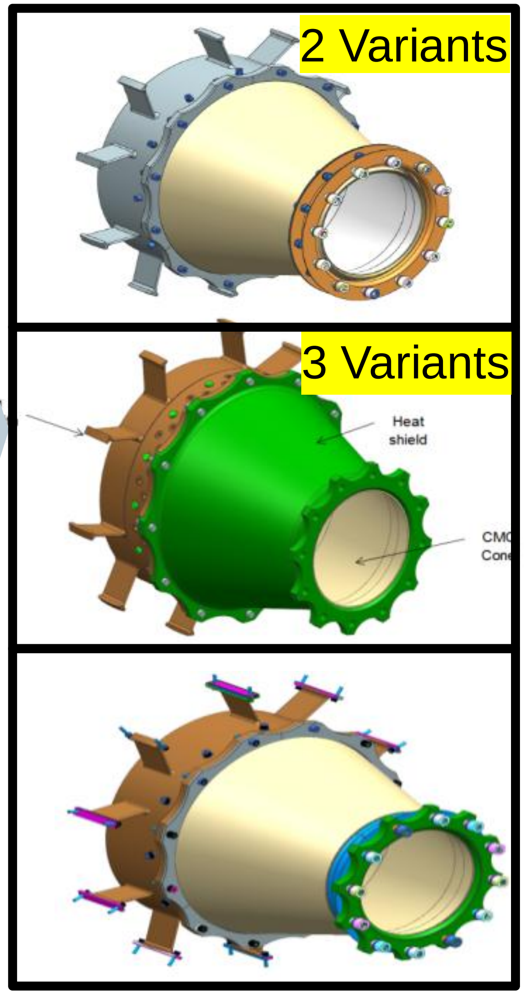
# Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle Efficiency

## *Combustor Rig Testing*




**6 cone tests planned at Siemens' Clean Energy Centre in Q1/Q2 FY18**

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# *Next Steps*

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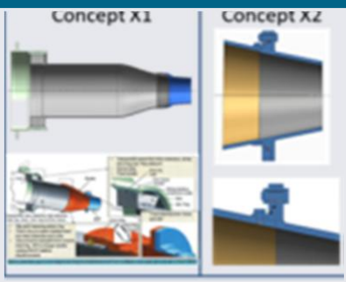
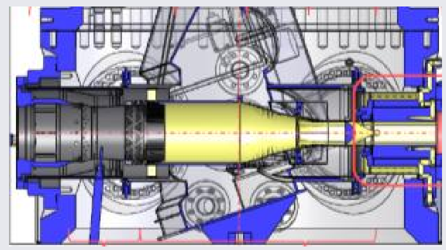
## PHASE 1
## Concept Feasibility




**Conceptual Design**

## PHASE 2
## Technology Development & Testing



**Manufacture & Combustor Rig Testing**

## PHASE 2/3
## Technology Demonstration

**Engine Testing**

**Next Steps:**

- **Complete hardware manufacture**
- **Assemble & Instrument**
- **Combustor rig test**
- **(Possible) engine test**

## Next Step: Technology Demonstration

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Answers for Energy.

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## Thank You. Questions?

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