An integrated approach to advanced materials and coatings development with rigorous validation is the future for extreme environment materials.
Siemens Provide a Range of Gas Turbine Products for Both 50 Hz and 60 Hz Grids

**Heavy-duty gas turbines**
- SGT5-9000HL: 593 MW
- SGT5-8000HL: 481 MW
- SGT5-8000H: 450 MW
- SGT5-4000F: 329 MW
- SGT5-2000E: 187 MW
- SGT6-9000HL: 405 MW
- SGT6-8000H: 310 MW
- SGT6-5000F: 215 to 260 MW
- SGT6-2000E: 117 MW

**Industrial gas turbines**
- SGT-A65: 60 to 71 / 58 to 62 MW
- SGT-800: 50 to 62 MW
- SGT-A45: 41 to 44 MW
- SGT-750: 40 / 34 to 41 MW
- SGT-700: 33 / 34 MW
- SGT-A35: 27 to 37 / 28 to 38 MW
- SGT-600: 24 / 25 MW
- SGT-400: 10 to 14 / 11 to 15 MW
- SGT-300: 8 / 8 to 9 MW
- SGT-100: 5 / 6 MW
- SGT-A05: 4 to 6 MW

**Aeroderivative gas turbines**
- SGT6-9000HL: 593 MW
- SGT6-8000H: 481 MW
- SGT6-5000F: 405 MW
Customer Needs and Market Drivers for Materials & Coatings for Industrial Gas Turbines

High Temperature Materials & Coatings

Lowest Cost of Electricity

High Efficiency

Low Emissions

Reduced Cost

High Availability

Increased Reliability

Lifing, NDE, Repair and Rejuvenation

Reproducible and reliable component quality & performance

Cost Effective Manufacturing & Design to Cost
Currently, high temperature materials are limited to approx. 1100 °C. In order to achieve the goal of gas turbine power plants with $\eta = 65\%$ (Flame temperature: 1800°C), materials with near gas temperature capabilities have to be developed.

Viswanathan et.al. (2000)

200°C improvement in 50 years, 250°C improvement desired in 20 years
Industrial Approach for Gas Turbine Materials/Coatings

Additive Manufacturing/ Low K TBC combination

New Low K TBC benefit

Allowable Hot Gas Temperature

Film Cooling

Convective Cooling

8YSZ TBC

CMC

TBC – Thermal barrier coatings

Need Design input on engine conditions and environments for technology download
Growing number of AM processes to accelerate the development of materials and their qualification
Testing and Validation Chain
Change in R&D paradigms

Integrated development: accelerated iteration cycles in few months

Conventional process
“Testing is final validation at the end of development process”
- Sequential development processes
- Conservative development approach
- Moderate development goals
- Long development cycles

Novel paradigm
“Testing is integrated part of development process”
- Parallel and integrated development processes
- Radical development approaches
- Ambitious development goals
- Accelerated development goals, short iteration cycles

3D Design  AM processing  Post processing  Instrumentation  Testing

Clean Energy Center
Test Bed

Integrated development: accelerated iteration cycles in few months
Additive Manufacturing: Potential benefits of AM for GT

**Product costs**
- **Cost reduction** for manufacturing of complex parts in smaller volume, reduced LCC (service, repair)

**Validation**
- **Faster validation** of new technologies and designs with minimized effort and lead time by use of rapid prototyping for rig test and later functional parts

**Time-to-market & development costs**
- **Reduced lead time and costs** for prototype development by use of rapid prototyping, rapid tooling and rapid qualification techniques

**Efficiency & Performance**
- **Increased** product design complexity far beyond today’s level enabled by new manufacturing technologies at competitive costs

**Design Flexibility/Topology Optimization for Redesign of Components**
System Level Engineering of Extreme Environment Materials

Base alloys mechanical/oxidation properties
- Tensile properties
- LCF/HCF/TMF properties
- Thermal expansion
- Creep properties
- Oxidation behavior
- Corrosion behavior

![Diagram showing temperature distribution and material layers](image)

Bond coat oxidation
- reduced fracture resistance at TBC/BC interface (TGO growth stress)
- degradation of BC properties (Al depletion) with HEA alloy

TBC degradation
- reduced TBC fracture resistance (strain tolerance)
- increased TBC stiffness and thermal conductivity/Sintering
- possible phase transformation

Temperatures:
- $T_{\text{Substrate}}$
- $T_{\text{Cooling air}}$
- $T_{\text{Gas}}$
- $T_{\text{Surface}}$
- $T_{\text{Bond Coat}}$

Material layers:
- Base Material
- Bond Coat
- Bilayer TBC

Thicknesses:
- ~1000s of microns (~100s of mils)
- ~100s of microns (~10s of mils)

$\Delta T \approx 1 \text{ K/\mu m}$
Siemens Corporation

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Observed Coating Failure Mechanisms

TBC: Thermal barrier coating
CMAS – Calcium magnesium alumino-silicate

Combination of tests needed to address risk/quantitative degradation for fuel flexible environments
• Testing provides Insight into degradation mechanism
• Component specific conditions (Ttbc/Tmetal) in gradient testing
• Reactions between TBC/bond coat with corrosives/metal loss

Critical Components have coating protection, System reliability needed in fuel flexible environments
Risk from Contaminants (Ca, Na, Ni, Fe, S, V)

- Environmental Factors
  - Salt composition and its melting temperature
  - Testing temperature and thermal cycles
  - Gas composition
  - Salt deposition rate
  - Thickness of salt layer
  - Prior environmental exposure (e.g., oxidizing environment)

- Compositional Factors
  - Alloy composition
  - Composition and thickness of thermally grown oxides (TGO)

CaSO₄: Calcium Sulfate hot corrosion on turbine blade

Na₂SO₄: Sodium Sulfate hot corrosion on turbine blade

Ni or Iron Oxide: TBC

CaO, CaSO₄ (solid): Crack formation

CaSO₄ (liquid): MCrAlY

Vanadium hot corrosion on turbine blade

Liquid to gas temperature

Temperature (°C)

B1, B2, B3, B4, V1, V2, V3, V4
Materials Related Turbine Development Goals for Industrial Gas Turbines

**Ring Segments**
- Increased temperature abradable coatings
- Multi-rub / long term rub tolerant

**Combustors and Transitions**
- Metallic coatings, increased oxidation resistance
- New TBC’s with increased temperature capabilities
- Oxidation/Corrosion resistance materials

**Blades and Vanes**
- New TBC’s with increased temperature capabilities
- Materials with oxidation/corrosion/fatigue/creep resistance
- New metallic coatings, increased oxidation resistance
- Materials life prognosis and health monitoring
Rigorous testing and validation based on a thorough understanding of failure modes and improving final system performance.