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Advanced Materials for Mercury 50 Gas Turbine Combustion System

Microturbine and Industrial Gas Turbine Peer Review Meeting

March 14, 2002

Jeffrey R. Price

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Overview

- **Program Description**
  - Program Objectives
  - Technical Approach
  - Project Team
- **2001 Program Activities**
  - Program Accomplishments
  - Problem Areas/Challenges
- **Future Program Plans**
- **Leverage of Funds/Collaborations**

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Advanced Materials Program

- Program Sponsor
  - U.S. Department of Energy (DOE)
    Office of Power Technologies, Washington, DC
  - Program Management - Debbie Haught, Merrill Smith

- DOE Project Management
  - DOE Chicago Operations Office, Argonne, IL
  - Project Manager - Jill Jonkouski

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Program Goals

- Improve Mercury 50 Advanced Combustion System Durability
  - Goal: 30,000 hrs / 3,000 cycles
- Reduce life cycle cost
- Minimize performance & engine/package design impact
- Maintain Single Digit Emissions
- Advanced Materials Technologies
  - Improved Thermal Barrier Coatings (TBCs)
  - Oxide Dispersion Strengthened (ODS) Alloys
  - CFCC Liner with Environmental Barrier Coatings
  - Monolithic Ceramics
- 4000 Hour Engine Demonstration at End User Site
- Expand Technologies to current and future gas turbine engines

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Program Tasks

- TASK 1 : Preliminary component concept design and evaluation
- TASK 2 : Sub-scale testing (Single-injector rig)
- TASK 3 : M50 engine adaptation to accept modified system
- TASK 4 : Full-scale hardware tests (rig and engine)
- TASK 5 : Field evaluation (4,000 hours)

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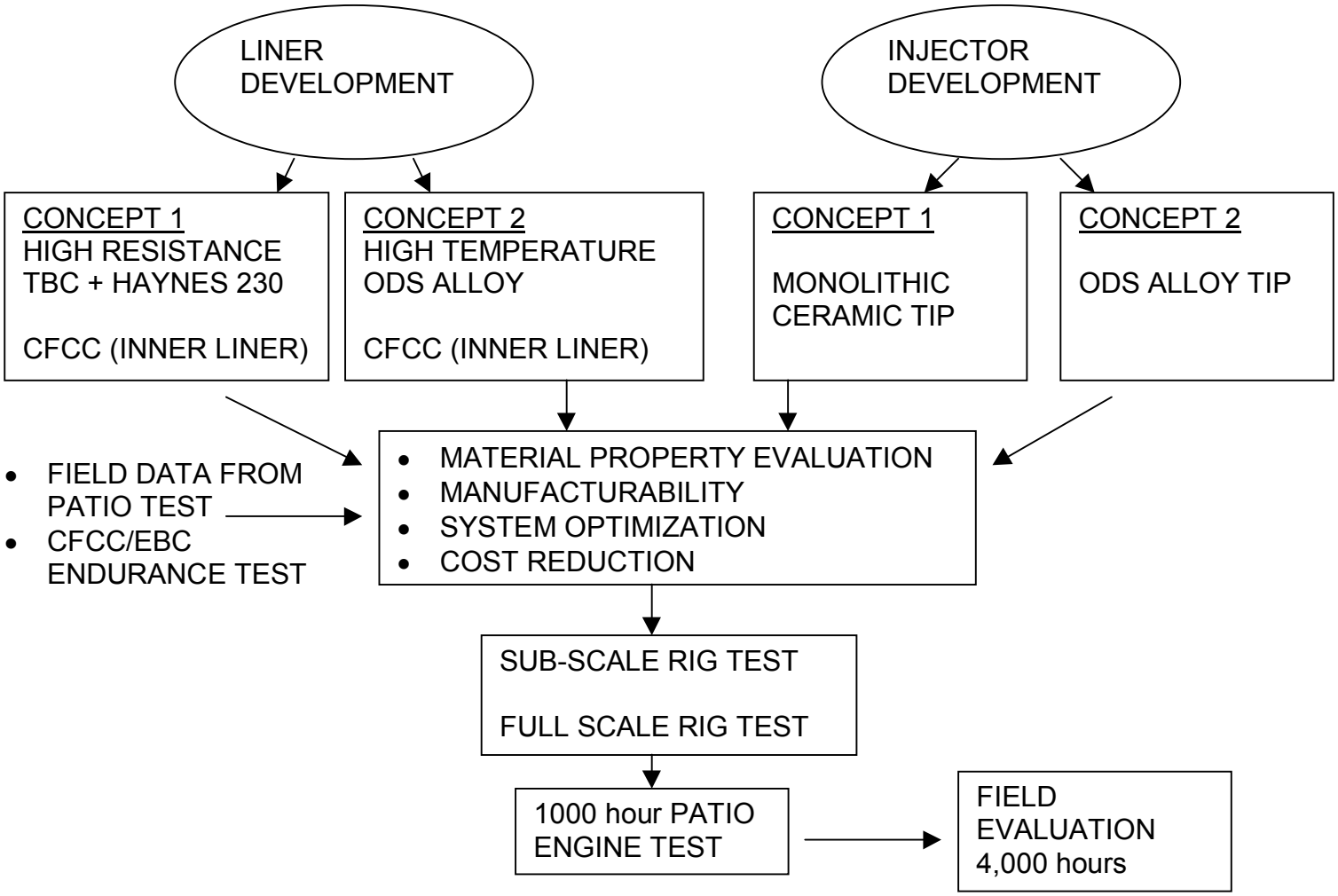
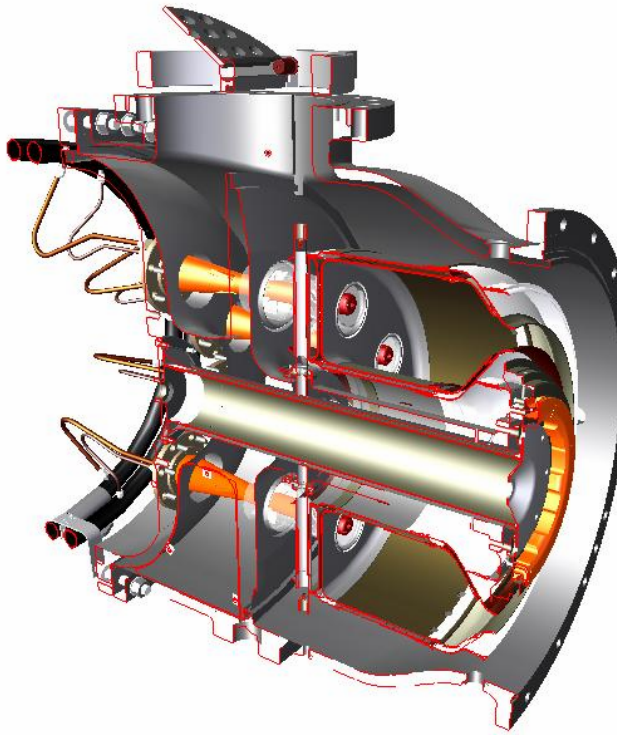
Dual Path Development Strategy



Technology Development

Improved Liner Durability

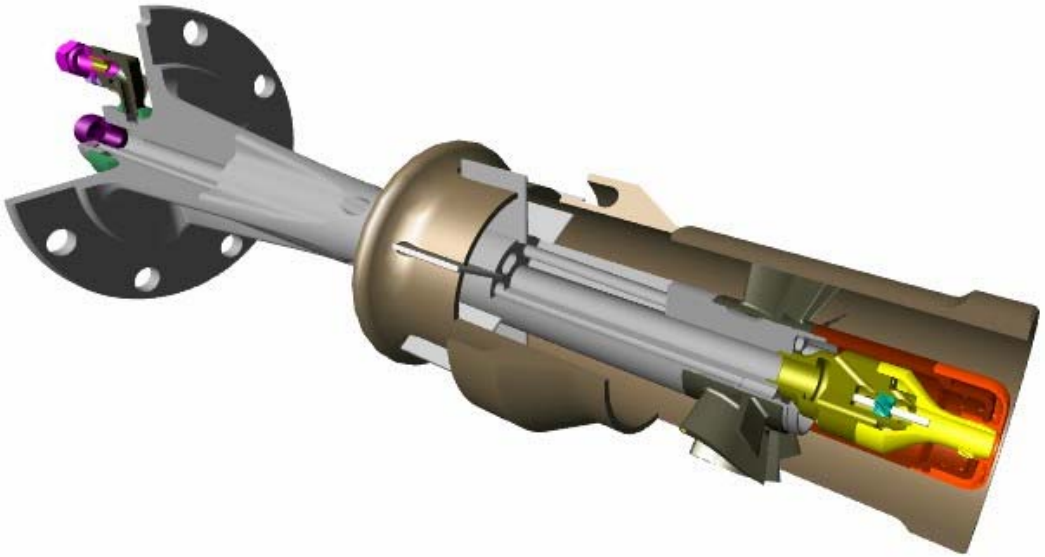
- High thermal resistance TBC systems
  - Thicker TBC systems
  - TBC systems with lower thermal conductivity
- High-temperature superalloys
  - Y_2O_3 oxide dispersion-strengthened (ODS)
- Continuous fiber-reinforced ceramic-matrix composite (CFCC)
  - environmental barrier coating (EBC)
  - Lower cost ceramic fibers



Technology Development

Improved Injector Tip Durability

- Monolithic ceramic, silicon nitride (Si_3N_4)
- High-temperature superalloy
  - Y_2O_3 oxide dispersion-strengthened (ODS)



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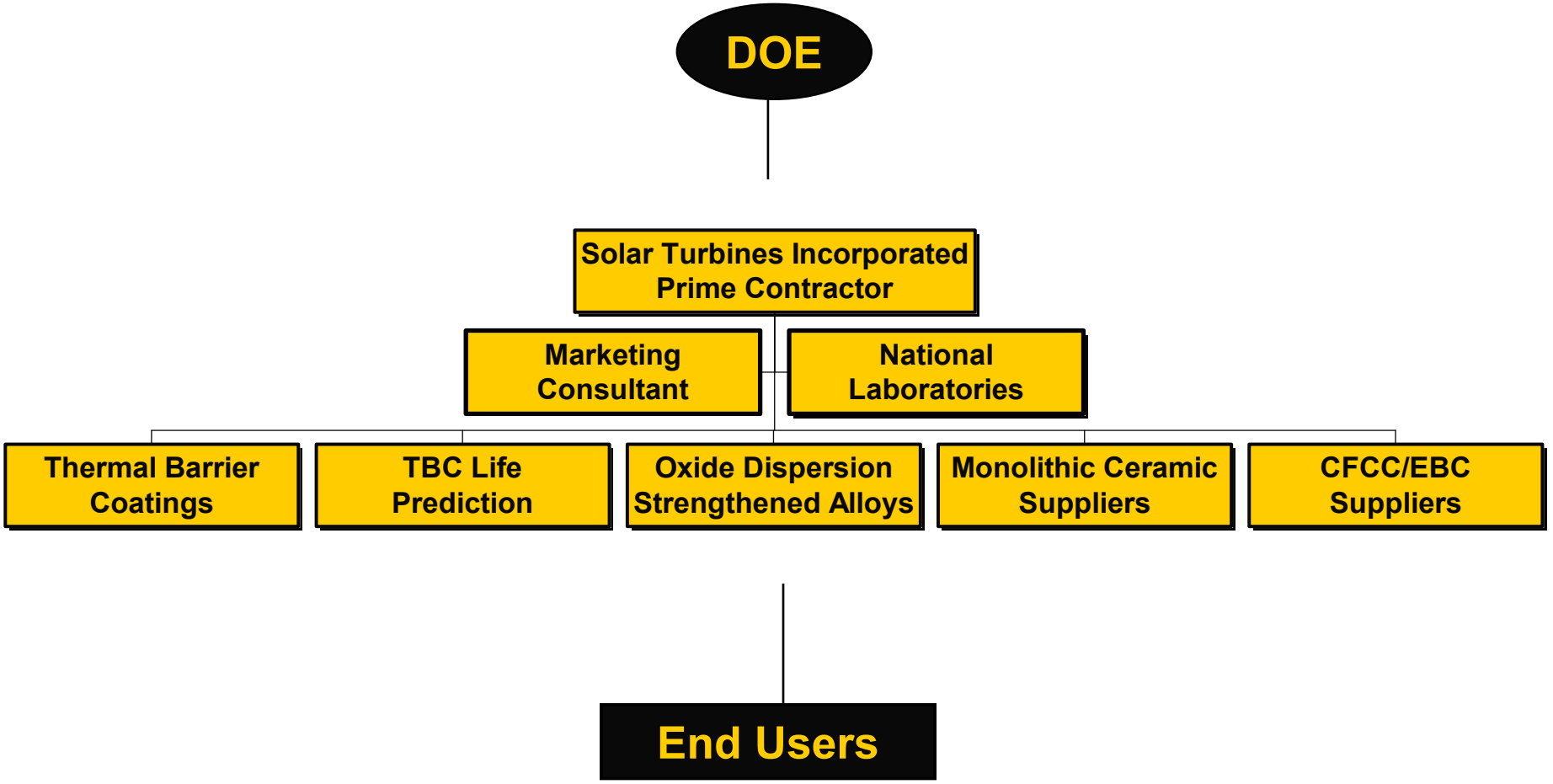
Program Team



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Program Team

- **Marketing Consultant**
  - Onsite Energy
- **Thermal Barrier Coating Suppliers**
  - Solar Turbines Incorporated
  - United Technologies Research Center
  - University of Connecticut
  - Praxair Surface Technologies, Inc.
  - The Welding Institute
- **TBC Life Prediction**
  - Research Applications, Inc.
- **Oxide Dispersion Strengthened Alloys**
  - Schwarzkopf Technologies Corporation
  - Special Metals Incorporated

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Program Team

- **CFCC Liner Suppliers**
  - Goodrich Corporation
  - GE Power Systems Composites
- **Environmental Barrier Coatings**
  - United Technologies Research Center
- **Monolithic Ceramic Suppliers**
  - Honeywell Ceramic Components
  - Kyocera Industrial Ceramics Corporation
- **Materials Characterization**
  - Oak Ridge National Laboratory
- **Nondestructive Evaluation**
  - Argonne National Laboratory

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End Users

Clemson University

Malden Mills Industries

Chevron/Texaco

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Combustor Thermal Barrier Coatin

Solar Baseline Thermal Barrier Coating

- 0.025” Yttria-Stabilized Zirconia top coating
- 0.005” MCrAlY bond coating
- Thermal conductivity
  - 1.0 $Wm^{-1}K^{-1}$
- 18,000 hours predicted liner life

Increased predicted liner life to over 30,000 hours through advanced TBCs

<u>High Thermal Resistance TBC’s</u>: Improved Temperature Drop by Lowering TBC Conductivity (~0.5 $Wm^{-1}K^{-1}$) and/or Increasing TBC Coating Thickness (~0.040” thick)

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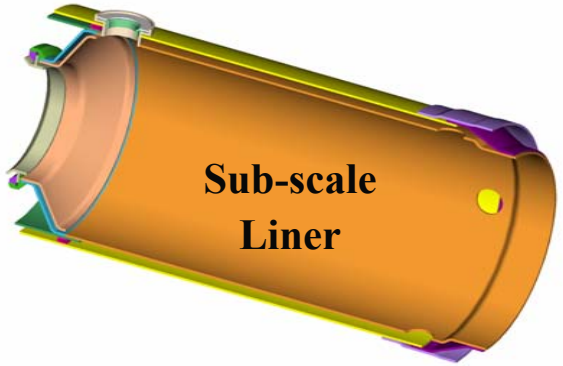
Advanced TBC Development

- Various TBC Coating Systems Evaluated through Cyclic Furnace Testing
  - Solar Baseline 0.025” YSZ TBC
  - Multiple Solar Deposited YSZ TBCs
  - Solar Advanced 0.040” YSZ TBC
  - Praxair 0.040” YSZ TBC
  - United Technologies 0.040” YSZ TBC
  - United Technologies 0.020” YSZ TBC (low thermal conductivity system)



- Six sub-scale liners have been coated for single injector rig testing
  - Each liner contains Solar Baseline, Advanced TBC, uncoated section
  - Modifications to the rig to prevent leakage have delayed testing
- Solar Advanced 0.040” YSZ TBC selected for early engine demonstation
  - Full scale combustor coated for testing at Solar
- Cost Reduction: Parameters have been developed for coating an assembled liner (Inner liner, outer liner and dome) with a six-axis robot

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Advanced TBC Development

- University of Connecticut
  - Initial development activities funded under the Advanced Gas Turbine Systems Research (AGTSR) program out of the South Carolina Institute for Energy Studies (SCIES)
  - 2 TBC systems down-selected for further development under the Advanced Materials Program
    - Slurry sprayed nano-structured YSZ TBC system
      - specimens with Solar bond coat sent to UCONN for application
    - Low thermal conductivity TBC, Gadolinium-modified Zirconia
      - Plasma spray sized powder sent to Solar for application
  - Coated Specimens will be thermally cycled at Solar and compared with previously tested TBC systems. Based on the results of cycling, sub-scale liners will be coated for further testing.
- The Welding Institute (TWI)
  - Solar is evaluating TWI's thick (up to 0.160") Barrikade thermal barrier material. Specimens using two attachment concepts are scheduled for delivery in March.

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ODS Alloy Development

High Temperature Superalloys, Ytrria Oxide Dispersion Strengthened (ODS) alloys

- Fuel Injector Tips
- Combustor liners

Sheet and bar stock received from both Schwarzkopf and Special Metals for mechanical and environmental testing

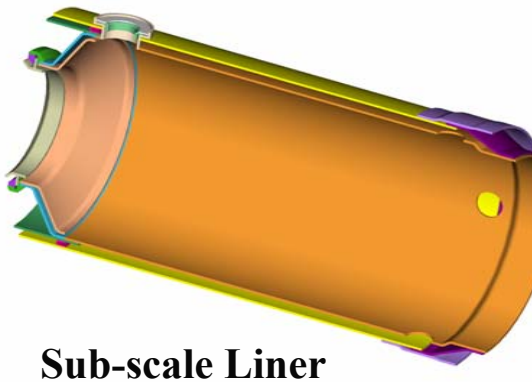
Significant drop in strength from welding

- must develop joining methods for injectors and liners

Various braze alloys are being evaluate to join ODS to ODS, and ODS to Haynes 230

- down-selected to three promising braze materials which are being further evaluated
- injector tips and sub-scale liners will be fabricated following selection of the best attachment method

Mercury 50 Fuel Injector Tip



Sub-scale Liner

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Ceramic Injector Tip

- Potential Advantages
  - Higher Firing Temperature Capability
  - Better Flame Stability
  - Lower Emissions
  - Cheaper to Manufacture

Centaur 50S Ceramic Injector Tip

- Attachment Concepts developed and tested under the DOE sponsored Ceramic Stationary Gas Turbine Program
- Problem: Silicon Nitride tips oxidize in gas turbine environment
  - Solar Nozzle Testing
  - Rolls-Royce Allison Nozzle Testing
  - Solar Injector Tip Testing
- EBC needed for long term durability
- Detailed design of Mercury 50 Ceramic Injector tip deferred until coating system further developed

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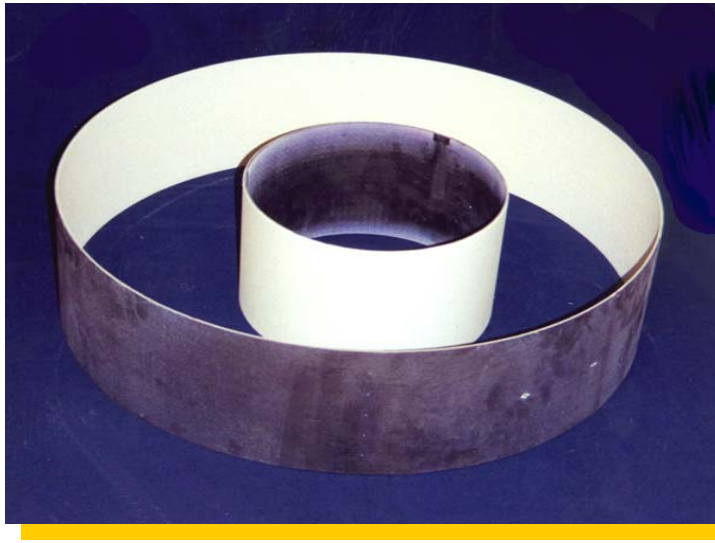
CFCC Liner Development

CFCC Inner Liner for Mercury 50

- Innovative Attachment Concepts are being developed by Solar, Agilis Group, and Goodrich Corporation
  - Attachments used in the CSGT program do not allow adequate sealing to obtain single digit emissions
- Preliminary Design Review was held in February 2002
- Detailed design and stress analysis underway

CFCC Durability Testing in Centaur 50S

- Continuation of Long term durability testing of CFCC/EBC liners initiated under the CSGT program



CFCC Liner with Environmental Barrier Coatin

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CSGT/Advanced Materials Field Testing of CFCC Liners

8 Field Installations - 2 sites

- More than 40,000 Total Hrs of Full-Load Field Operation - 13,937 Hours on One Set of Liners Coated with an EBC
- Chevron/Texaco, Bakersfield, California
  - over 3000 hrs on refurbished liners previously tested for 7238 hrs
- Malden Mills Industries, Lawrence, Massachusetts
  - over 12,000 hrs on current test of lower cost Tyranno fiber CFCC liner
- Reduced Emissions:
  - < 15 ppmv NOx
  - < 10 ppmv CO

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Program Accomplishments
Mercury 50 Combustor Durability

- Down-selected Solar 0.040” advanced TBC for first engine test
- Increased predicted liner life from 18,000 to over 30,000 hours through advanced TBCs
- Six sub-scale liners have been coated for single injector rig testing
- Initiated braze suitability studies on four ODS materials
  - down-selected braze alloys: ODS-ODS; ODS - Haynes 230
  - initiated mechanical testing for joint strength
- Deferred development of monolithic ceramic
  - pending development of EBC or alternate material
- Submitted Topical Report: Market Assessment
- Completed Conceptual Design Review for Mercury 50 CFCC inner liner attachment scheme

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Program Accomplishmen
CFCC Durability Testin

- SiC/SiC CFCC Liners Have Been Tested for over 40,000 Hours in Field Testing at the Texaco and Malden Mills Sites
- 13,937 Hours on One Set of Liners Coated with an EBC
- Over 3000 hrs on refurbished liners previously tested for 7238 hrs
- Over 12,000 hrs on current test of lower cost Tyranno fiber CFCC liner
- SiC/SiC CFCC Liners Have Reduced Emissions of NOx to <15 ppmv and CO to <10 ppmv in Engine Testing at Chevron/Texaco and Malden Mills

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Challenges/Problem Areas

- Sub-scale Liner Test Rig Leak at Aft end
- ODS Alloy Attachment Concepts
- Engine Availability for 1000+ hr test of advanced 0.040” YSZ TBC
- Ceramic Injector Tip: Silicon Nitride Oxidation in Gas Turbine Environment - requires EBC
- CFCC Liner Attachment for Mercury 50
- Field Demonstration Location? Clemson currently run Mercury 50 only 12 hours per month
- Crack in CFCC Liner with Tyranno Fiber at Malden Mills

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Future Program Plans

- TBC Development
  - Continue Cyclic Testing of Promising TBC systems
  - Conduct Sub-scale Liner Test of down-selected TBC Systems
  - Start 1000+ hr engine demonstration of advanced 0.040” YSZ TBC
  - Down-select TBC system(s) for 4000 hr Field Demonstration
- ODS Alloy Development
  - Complete mechanical and environmental testing
  - Identify joining methods for liners and injector tips
  - Conduct Sub-scale Test of ODS Liner
  - Conduct Test of ODS Injector tip

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Future Program Plans

Complete Mercury 50 CFCC Liner Attachment Design

Continue Field Durability Testing of CFCC Liners/EBC in Centaur 50S Engine

- **Texaco: refurbished liners**
- **Malden Mills: Lower Cost Tyranno MI liners**

Confirm Field Test Site for Final 4000 hr Engine Demonstration

Down-select most promising advanced materials technologies for Mercury 50 field demonstration

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Leverage of Funds/Collaboration

- DOE Advanced Turbine Systems Program
- DOE Ceramic Stationary Gas Turbine Program
- DOE Continuous Fiber Ceramic-Matrix Composite Program
- South Carolina Institute for Energy Studies - AGTSR Programs
- NASA Enabling Propulsion Materials Program
- United Technologies Research Center
- National Laboratory Support: Oak Ridge and Argonne National Laboratories
- Subcontractor Cost Share - Goodrich Corporation
- End User Contribution - Cost Share of Natural Gas
  - Chevron/Texaco, Malden Mills, Clemson University
- DOE Support:
  - Chicago Operations Office: Steve Waslo, Jill Jonkouski
  - Office of Power Technologies: Pat Hoffman, Debbie Haught, Merrill Smith