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Ceramic Stationary Gas Turbine Development Program

Jeffrey R. Price

Program Manager

VP19990487-001

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Overview

- Project Description
- Ceramic Component Development
- Field Testing
- Summary

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Project Description

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Ceramic Stationary Gas Turbine (CSGT) Program

- **Program Sponsor**
  - U.S. Department of Energy (DOE)
  - Office of Industrial Technology, Washington, DC
  - Program Manager - Patricia Hoffman
- **DOE Project Management**
  - DOE Chicago Operations Office, Argonne, IL
  - Project Manager, Stephen Waslo

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Program Objectives and Approach

- **Improve Stationary Gas Turbine Performance in Cogeneration through Selective Replacement of Cooled Metallic Hot Section Components with Uncooled Ceramic Parts**
- **Retrofit Industrial Gas Turbine Engine - Centaur 50S**
  - **1st-Stage Ceramic Blades**
  - **1st-Stage Ceramic Nozzles**
  - **Ceramic Combustor Liners**

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Program Objectives and Approach

- **Increase TRIT: 1010°C → 1121°C (1850°F → 2050°F)**
  - **Improve Thermal Efficiency: 29.6% → 31.3%**
  - **Increase Output Power: 4 → 5 MW**
- **Reduce Gas Turbine Emissions**
  - **Demonstrate < 25 ppmv NOx**
  - **Potential < 10 ppmv NOx**
  - **Potential < 25 ppmv CO**

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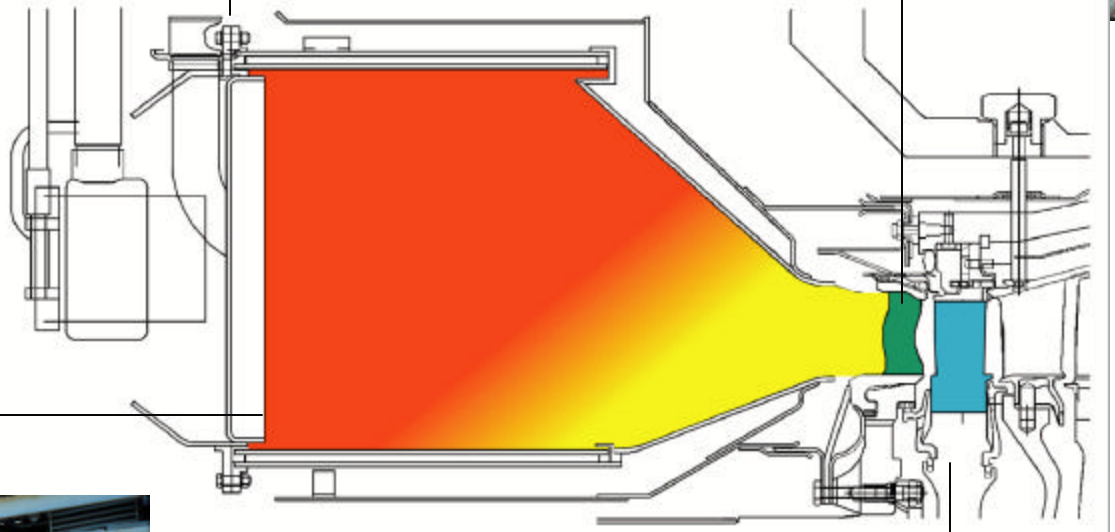
CSGT Ceramic Retrofit

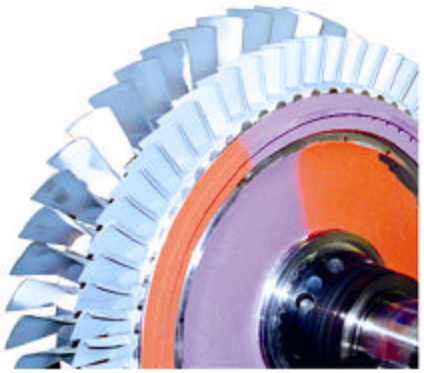
Combustor with
Ceramic Liners

Ceramic
Nozzle



Centaur 50S Engine
at Texaco Site

Disk with
Ceramic Blades



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CSGT Program Team

Prime Contractor	Solar Turbines Incorporated
Monolithic Ceramic Materials	
AS-800 Silicon Nitride	AlliedSignal Ceramic Components
SN-281/SN-282 Silicon Nitride	Kyocera Industrial Ceramics Corp.
CFCC Combustor Liner Materials	
SiC/SiC Composites	AlliedSignal Composites, Inc.
SiC/SiC Composites	BFGoodrich Aerospace
Environmental Barrier Coatings	Pratt & Whitney
Nondestructive Evaluation	Argonne National Laboratory
	Caterpillar Technical Center
Materials Testing Support	Oak Ridge National Laboratory
	University of Dayton Research Institute
Cogeneration End User	Texaco (Formerly ARCO Western Energy)
	Malden Mills Industries

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Ceramic Component Development

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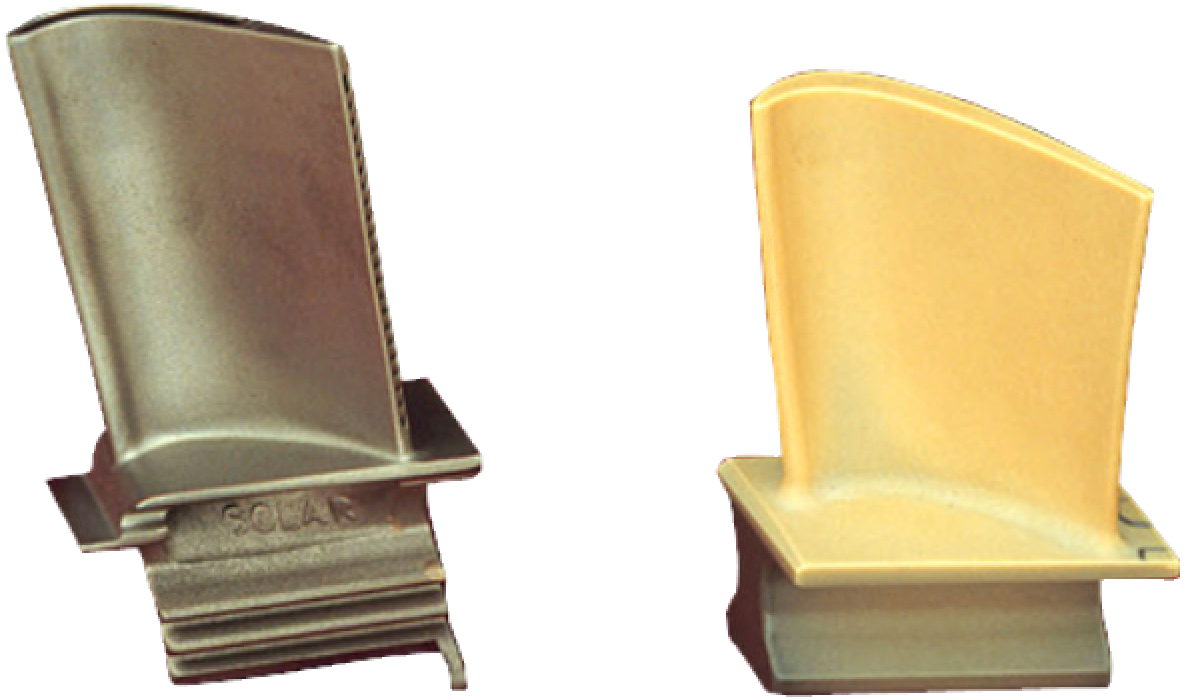
Metallic and AS-800 Ceramic Blades



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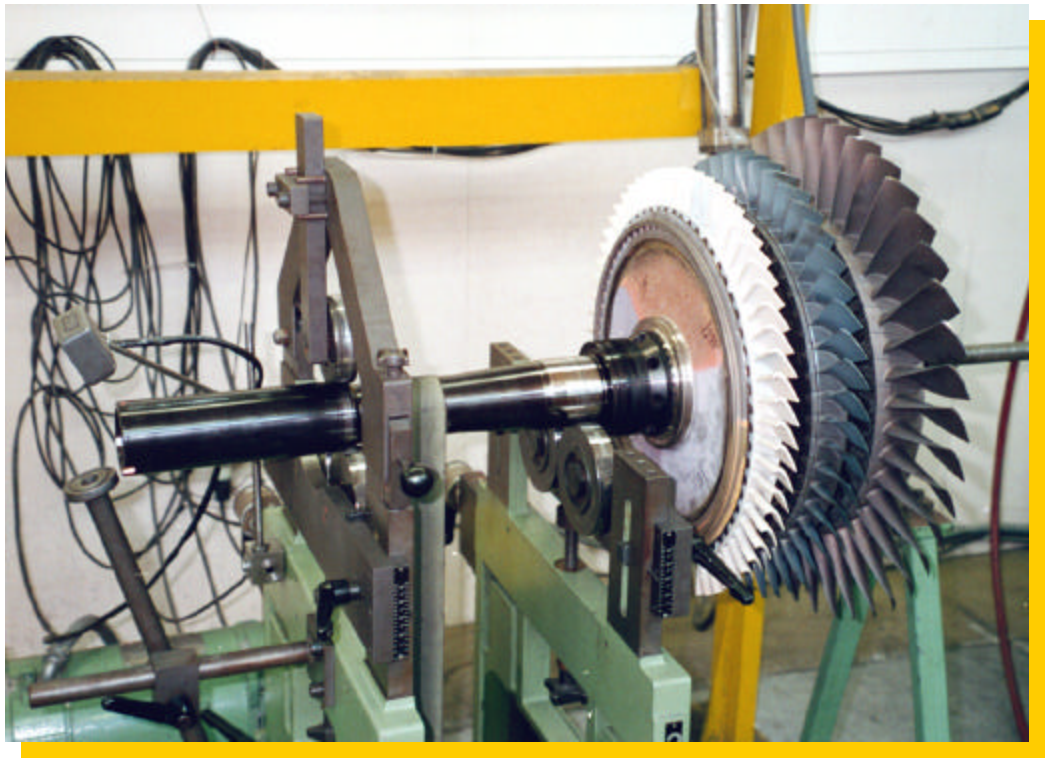
Ceramic Blade Testing

Two Field Installations at Texaco

- May 1997, AS-800 Blades
  - Terminated after 948 Hours
  - Foreign Object Damage
- May 1998, AS-800 Blades
  - Terminated after 352 Hours
  - Foreign Object Damage



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Ceramic Blade Development Issues

- **Improve Impact Resistance of Ceramic Blade Materials**
  - Conduct Impact Study
  - Improve Material Properties
  - Energy Absorbing Coatings
  - More Robust Airfoil Designs
- **Evaluate Alternate Attachments**
  - More Robust Attachments
  - Non-Compliant Layer Designs

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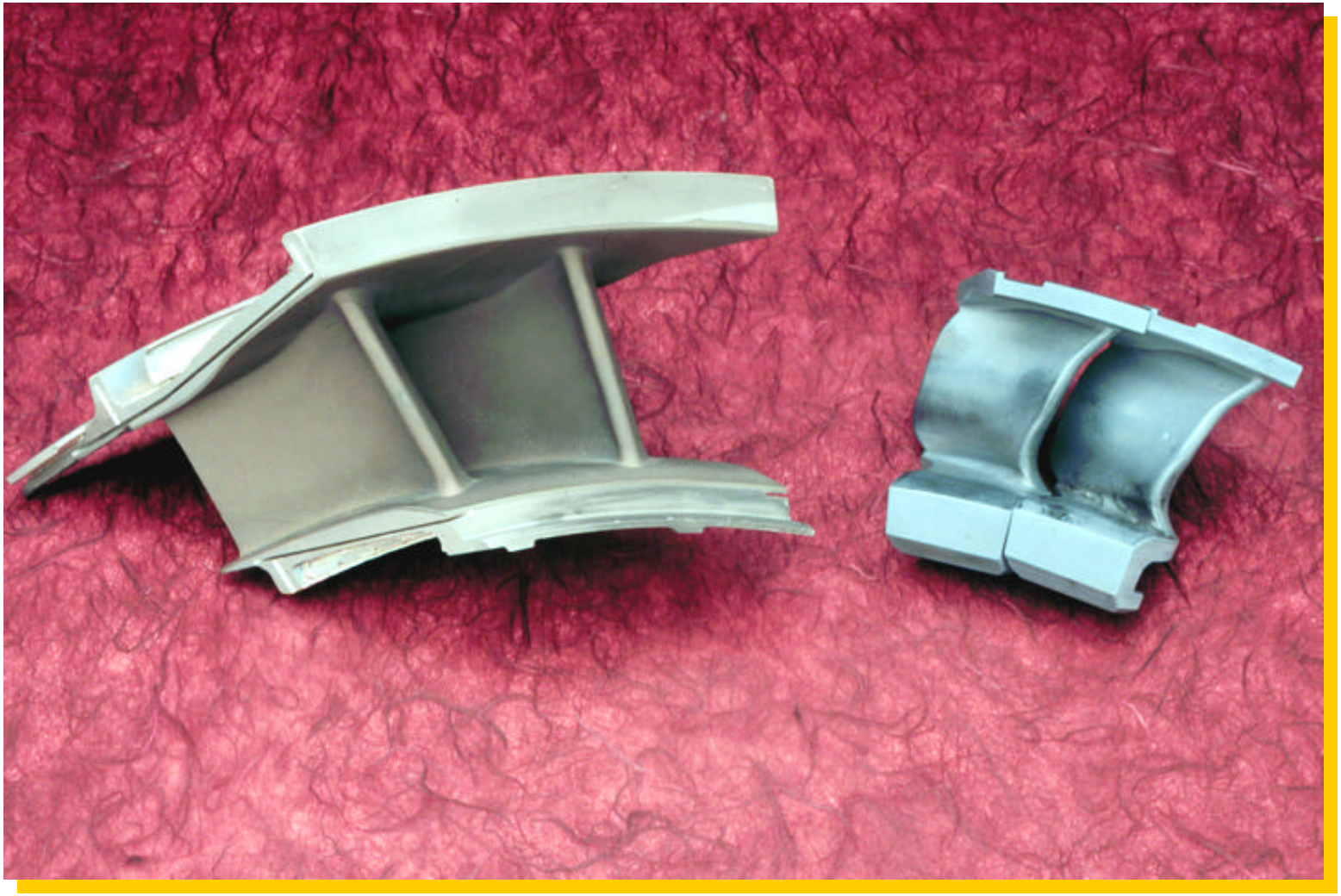
Cooled Metallic and Uncooled Ceramic Nozzles



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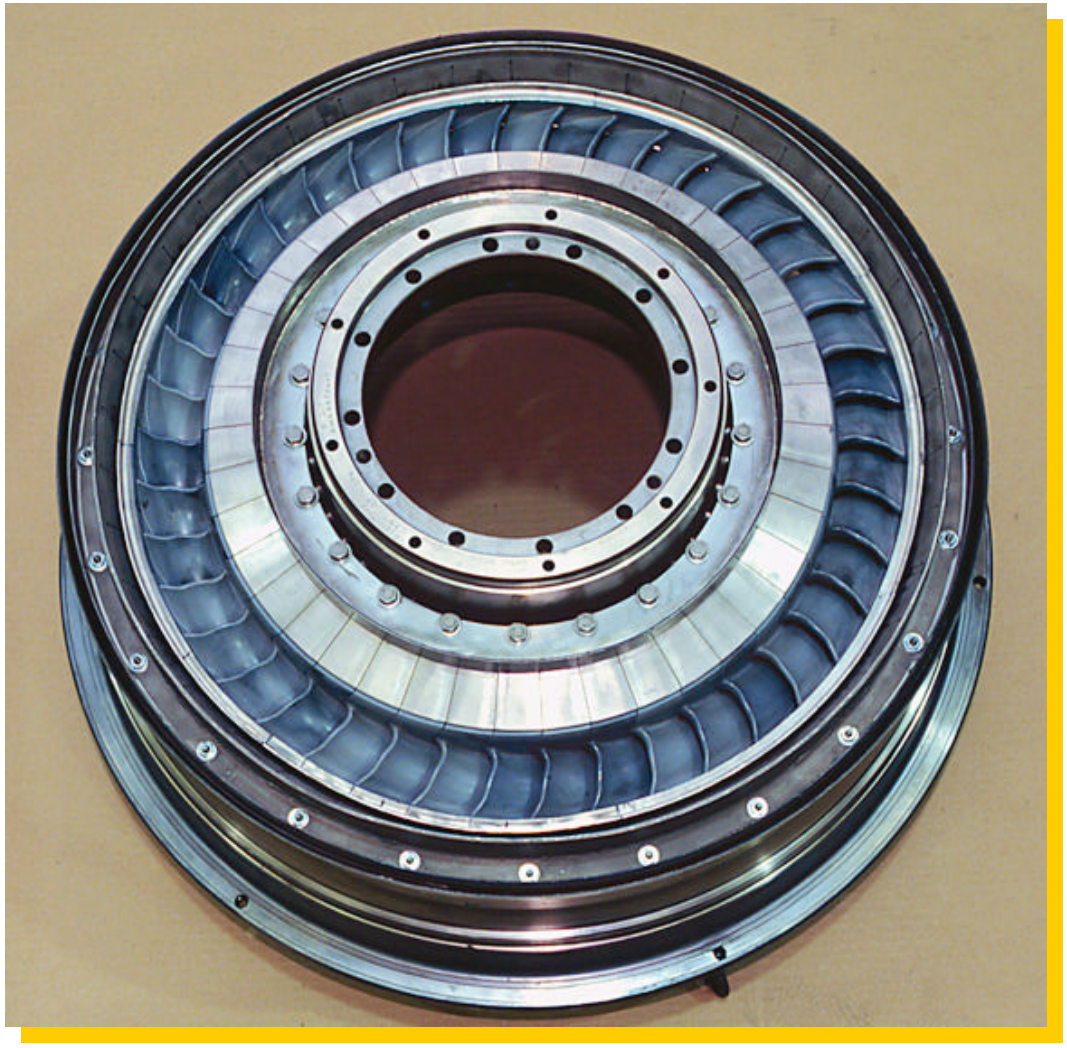
SN-88 Silicon Nitride Nozzle Assembly



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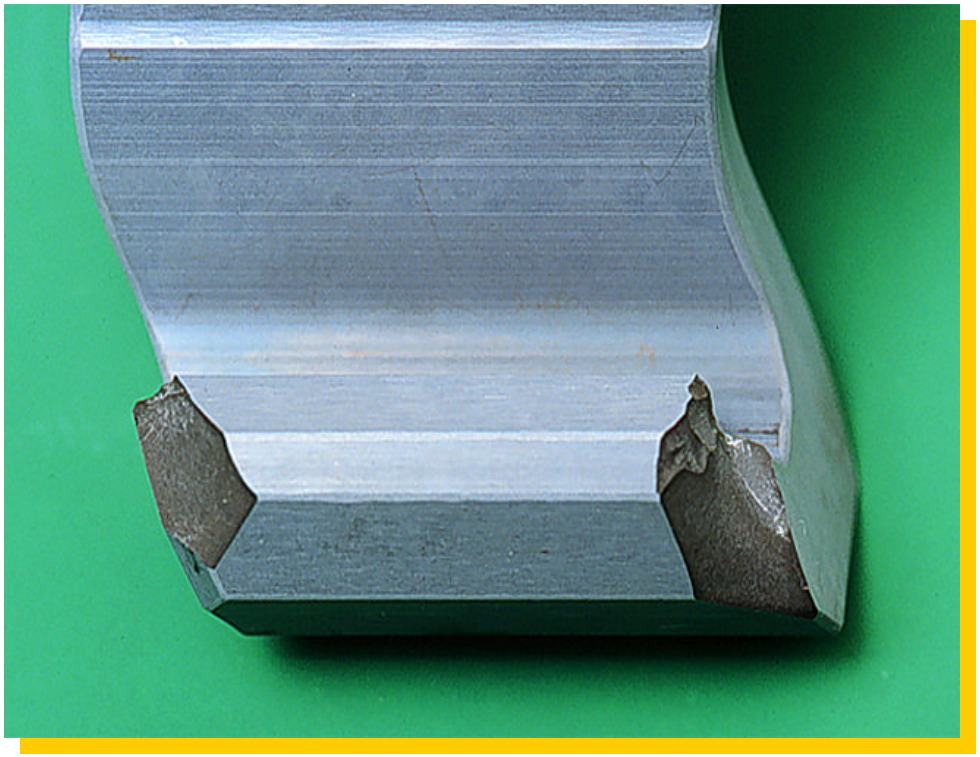
Ceramic Nozzle Testing

Initial Design Validation

- Short-Term Engine Test - 1 Hr at Full Load
- No-Load Idle, 50% Load, 100% Load
- Nozzle Airfoil Performed Well
- Chipping in Nozzle Attachment and Outer Shroud Area



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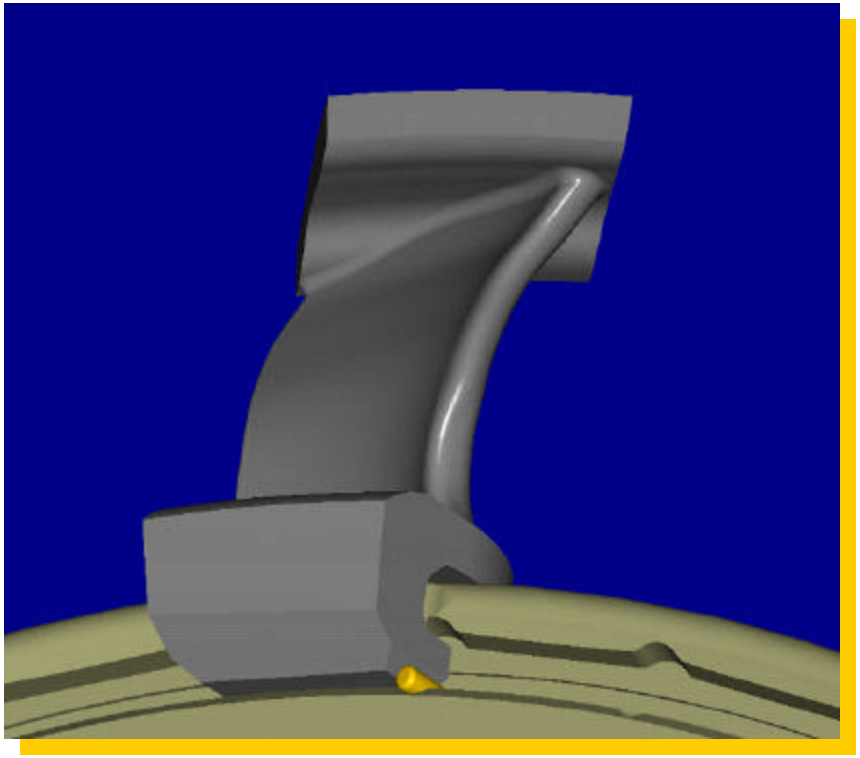
Ceramic Nozzle Testing

Further Design Validation

- 2nd Short-Term Engine Test - 1 Hr at Full Load
- Design Modifications to Attachment Structure
- Chipping Was Eliminated during Second Test
- 100-Hr Cyclic Engine Test



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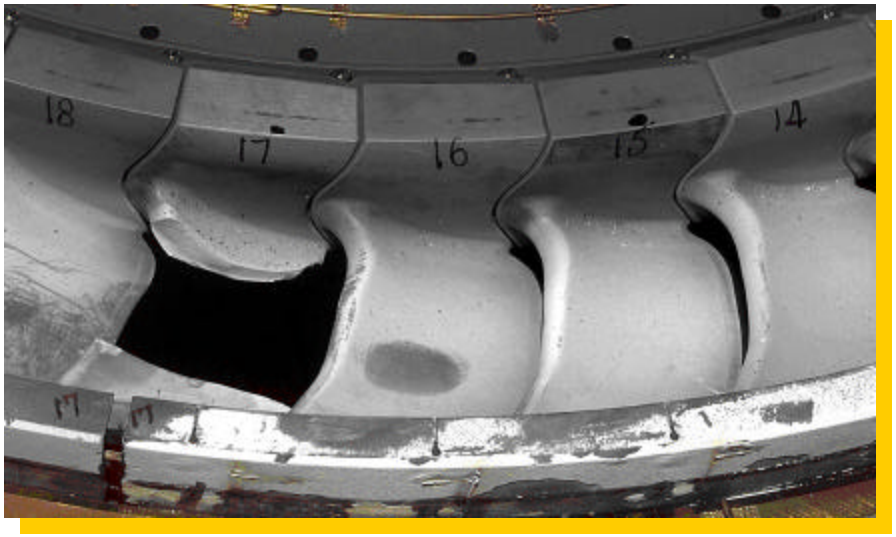
Some Nozzles Cracked in 68-Hr Engine Test

- Nine of 11 Nozzles in 120º arc
- White Deposit on All Airfoils
- Cracks Originated From Trailing edge: 3(OD), 6 (ID), 2 (OD+ID)
- OD and ID Attachment in Good Condition



- Materials Degradation - Need Environmental Barrier Coating
- Re-evaluate Ceramic Nozzle and Attachment Structure Design

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Ceramic Nozzle Testing

Instrumented Engine Test - August 1999

- 4 Hours
- 172 Pieces of Instrumentation
  - 74 Metal Thermocouples
  - 38 Air Thermocouples
  - 60 Pressure Taps
- 11 Nozzles with Laser-Drilled Holes on Inner and Outer Shrouds
- Thermal Paint
  - Secondary Clamp Ring
  - Outer Shrouds
  - Tip Shoe Support Ring
- Data Currently Being Analyzed

Redesign Efforts in Progress

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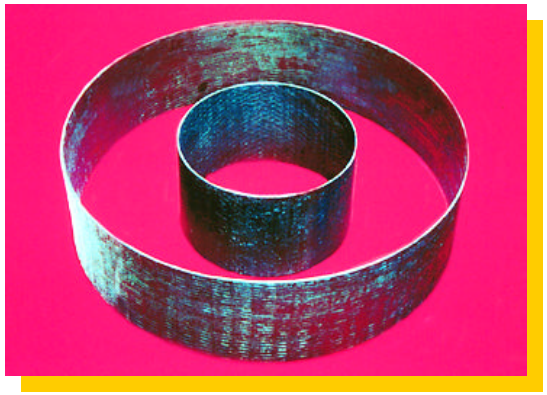
CFCC Combustor Liners

ACI 2-D Enhanced Nicalon/SiC (CVI)



BFG 3-D Nicalon/SiC (CVI)

- **Simple Design: *SoLoNOx* Retrofit**
- **ACI and BFG SiC/SiC CFCC Cylindrical Liners**
- **Hi-Nicalon / SiC CFCC**
  - **CVI**
  - **Melt Infiltration**

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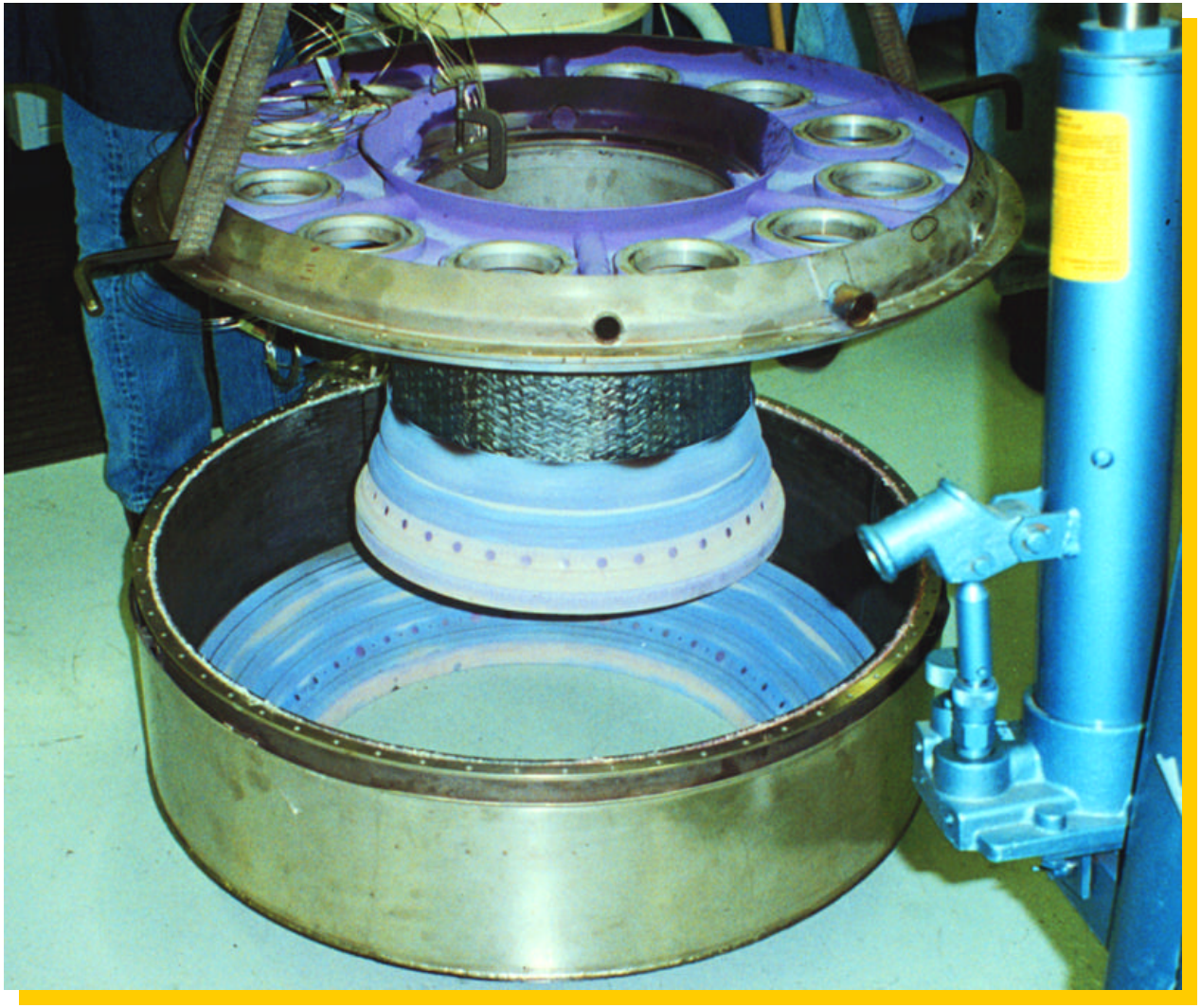
CFCC Combustor Liner Assembly



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CFCC Combustor Liner Testing

- > 400 Hr of In-House Engine Test Time
  - 100 Hr - Max. Time on Single Build
- Excellent Durability
  - NDE Inspection Before and After Tests
- Emissions
  - 50 - 100% Load Range
  - NOx < 15 ppmv
  - CO < 10 ppmv

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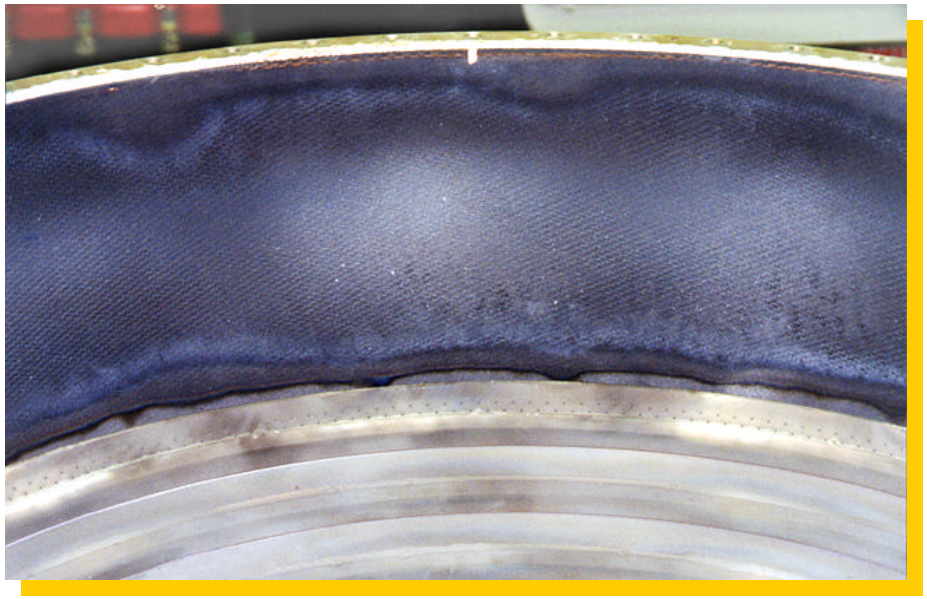
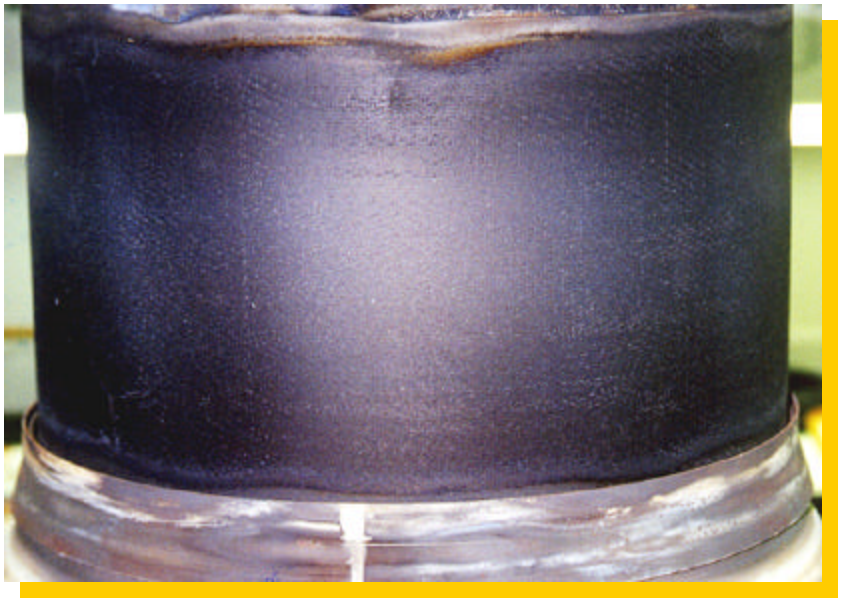
DLC Enhanced SiC/SiC CFCC Combustor Liners after 100-Hr Engine Test





Acceptable for Field Testing

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Field Testing

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Texaco Field Test Site

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CSGT Field Testing

5 Field Installations

- Texaco (Formerly ARCO Western Energy), Bakersfield, California
- Steam and Electricity Cogeneration
- Reduced Emissions
  - < 15 ppmv NOx
  - < 10 ppmv CO
- More than 10,000 Total Hours of Full-Load Field Operation

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CSGT Field Testing

- **World's First Commercial Installation**
  - **May 21, 1997**
  - **1st-Stage AS-800 Silicon Nitride Blades**
  - **Ceramic-Grade Nicalon Enhanced SiC/SiC Liners**
- **Test Terminated after 948 Hrs of Field Operation**
  - **Failure of 1st-Stage AS-800 Blades Attributed to Foreign Object Damage**

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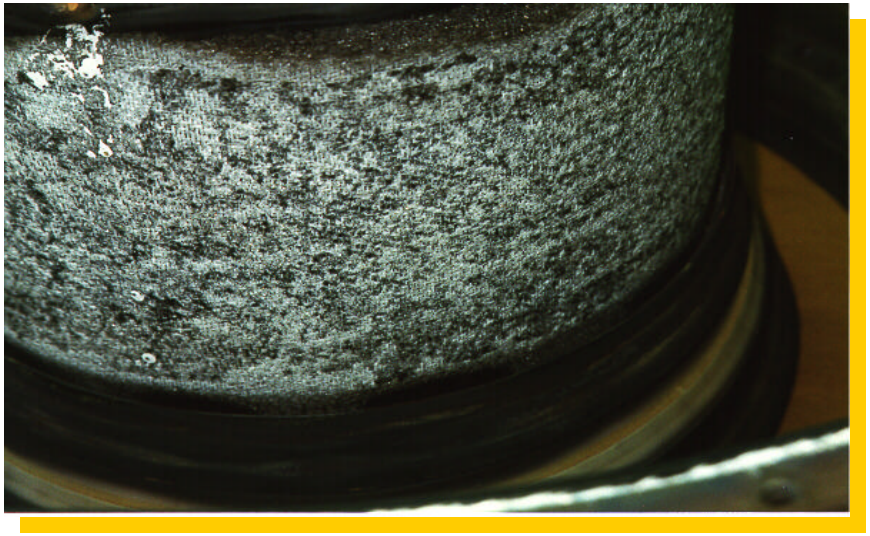
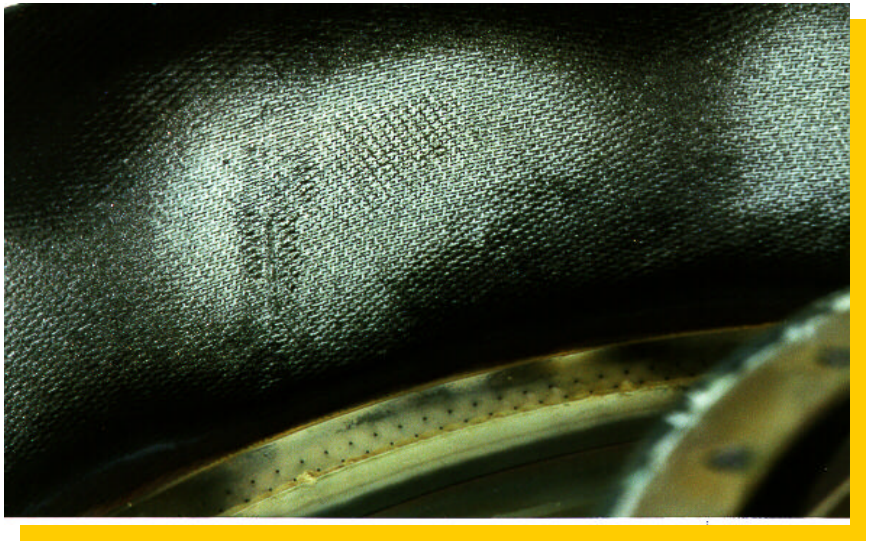
CFCC Liners after 1st Field Test





- Inner Liner Heavily Oxidized
- Localized Oxidation on Outer Liner
- No Degradation of Secondary Components
- Need for Environmental Barrier Coating and Better Heat Transfer Identified

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2nd CSGT Centaur 50S Field Test

- ARCO Western Energy - February 27, 1998
- Hi-Nicalon Enhanced SiC/SiC Combustor Liners
  - More Stable Fibers
  - Higher Density
  - Thick SiC Protective Seal Coat
- Combustor Modifications to Reduce CFCC Liner Wall Temperature
  - Maximum Temperature Measured: 2103°F
- Reduced Emissions
  - < 15 ppmv NOx, < 10 ppmv CO

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CFCC Liners after 2258-Hr Field Test

- Inner Liner Sectioned for Analysis
  - Oxidized vs Unoxidized Areas
  - Microstructure
  - Recession
  - Residual Strength
- Liner Degradation Closely Matches Exposure Testing at ORNL

- Significantly Less Oxidation than 1st Field Test
- Part Could Have Continued in Service
- Outer Liner Accepted for Additional Field Testing

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CSGT Centaur 50S Field Test

- December 1998, Start of 4th Quarter Field Installation
- Hi-Nicalon/Enhanced SiC CVI Outer Liner (ACI)

  - Reused from Field Test 3
- Hi-Nicalon/SiC MI Inner Liner (BFG)

  - New
- 4-Hrs Acceptance Test at Solar
- 2758 Hrs of Full-Load Operation
- 2758 Hrs on Inner Liner
- 5016 Cumulative Hrs on Outer Liner
- Test Stopped to Evaluate Liners on April 11, 1999

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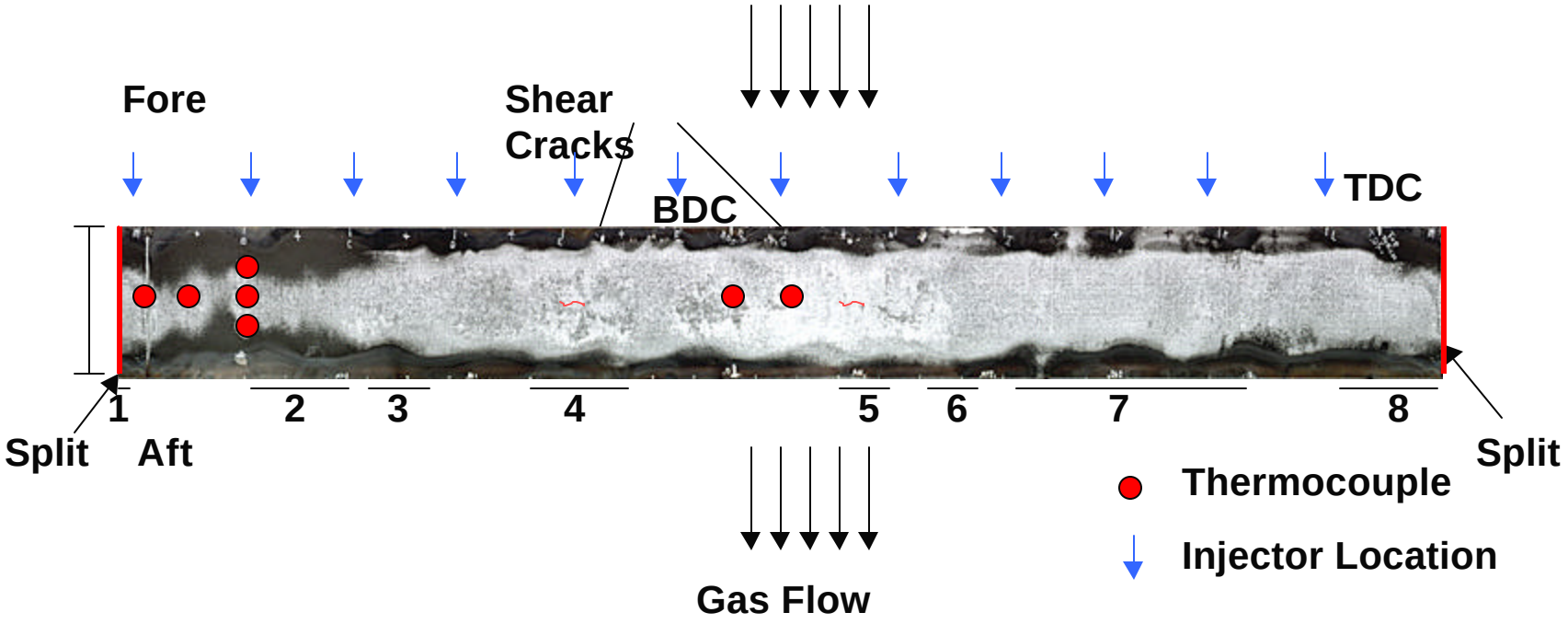
Hi-Nicalon/Enhanced SiC CVI Outer Liner

After Field Test 4 (5016 Hours on Liner)



TDC: Top Dead Center

BDC: Bottom Dead Center

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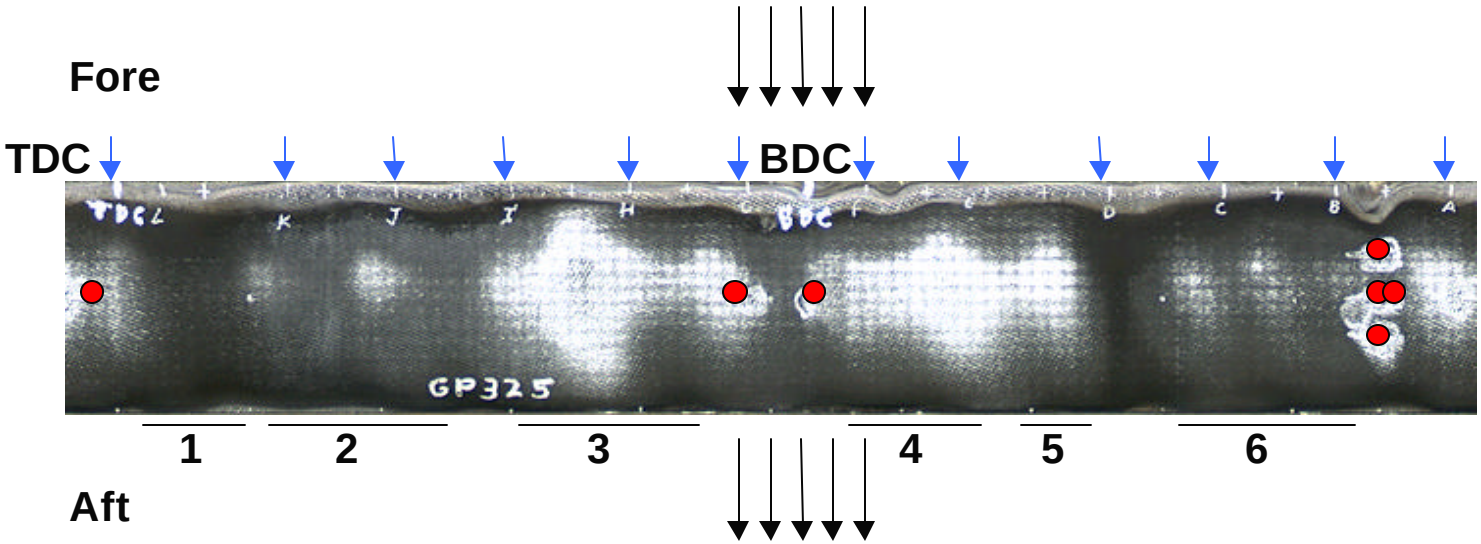
Hi-Nicalon/SiC MI Inner Liner

After Field Test 4 (2758 Hours on Liner)



- Thermocouple
- Injector Location

TDC: Top Dead Center

BDC: Bottom Dead Center

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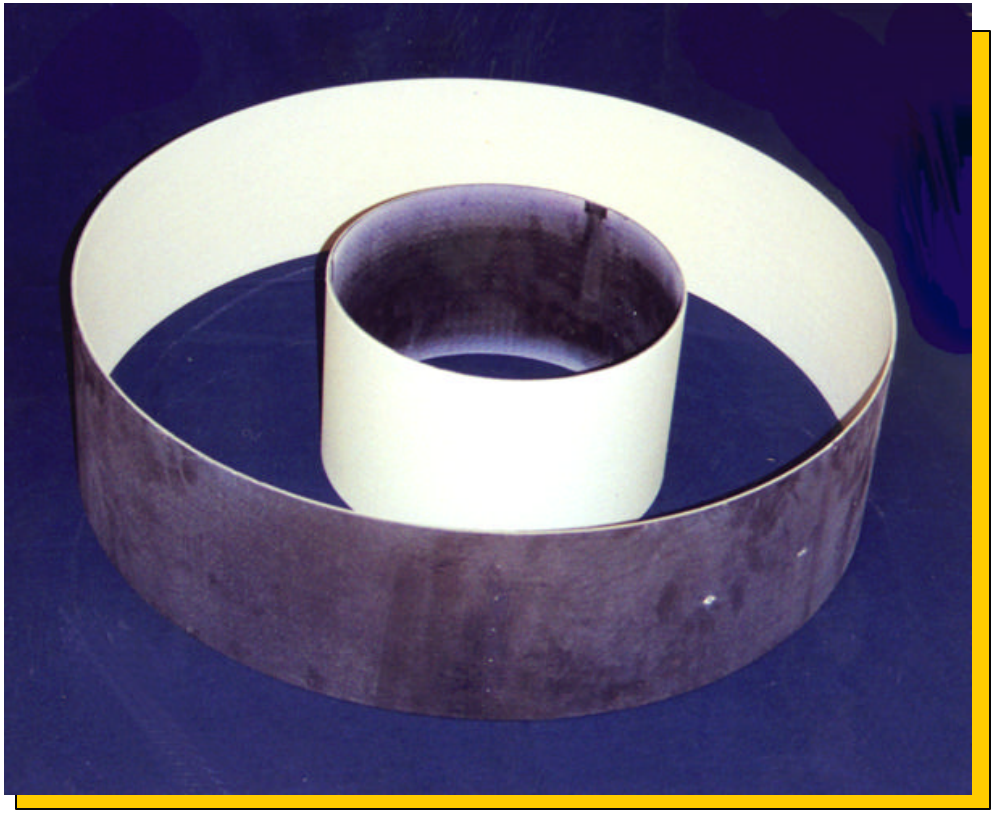
Field Test of Environmental Barrier Coatings

- Start Date - April, 1999
- Inner Liner: Ni-Nicalon/SiC MI (ACI)
- Outer Liner: Hi-Nicalon/E-SiC CVI (ACI)
- EBC: Plasma-Sprayed Oxide (P & W)
  - Optimized EBC from NASA EPM Program
- Over 4900 Hrs Field Exposure
  - 22 Starts
- Periodic Borescope Inspections



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Malden Mills Industries
Low Emissions Demonstration

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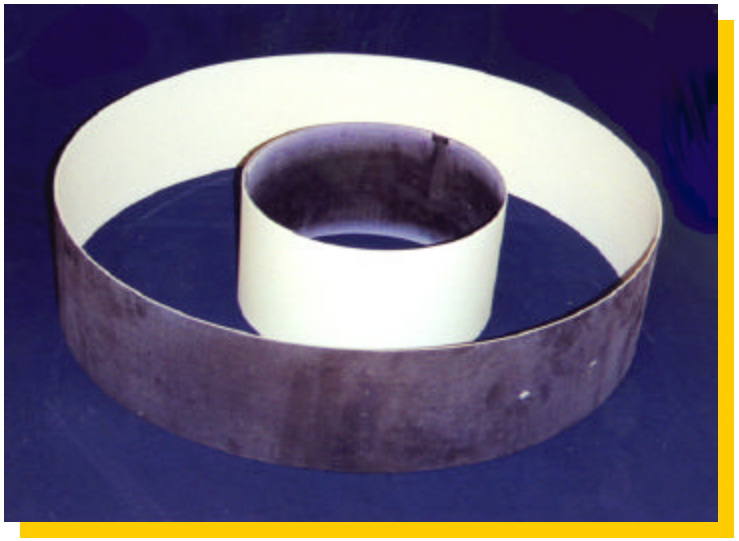
Low Emissions Combustor Demonstration

- CFCC Hot-Wall Combustor Liners with Environmental Barrier Coating
  - Inner Liner: BFGoodrich Melt-Infiltrated SiC/SiC
  - Outer Liner: AlliedSignal Composites CVI SiC/SiC
  - Environmental Barrier Coating: Plasma-Sprayed Oxide Deposited by Pratt & Whitney
- Similar Combustion System in Operation at Texaco in Bakersfield
  - Over 4900 Hours of Full-Load Operation
  - Low Emissions Demonstrated
    - NOx < 15 ppmv
    - CO < 10 ppmv



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Low Emissions Combustor Demonstration

- Acceptance Test of 1st CFCC Low Emission Centaur 50S Completed July 28 at Solar's DeSoto Facility
- Acceptance Test Emissions
  - 50 to 100% Load
    - NOx < 15 ppmv
    - CO < 10 ppmv
- Engine Shipped to Malden Mills on July 29

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Malden Mills Low Emissions Demonstration

- Two Centaur 50S Engines
- Installation of Low Emission CFCC Combustion System in 1st Engine Initiated August 9
- Full Production August 23
  - 8000-Hr Demonstration
- Emissions Requirements
  - NOx < 15 ppmv
  - CO < 10 ppmv
- Installation in 2nd Engine - July / August 2000
- Over 1200 hrs of Operation - 34 starts

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CSGT Milestones/Accomplishments

- 2758 hour Field Test Operation of BFG MI Inner Liner
  - April 1999
- 5016 hour Field Test Operation of ACI CVI Outer Liner
  - April 1999
- EBC's Developed/Optimized for CFCC Liners
  - Field Test Started in April 1999
- Malden Mills Installation Completed on Schedule
  - August 1999
- Over 1200 Hours of CFCC/EBC Operation at Malden Mills
- Over 4900 Hours of CFCC/EBC Operation at Texaco
- Instrumented Engine Test of Ceramic Nozzle Assembly
  - August 1999

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Summary of CSGT Program

- Functional Designs Have Been Completed for Monolithic Blades, Nozzles, and Combustor Liners
- Designs Have Been Demonstrated in Rig and Engine Testing
- Gas Turbine Emissions Have Been Reduced Using CFCC Combustor Liners
- Over 11,000 Hrs of Engine Testing at the Commercial Cogeneration Field Test Sites
  - Over 1300 Hrs on Ceramic Turbine Blades
  - Over 11,000 Hrs on SiC/SiC CFCC Combustor Liners
  - Over 6000 Hrs on CFCC Liners with EBCs

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Summary of CSGT Program

- Critical Materials and Design Issues Need to Be Resolved
  - Better Fracture Toughness of Monolithics
  - Combustor Liners: Environmental Resistance: EBC Coatings
  - Blades: FOD Resistance, Long Term Durability of Attachment
  - Nozzles: Attachment Durability, Material Durability, EBC Coatings
- Engine Testing Will Continue
  - Ceramic Nozzle Engine Test In-House: 100+ Hrs
  - Continued Field Testing
    - Texaco Site: EBC Coated SiC/SiC CFCC Liners
    - Two 8,000-Hr Engine Tests at Malden Mills, MA


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