

# REPORT DOCUMENTATION PAGE

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# ADVANCED CERAMICS for NAVY AIR VEHICLE APPLICATIONS

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Patuxent River, Maryland

With helpful input from D. Carper, J. Steibel, V. Barry (GE), D. Foley (Honeywell Adv Ceram), K. Hatton (HCI), J. Armstrong & F. Zupank (HES), T. Carstensen (Sikorsky), R. Williams & K. Goodman (Bell), M. Rigaldi and T. Mulligan (ACR), M. Richman, A. Young, J. Bentz, L. Parish, J. Rubinsky, W. Voorhees, J. Young, A. Penterman, R. Kowalik (NAVAIR), D. Lewis (NRL).

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*AEROMAT 2000*



Advanced/Toughened Ceramics and CMC's are Increasingly being Sought to Replace or Protect Metallic Components for Navy Air Vehicle Applications

- Ultra High Temperature Applications to meet performance goals e.g. 2400 F IHPTET combustor liners & turbine components (vanes, shrouds, airfoils).
- Intermediate Temp Applications, e.g. 1200F, IRS components
- Lighter Weight,  $\rho = 2.2, 4.4, 7.8, 8.2 \text{ g/cm}^3$  for CMC, Ti, SS, Ni
- Higher Modulus
- TPS for short duration temp spikes
- Erosion & Wear Resistance
- LO Characteristics (RF and IR signatures)



# Why Ceramics/CMCs

## Evolution of Jet Engine Technology

	<u>1942</u>	<u>Today</u>	<u>2005+</u>
Thrust/Wt.	1.6:1	9:1	15:1
Turbine Inlet Temp.(F)	1500	2800	3000+
Engine Life(Hot Sections)	7.5	2000	4000
Fuel Efficiency	base	+46%	+65%



## Why SiC/SiC\* CMC

- High temperature, low weight material for combustor, turbine, turbine frame applications
- Low coefficient of thermal expansion for seal clearance control
- Potential for longer life, reduced emissions, growth margin, reduced weight, and increased performance

**SiC/SiC CMC has significant advantages over Ni-based superalloys**

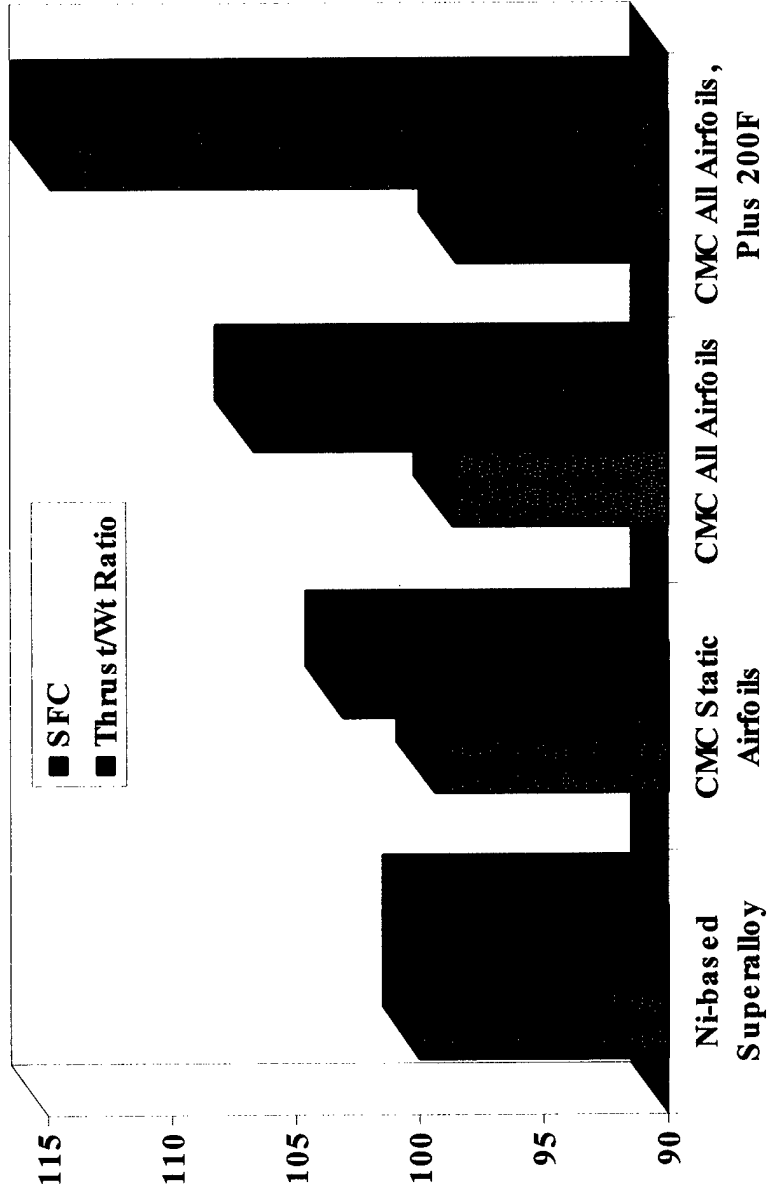
\* SiC≡Silicon Carbide

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# Why SiC/SiC CMC



**CMC has SFC and thrust/weight benefits over Ni-based superalloys**



# CMC\* vs N5 Material Property Comparison

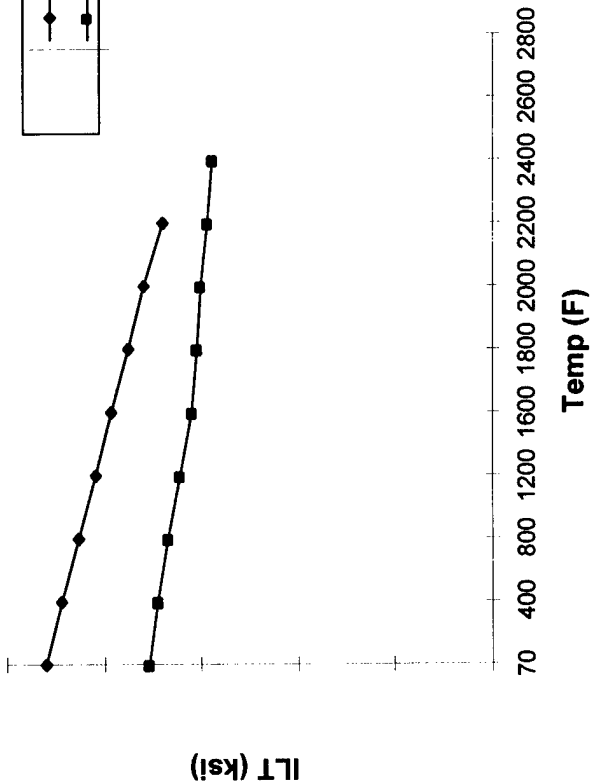
<u>Material Property</u>	<u>Ratio</u>	<u>Impact on CMC Design</u>
Density [ $\rho$ ]		<p>Lowers weight Increases response time</p>
Thermal conductivity [K]		<p>Drives thermal gradients Increases thermal stress</p>
Coefficient of thermal expansion [ $\alpha$ ]		<p>Lowers thermal stress &amp; distortion</p>
Young's modulus [E]		<p>Increases thermal stress</p>
Specific heat [Cp]		<p>Higher at lower temperatures Decreases response time</p>

\*Melt Infiltrated, Hi-Nicalon

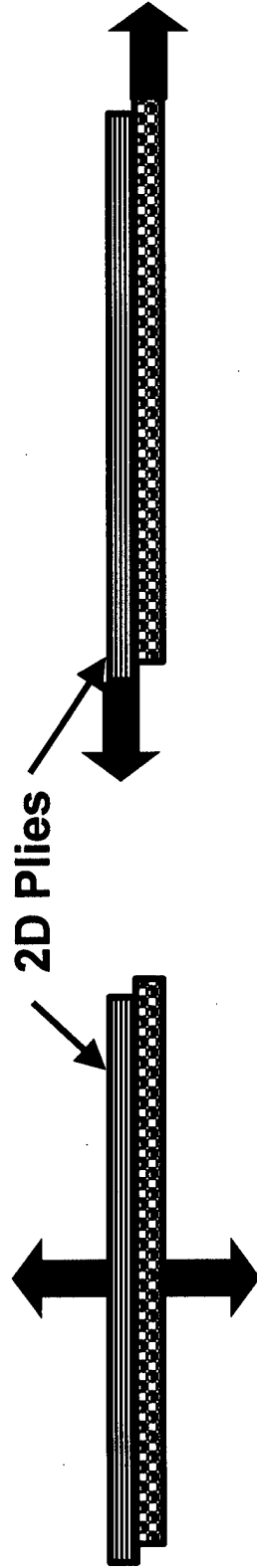
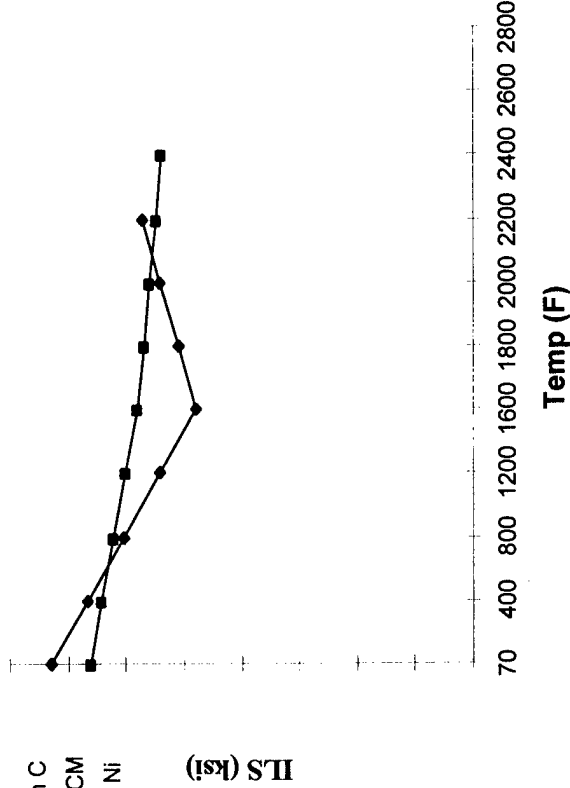


# Low Interlaminar Strength

Interlaminar Tensile Strength



Interlaminar Shear Strength



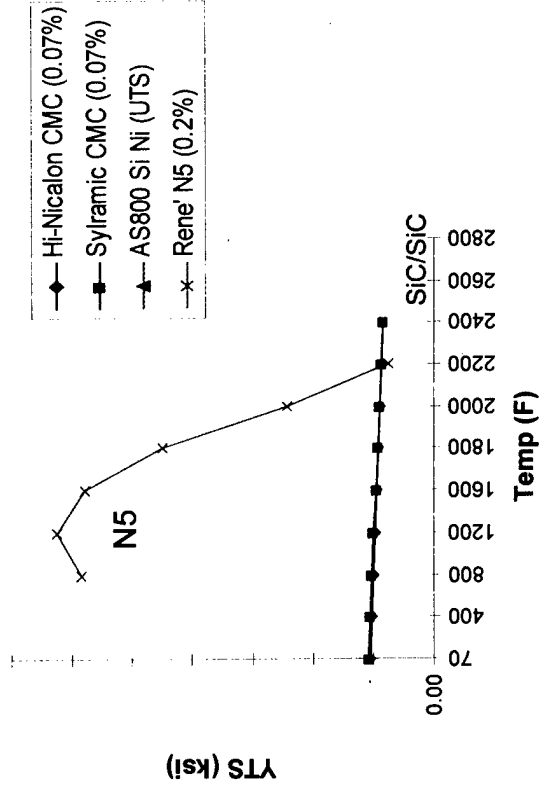
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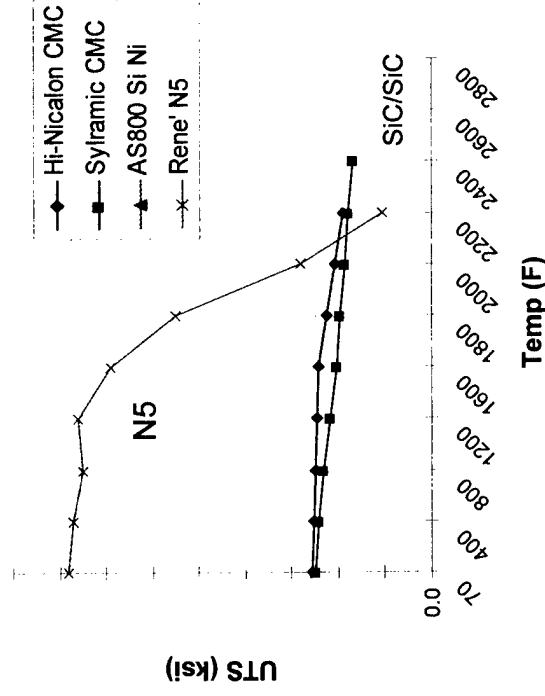


# Low Tensile Strength Challenge to Design

Yield Tensile Strength



Ultimate Tensile Strength





# CMC Programs

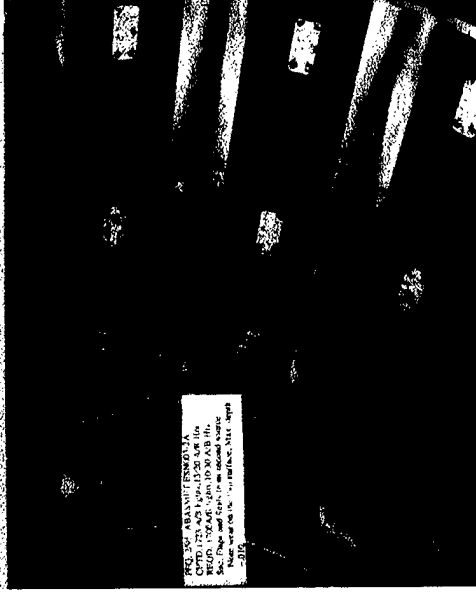
- F414 Flaps & Seals
  - Flight Program
  - MANTECH Program
  - Affordability Program
- GE23A Component Technology Development
- X-31 Vector Program
- IHTPET
  - Combustor, JTAGG III, I
  - Vanes
- H60, H1 IR Suppressor, MANTECH
- AV-8/Pegasus
  - Turbine Vane Inserts
  - Blast Shield - Flight, Repair
- F-14/F110 Flameholder Inserts
- V-22 SDC Impeller



# F414 CMC FLAPS & SEALS

Insertion Success: CMCs have enabled significant performance gains to be achieved with the F18.

- CMC System: BFG SiC/C with dual top coats
- top coats are CVI SiC and a glass frit outer coating for wear resistance and oxidation-protection.



## F18-E/F (Super Hornet)



### *Breaking The Barrier*

#### Status:

- Many components have logged over 800 hours flight time with significant A/B lights.
- Affordability/Life Cycle being addressed.
- Potential Programs to Address:
  - reduction in thermal gradients  $\Rightarrow$  cracking (flaps)
  - reduction in coating spallation  $\Rightarrow$  composite oxidation  $\Rightarrow$  component recession
  - attachment design to prevent cracking from bending,  $\Delta P$  VEN
  - improved rub wear resistance

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## AFFORDABLE SiC/C CERAMIC EXHAUST COMPONENTS



**Objective:** Reduce the cost of SiC/C flaps and seals for the F414.

- Goal is a 20% cost reduction.
- Reduced Part Dimensional Inspection (4-5% savings).
- Reduced CVD cycle time (2-3% savings).
  - eliminate second CVD cycle.
  - combine carbonization and pyrolysis - new BFG furnace.
- Lower Cost SiC fiber.
  - substitute Tyranno (\$400/lb) for Nicalon (15% savings).



**BFGoodrich**

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# F414 DIVERGENT FLAP & SEAL AFFORDABILITY PROGRAM



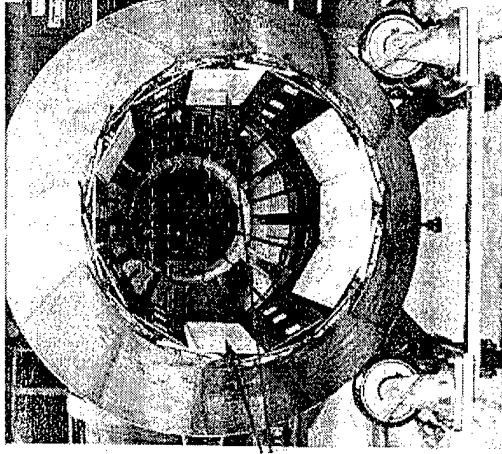
**Objective:** Qualify an alternate CMC system for the F414 flap & seal application that offers significant cost savings without a weight or life penalty.

**Background:**

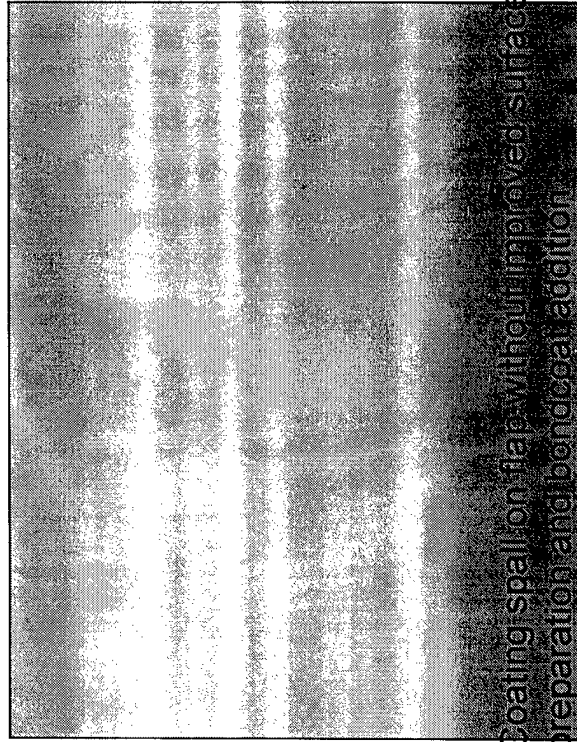
GE IR&D program has developed an O-O CMC system (N720/AS) that is a viable replacement to SiC/C.

**Benefits (O-O vrs existing SiC/C)**

- Reduced material cost (approx. 25%)
- Oxidation not an issue
- Standardized manufacturing technology



Divergent Seals



**Status:**

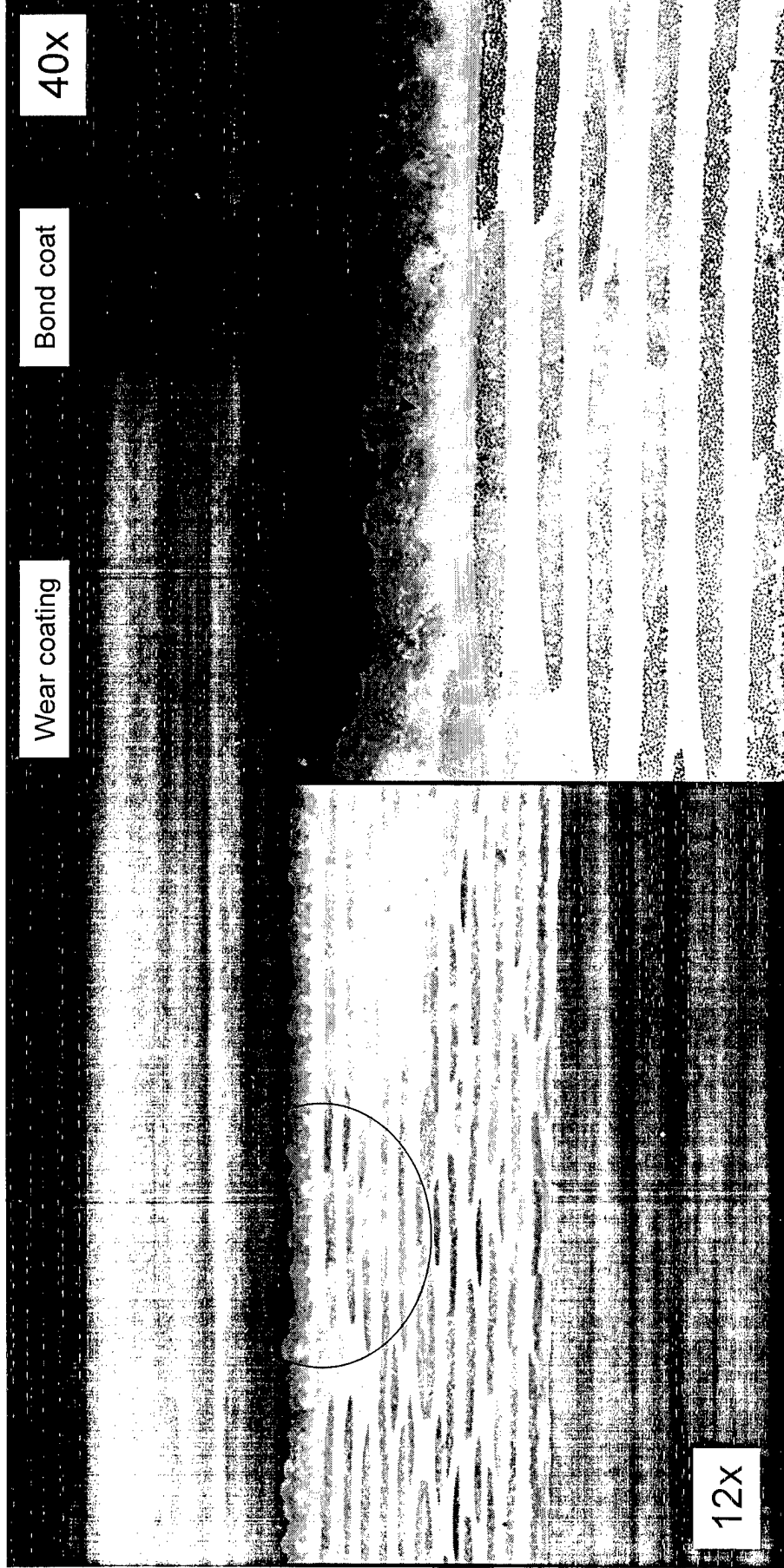
- Instrumented engine test - 85 hrs
- Wear resistant composite coating (AS)
- Production sources being identified for F&S mfg.
- Legal agreement established with Hexcel, Inc. first production lot in June, 00.
- NAVAIR- Environmental testing and qualification
- Engine Test on Vendor hardware, Apr, 01.



**GE Aircraft Engines**

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## Wear Coating Application to Oxide CMC Flap



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**Ceramic Materials**

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# VECTOR PROGRAM

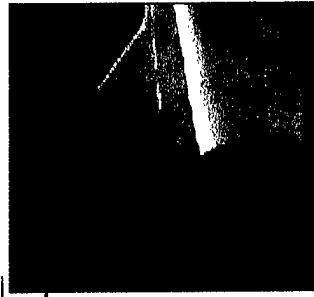


- International (GER/US) Cooperative Program**
- Follow-on to GER/US X-31 Enhanced Fighter Maneuverability (EFM) Program (1990).
  - Use the single existing X-31 Aircraft

**VECTOR Products**

- Technology Development and Demonstration of
- ESTOL - Extremely Short Take-Off and Landing
- AADS - Advanced (Flush) Air Data System

**All flight tests conducted at NAVAIR Patuxent River, MD**

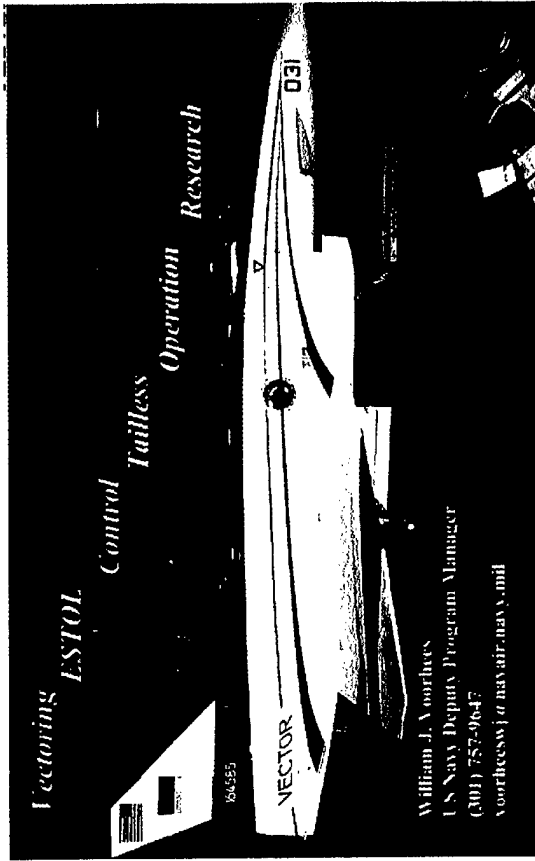


**THRUST VECTORING:**

- controlling the direction of the engine exhaust to achieve dramatic aircraft maneuvers
- Carbon/Carbon composite paddles

**ESTOL**

- Extremely Short Take-Off and Landing



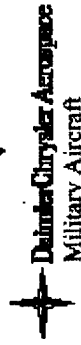
**X-31 Experimental Aircraft**

(Arrived at PAX on Apr. 13, 00)

**The VECTOR Team**



Naval Air Systems Command      Bundesamt für Wehrtechnik und Beschaffung (BWB)



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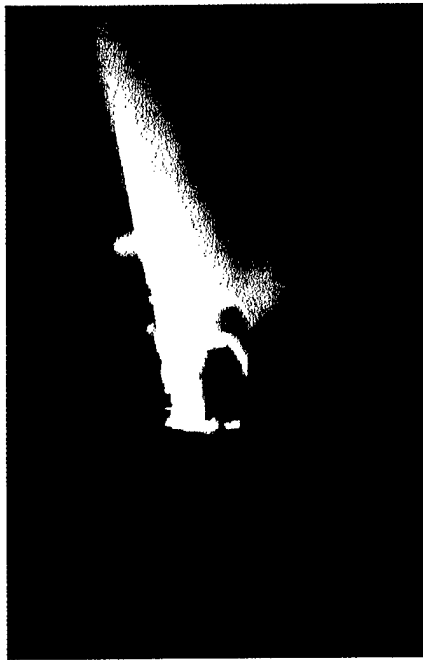


## Multi-Axis Thrust Vectoring - Key Technology for the Demonstration

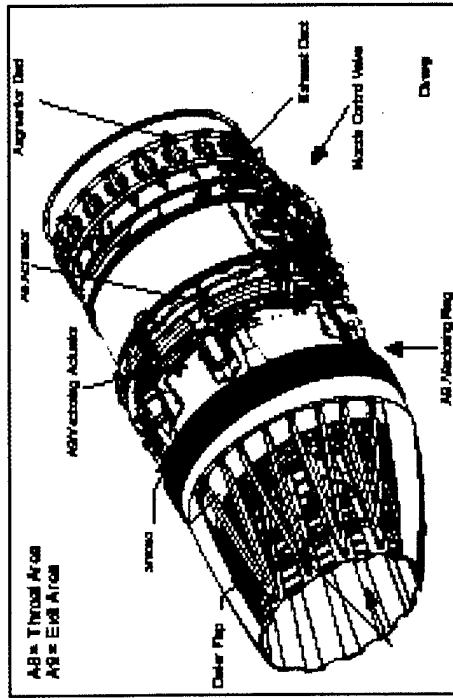


VECTOR

- Multi-axis thrust vectoring
  - Use of existing TV vane systems allows development of other technologies to proceed
  - Production nozzle not required for demos
    - » TV paddle performance is sufficient
    - » Fail-safe redundancy sufficient



Thrust Vectoring Vanes Design



G.E. AVEN@ Nozzle

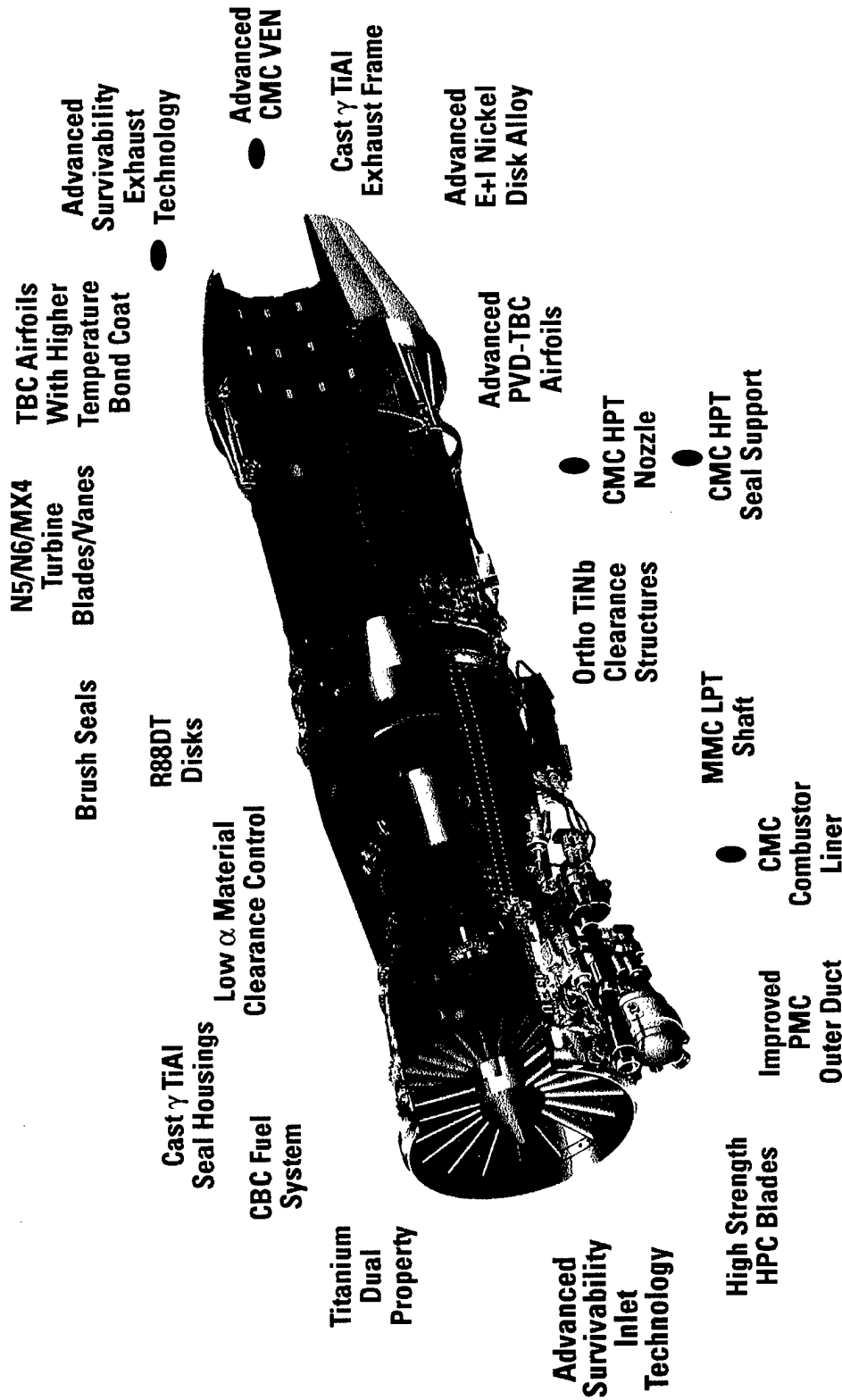
- AVEN@

- Performance representative of production systems
  - » Higher control power and rates
  - » Redundancy for full envelope fail safe
- Broader range of control authority





# GE23A - ADVANCED TECHNOLOGY ENGINE ADVANCED MATERIALS AND TECHNOLOGY



**AEROMAT 2000**



# High Temperature Rise CMC Combustor (IHPTET/JTAGG III - Helicopter Engine)

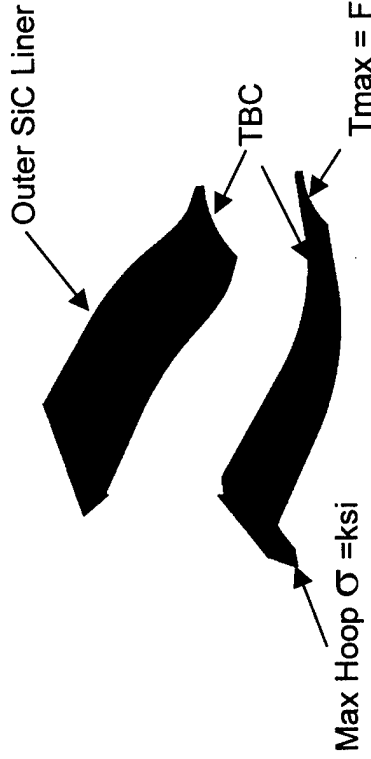
## OBJECTIVES

- Develop a full life combustion design w/Phase III T4 capability (+1000F).
- Reduce Pattern Factor (PF) to 0.13 from .25.
- want more uniform combustor exit temp (longer turbine life downstream, e.g. vanes) which is achieved with higher combustor temp's and control of air flow, e.g. swirlers.
- Decrease Weight by 67%

## TECHNICAL CHALLENGES

- Achieve full life (2000hrs) under high heat load conditions while minimizing cooling requirements
- Maintain acceptable combustor performance & operability (aerodynamics and proper lighting) with an increased  $\Delta T$
- Limited structural capability of cmc liner material, i.e. designing with reduced stress tolerance.

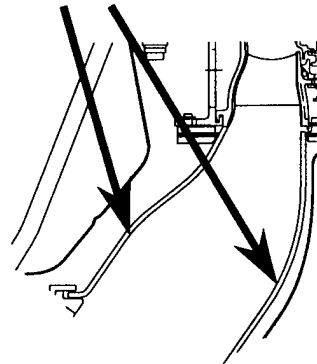
## ANSYS/CFD Results



## STATUS

- Full annular metal prototype, i.e. design, is being Rig tested.
- Full annular CMC scheduled for Rig Test in Sept, 00.

CMC Liners  
Sylramic MI  
SiC/SiC



CMC Outer liner

CMC Inner liner

Cooling holes to be drilled following metal design test

**Honeywell**

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# High Temperature Rise Combustor (IHPTET/JTAGG I - Helicopter Engine)

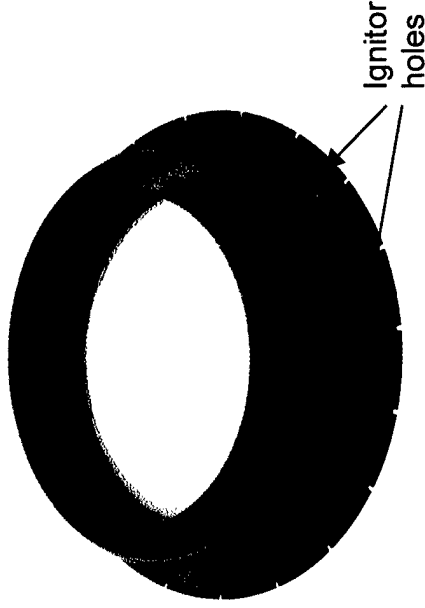
## Objectives

- Used CMC liners as structural members, not insulative tiles
- DuPont CG Nicalon/Enhanced SiC, triaxial braided architecture
- Design low-stress combustor with full life
- Measure CMC conditions during testing
- Demonstrate combustor in gas generator

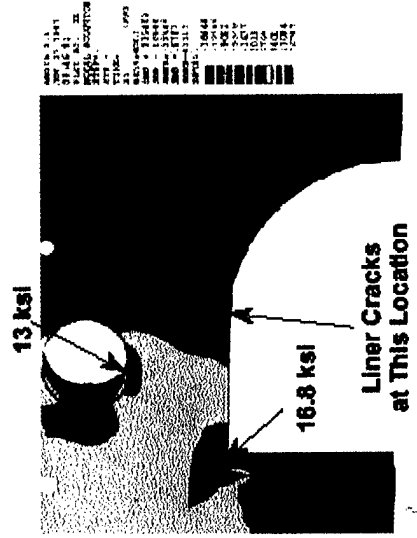
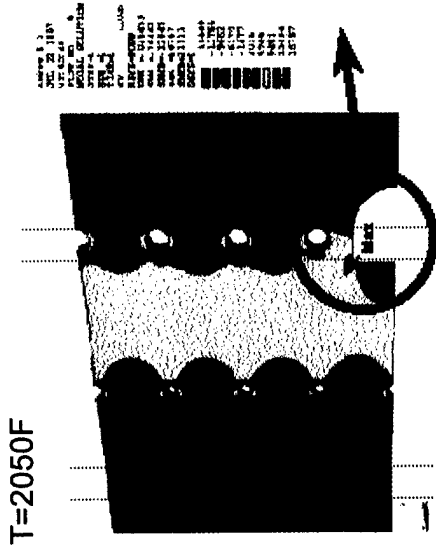
## Results

- Rig Test - Combustor survived complete test - 30hr, 50 cycles
- Engine test - 11 hours 35 min's, (1hr 7 min at max power)
- multiple cracks occurred on OD liner (initiated near "D" hole ignitor ports).
- ID liner in pristine condition

Inner & Outer JTAGG I Combustion Liners



## ANSIS RESULTS



## Post Test Analysis

Outer liner cracked due to stress rupture

- Total Stress = 16.8ksi
- thermal stress = 15.8 ksi
- Pressure stress = 1 ksi

T=1400F

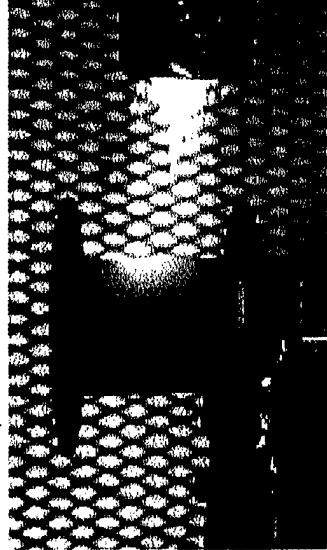
**Honeywell**

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# HPT Nozzle/Shroud Program JTDE (XTE77SE) General Electric Aircraft Engines



<p><b>OBJECTIVES</b></p> <ul style="list-style-type: none"> <li>• Design, fabricate, and component test a CMC nozzle</li> <li>• Transition technology to F414 Upgrade.</li> </ul> <p><b>TECHNICAL CHALLENGES</b></p> <ul style="list-style-type: none"> <li>• Ability to provide effective cooling to CMC airfoil shapes</li> <li>• Mechanical design of a CMC vane to survive a high thermal gradient environment</li> <li>• Ability to provide sufficient structural integrity using CMC material properties</li> <li>• Attachments to a metallic engine structure in a high thermal differential environment</li> </ul>	<p><b>APPROACH</b></p> <ul style="list-style-type: none"> <li>• Utilize CMC experience gained through other programs</li> <li>• Examine processing concerns and thermal shock capability using test specimens</li> <li>• Explore various concepts during the preliminary design phase - integration of airfoils with platform, Trailing Edge, etc.</li> <li>• Final design, fabricate and rig test most promising design concept</li> </ul>
 <p><b>NAVY BAA 6.2 CMC HPT Nozzle</b></p> <ul style="list-style-type: none"> <li>• 3D preform</li> <li>• Flame testing</li> </ul>	<p><b>MAJOR MILESTONES</b></p> <ul style="list-style-type: none"> <li>• Coupon thermal and mechanical tests (9/1999)</li> <li>• Design of nozzle for rig test (6/2000)</li> <li>• Component rig test, partial engine set (6/2001)</li> </ul> <p><b>CONTRIBUTION to TECHNICAL EFFORT OBJECTIVE(S)</b></p> <ul style="list-style-type: none"> <li>• Significant increase in T4.1</li> <li>• Weight reduction ( ~50%)</li> <li>• Reduced engine cooling requirements (10% less for nozzle)</li> </ul>

# Navy IR Survivability Assessment



NAVIC

HEADQUARTERS AIR SURFACET CENTER



- Increased Rotary Wing Aircraft Survivability Against Current & Emerging Threat Systems
- Man portable surface to air heat seeking msls.

• CH-60, SH-60R and AH-1, UH-1

• Phase I - Develop a preliminary design of a CH-60 / SH-60R Advanced IR Exhaust Suppressor

• Phase II - Fabricate one flight worthy suppressor unit for ground test demonstration using production materials and processes.

Ground Demo with CMC nozzle

• Phase III - Flight Test production suppressor

March 1998 - February 2000

\$650K

March 1999 - April 2000

\$1.15M

Sept. 00 (CMC MANTECH PROGRAM)

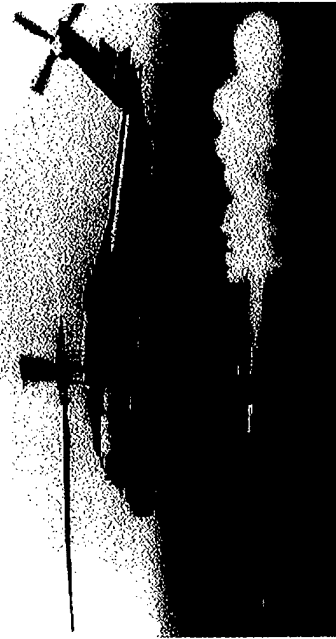
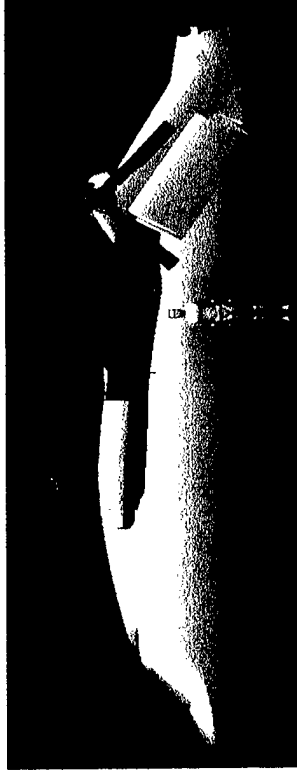
April 2000 - December 2001

\$1.5M



**BACKGROUND**

- Develop affordable CMC Manufacturing Techniques for Cost Effective Applications.
  - Aircraft Structures for IR Suppression.
- Program Complements Navy's Advanced IR System Development Program (replace HERRS system) for H-60.
  - Leveraged off Army/Sikorsky CRADA that flight tested an advanced H-60 suppressor system.
  - flight test scheduled for Q2, 2001.



SH60B SEAHAWK

**PROGRAM INFORMATION**

- **Start/End:** October 1999 - October 2001
- **Sponsor:** H-60, H-1 also UAV & V-22 interests (multiple targeted helicopter platforms).
- **Contractor Teams:**
  - Team 1: Sikorsky, Composite Optics Ceramics Inc.
  - Team 2: BellHelicopter Textron Inc., COI

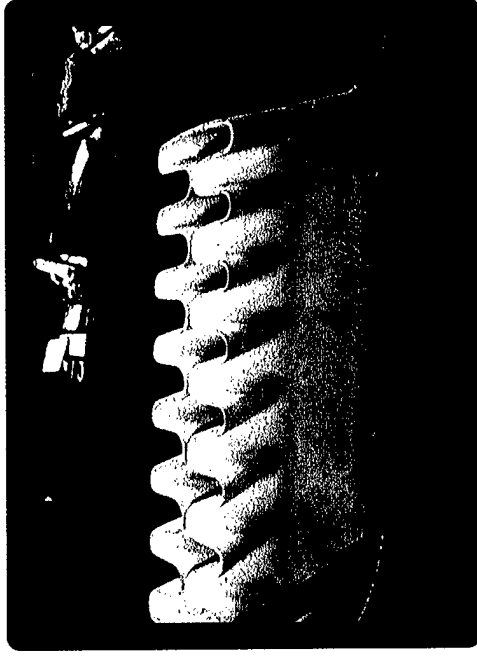


**Sikorsky**  
 A United Technologies Company

**Bell Helicopter TEXTRON**

**AEROMAT 2000**

- **Team 1:** Sikorsky Aircraft, Composite Optics Ceramics, Inc. (COCI)
- **Objective:** Develop affordable and reproducible CMC Processing and Manufacturing for complex shaped exhaust washed Aircraft Structures - CMC nozzles for IR system. H60 Max exhaust temp = 1200F.
- **Benefit:** Acquisition Cost Avoidance, Weight savings.
- **System Impacted:** H-60 Helicopter Platform, Nozzles for Advanced IR suppressor system.



Ceramic Matrix Composite Nozzle



H-60 Sea Hawk

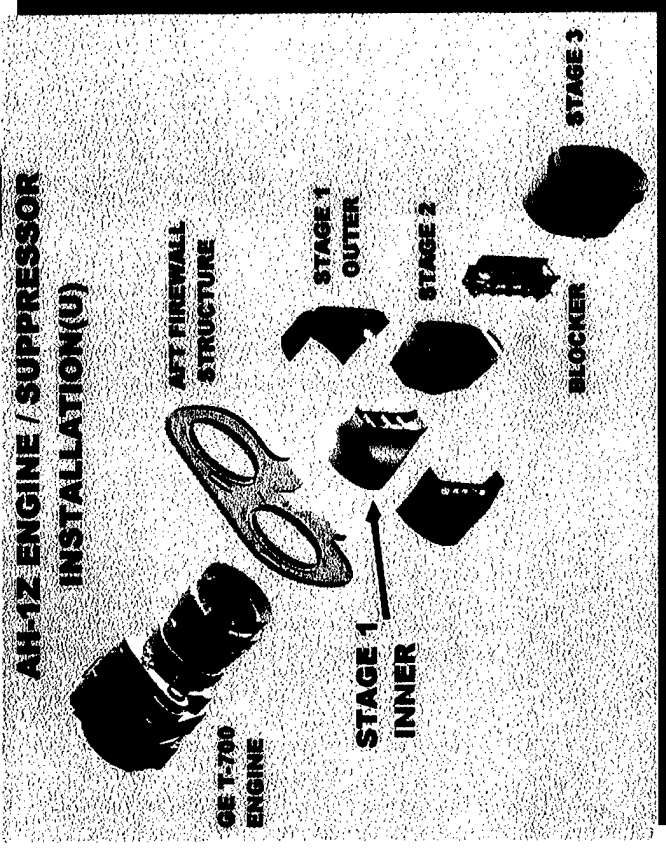


**Program Status**

- **Material System:** Oxide-Oxide (sol gel aluminosilicate), Nextel 610, 8HS. Max operating temp = 1800F.
- **Completed Manufacturing/Productibility Assessment of the H-60 Nozzle Geometry. Fabricated Two Full-Scale Proof-of-Concept Articles.**
- **Completed materials properties (RT, 1200F), Initiated: Effects of Defects, NDI, and Repair Development Tasks.**



- **Team 2:** Bell Helicopter Textron Inc., System Integrator
- **Composite Optics, Material & Component Fabricator**
- **Objective/Focus:** Develop and demonstrate affordable & reproducible manufacturing of CMCs for air vehicle applications
- **Benefit:** Acquisition Cost Avoidance- Lower initial cost as compared to existing stainless steel component, weight savings, survivability enhancement
- **System Impacted:** AH-1W, AH-1Z Cobra and UH-1Y Huey Helicopters Stage 1 IR suppressor



**Program Status**

- Contract work initiated Dec 1999
- Identified AH-1Z / UH-1Y Stage 1 Exhaust Suppressor as candidate component.
- Identified Nextel 610/Alumino Silicate as material system
- AH-1Z / UH-1Y Stage I inner duct non-flightworthy demonstration component being fabricated



**AH-1W Super Cobra**

**Bell Helicopter TEXTRON**

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## DEMONSTRATION COMPONENT

### AH-1Z / UH-1Y SUPPRESSOR STAGE I INNER DUCT

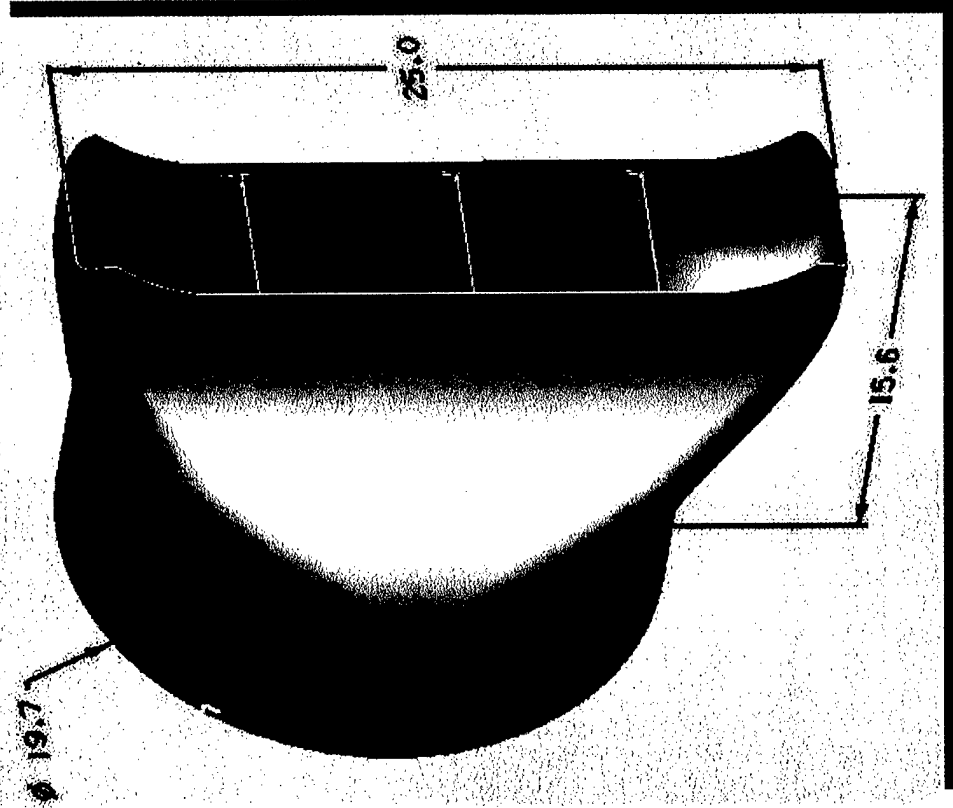
BHTI Part Number: 209-064-218-103

Material: 0.040" stainless steel

Weight: 12.8 lb

Max. Operating Temp: 1220°F

Max. Continuous Power Temp: 1100°F



**Bell Helicopter** **TEXTRON**

**AEROMAT 2000**



# CMC HPT VANE INSERTS

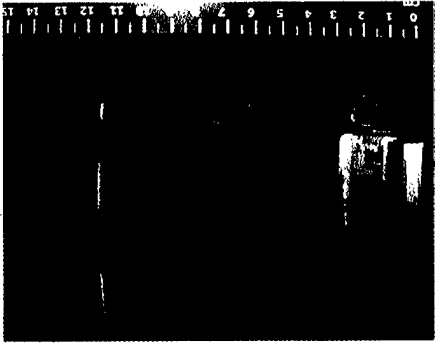


**Background:** Thermal Fatigue of hpt vane leading edge.

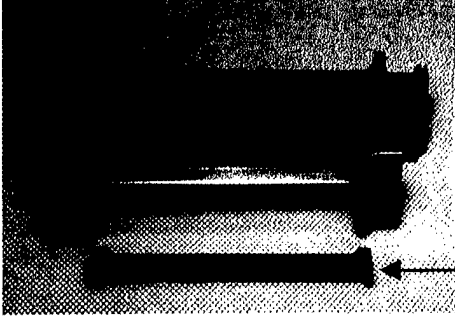
- hot spots up to 2280 F
  - thermal gradients > 600F
- Loss of aircraft, Sept 1, 1995; double vane burn thru and outer platform release (into gas path).

**Approach:** Insert SiC/SiC CMC shield to reduce the metal vane temperature and thermal gradients at the leading edge.

**Benefits:** Increase component Life, Increase operating temperatures (408 engine upgrade), Eliminate leading edge cooling holes.



HPT2 vane doublet removed from service



CMC insert



Pegasus F402-RR-406 engine

AV8 Harrier

**Status:**

- Program is complete, application looking for a home.
- Burner Rig Insert testing results:
  - CMC withstood thermal shock, CMC/metal attachment design worked, no sign of thermal fatigue cracks in metal vanes
  - Metal leading edge temp reduced (only) 50F with insert.
  - MI SiC/SiC 2x decrease in surface temp vrs. CVI SiC/SiC.
- Rig testing continuing at NASA to test possibility of eliminating the cooling hole requirement.
- 406 engine is being phased out in 2 years, engine life has been reduced from 1000 to 500 hrs.
- 408 engine upgrade is going with a redesigned vane -sand tolerant design, revised inner cooling scheme.

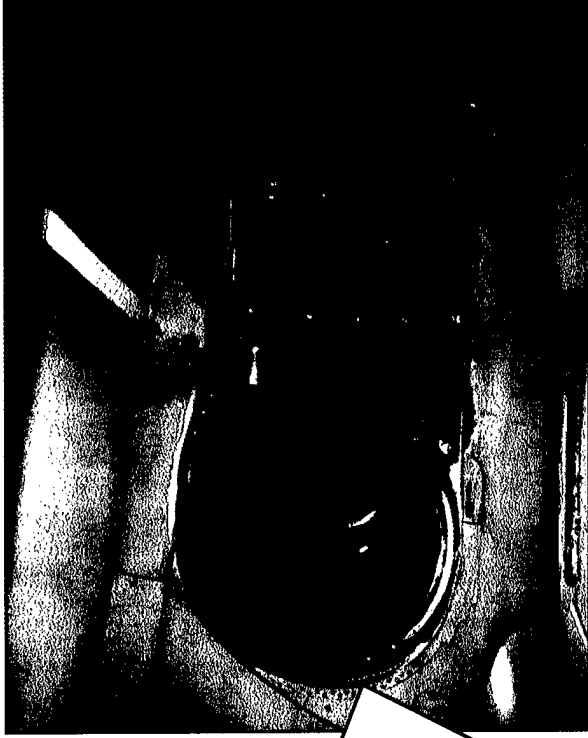


## FLIGHT TEST OF CMC BLASTSHIELD

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**AV-8B Harrier heatshield (a stainless steel exhaust blastshield) is subjected to an extreme thermal and acoustic environment which leads to short service life.**

- Component begins to crack after few flight hours requiring frequent stop-drilling repairs.
- Northrop Grumman identified this component as ideal for demonstrating the company CMC experience.
- A cooperative IR&D program with NG and MDC (now Boeing) designed and fabricated 2 heatshields.
  - Nextel/Blackglass (Silicon-Oxy-Carbide via polymer pyrolysis), cmc system capability 1500F, component sees 900F.
- Ground engine and flight testing successfully completed in 1997.



- Non-destructive inspection following flight showed no deterioration of the component.
- Second blast shield remains available for future flight and endurance testing.

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# SBIR REPAIR OF CMC's FOR EXHAUST WASHED STRUCTURES



<p><b><u>BACKGROUND</u></b></p> <ul style="list-style-type: none"> <li>Existing AV-8B Metallic Blastshield Degrades Under Extreme Thermo-Acoustic Environment Creating Significant Maintenance Burden</li> <li>NGC Has Demonstrated Prototype Nicalon/Blackglas Blastshields</li> <li>Prior To Fleet Introduction, Repair Approaches Are Required To Be Developed</li> </ul>	<p><b><u>APPROACH</u></b></p> <ul style="list-style-type: none"> <li>Issue Phase I SBIR For The Development of Repair Procedures</li> <li>Phase II SBIR Will Demonstrate Repair Approach By Testing a Repaired Blastshield Under Thermo-Acoustic Conditions</li> <li>Team With AFRL For Acoustic Testing</li> </ul>
<p><b><u>STATUS</u></b></p> <ul style="list-style-type: none"> <li>Preliminary Repair Designs Have Been Developed</li> <li>Phase I Option Currently Evaluating Matrix Re-impregnation Approach</li> <li>Phase II Program Expected To Start May 2000</li> </ul>	<p><b><u>PROGRAM INFORMATION</u></b></p> <ul style="list-style-type: none"> <li>Sponsor: AV-8B Program Office</li> <li>Contractor: Materials Research &amp; Design Kent Buesking (610) 526-9540</li> <li>NAVAIR TPOC: Jerry Rubinsky - NAVAIR Structures (301)-342-9355</li> </ul>



**NORTHROP GRUMMAN**



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# F110-GE-400 Flameholder Ceramic Insertion

## NAVAIR Component Improvement Program/ARPA Ceramic Insertion Program

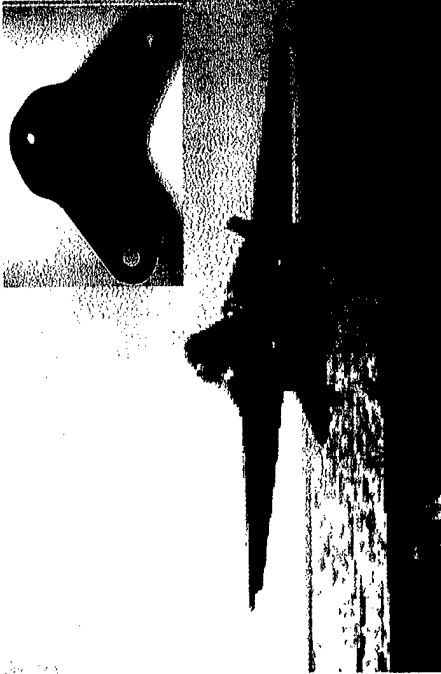
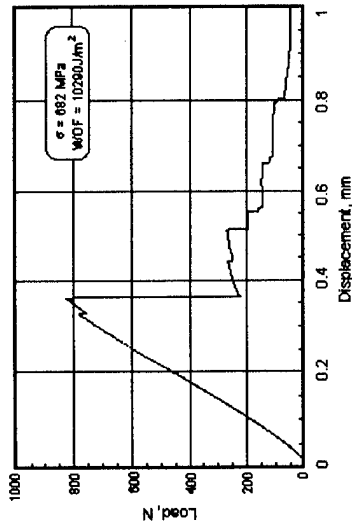
Design and Develop a ceramic flameholder more durable than current HS188 (Ni-Co superalloy)  
 - thermal cycling stress → cracking, creep, erosion

### Navy Benefits

- Reduced support costs - fewer replacements, mtbf = 1000EFH
- Improved mission readiness
- Safety - reduce potential for direct flame impingement on A/B liner

### Approach

Attach (24) ceramic inserts to highly stressed "hot" spots on the flameholder assembly. ACR silicon nitride FM chosen based on cost and graceful failure mode.



GEAE F110 platform for F-14, F-15 and F-16 aircraft platforms.

### Status

- Initial engine tests with BFG SiC/C CMC
- demonstrated need for redesign of attachment.
- CMC eliminated from consideration due to cost
- Silicon Nitride Fibrous Monolith was engine tested
- HS188 metal attachment failed (thermal stress).



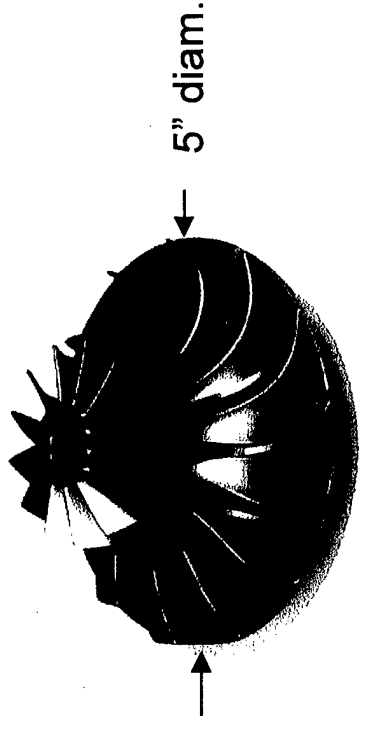
# CERAMIC IMPELLER for V-22 SHAFT DRIVEN COMPRESSOR



**Problem:**  
Honeywell manufactured Shaft-Driven-Compressor Impeller (100k rpm) is experiencing short (200-300 hr) life due to sand erosion.

**Approach:**  
Replace existing Ti-6Al-4V impeller with Honeywell's GS-44 in-situ reinforced silicon nitride.

**Developmental Program:**  
ONR TOC Initiative, Start FY02



V22

**Honeywell**

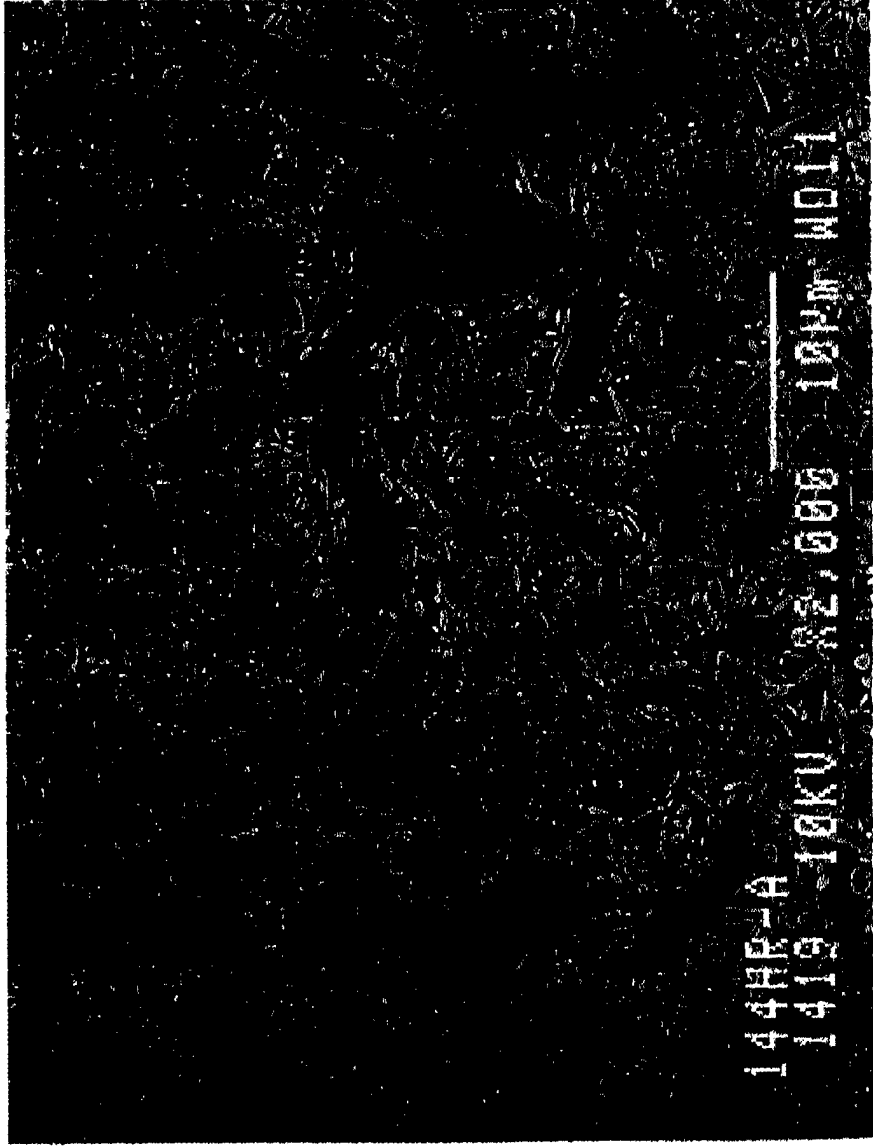
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**Benefits:**

- Extended component life from (10x) improved erosion resistance.
- Reduced component and containment weight.
- Total Ownership Cost (TOC) reduction = \$ 121M
  - includes O level and D level replacement costs
  - significant reduction in spares requirement over existing Ti component.

**Implementation Program (FY03 Start)**

- Tasks approved, V22 program funds set aside contingent on successful developmental program.



RT Flex Strength = 1051MPa  
Weibull Modulus = 20-30  
Fracture Tough. = 8.25 Mpa \*  
m<sup>1/2</sup>

Density = 3.2 g/cc  
Elastic Modulus = 300 GPa  
Hardness = 1460 GPa

**Honeywell**

GS-44 Microstructure.ppt

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Ceramic Components  
March, 2000

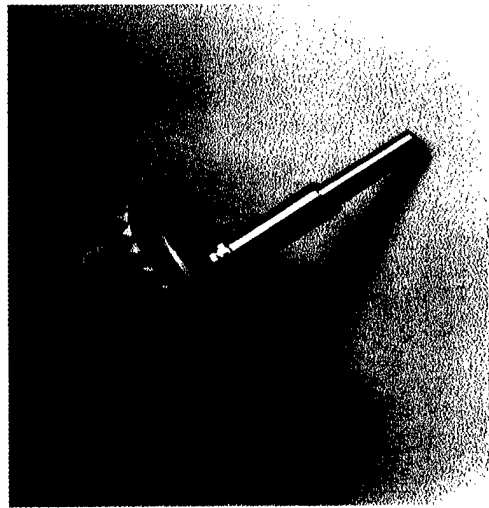


## Relevant Experience



### **B52 - Air Starter Wheel (Gelcast)**

- 5.0" Diameter (tip speed 2182 ft/sec)
- 100K RPM Operational (125K RPM Proof)
- Metal Shaft Attachment
  - 0.8 inch diameter
  - 160 ft-lb Static Torque at 400 degrees F
  - > 250 ft-lb Static Torque at 70 degrees F



### **Power Turbine Rotor (Gelcast)**

- 7.0" Diameter (tip speed 1985 ft/sec)
- 65K RPM Operational (88K RPM Proof)



### **Status**

- Design modifications to gel-cast mold to eliminate air pockets/bubbles.
- Engine Rig Test.

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# BURST TEST AND CONTAINMENT Starter Wheel



55% weight savings in the containment ring  
when a silicon nitride ceramic turbine wheel  
replaces a metal wheel

**Honeywell**

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