**Title:** Advanced Ceramics for Navy Air Vehicle Applications

**Author(s):** Dr. George Y. Richardson

**Performing Organization:** Naval Air Warfare Center Aircraft Division
22347 Cedar Point Road, Unit #6
Patuxent River, Maryland 20670-1161

**Abstract:**

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ADVANCED CERAMICS for NAVY
AIR VEHICLE APPLICATIONS

Dr. George Y. Richardson
Aerospace Materials Division
NAWC-AD
Patuxent River, Maryland


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, \( \rho = 2.2, 4.4, 7.8, 8.2 \) 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

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

AEROMAT 2000
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
Why SiC/SiC CMC

CMC has SFC and thrust/weight benefits over Ni-based superalloys
# CMC* vs N5 Material Property Comparison

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Ratio</th>
<th>Impact on CMC Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [ρ]</td>
<td></td>
<td>Lowers weight, Increases response time</td>
</tr>
<tr>
<td>Thermal conductivity [K]</td>
<td></td>
<td>Drives thermal gradients, Increases thermal stress</td>
</tr>
<tr>
<td>Coefficient of thermal expansion [α]</td>
<td></td>
<td>Lowers thermal stress &amp; distortion</td>
</tr>
<tr>
<td>Young's modulus [E]</td>
<td></td>
<td>Increases thermal stress</td>
</tr>
<tr>
<td>Specific heat [Cp]</td>
<td></td>
<td>Higher at lower temperatures, Decreases response time</td>
</tr>
</tbody>
</table>

*Melt Infiltrated, Hi-Nicalon

---

* AEROMAT 2000
Low Interlaminar Strength

Interlaminar Tensile Strength

Interlaminar Shear Strength

Hi-Nicalon C
Sylramic CM
AS800 Si Ni

ILT (kSI)

ILS (kSI)

Temp (F)

2D Plies

AEROMAT 2000
Low Tensile Strength
Challenge to Design

Yield Tensile Strength

Ultimate Tensile Strength

N5

Hi-Nicalon CMC (0.07%)
Sylramic CMC (0.07%)
AS800 Si Ni (UTS)
Rene' N5 (0.2%)

UTS (ksi)
0.00
SiC/SiC

Temp (F)
70 400 800 1200 1600 2000 2400 2800 3200

AEROMAT 2000
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
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)**

**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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**AEROMAT 2000**
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).
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

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.
Wear Coating Application to Oxide CMC Flap

Ceramic Materials
VECTOR PROGRAM

International (GER/US) Cooperative Program
• 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)

Delmar/Chrysler Aerospace
Military Aircraft

AEROMAT 2000
Multi-Axis Thrust Vectoring - Key Technology for the Demonstration

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

- **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

- Cast γ TiAl Seal Housings
- CBC Fuel System
- Titanium Dual Property
- Advanced Survivability Inlet Technology
- High Strength HPC Blades
- Improved PMC Outer Duct
- CMC Combustor Liner
- CMC LPT Shaft
- Ortho TiNb Clearance Structures
- Advanced PVD-TBC Airfoils
- Advanced CMC HPT Nozzle
- CMC HPT Seal Support
- Advanced E+1 Nickel Disk Alloy
- Advanced Survivability Exhaust Technology
- Advanced CMC VEN
- Cast γ TiAl Exhaust Frame
- Advanced Technology
- N5/N6/MX4 Turbine Blades/Vanes
- TBC Airfoils With Higher Temperature Bond Coat
- Brush Seals
- R88DT Disks
- Low α Material Clearance Control
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 ΔT
- Limited structural capability of cmc liner material, i.e. designing with reduced stress tolerance.

ANSYS/CFD Results
- Outer SiC Liner
- TBC
- Max Hoop $\sigma$ = ksi
- $T_{max} = F$

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
Cooling holes to be drilled following metal design test

CMC Inner liner

Honeywell
FOR OFFICIAL USE ONLY
AEROMAT 2000
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

ANSIS RESULTS

Post Test Analysis
- Outer liner cracked due to stress rupture
  - Total Stress = 16.8 ksi
  - Thermal stress = 15.8 ksi
  - Pressure stress = 1 ksi
HPT Nozzle/Shroud Program
JTDE (XTE77SE)
General Electric Aircraft Engines

OBJECTIVES
- Design, fabricate, and component test a CMC nozzle
- Transition technology to F414 Upgrade.

TECHNICAL CHALLENGES
- Ability to provide effective cooling to CMC airfoil shapes
- Mechanical design of a CMC vane to survive a high thermal gradient environment
- Ability to provide sufficient structural integrity using CMC material properties
- Attachments to a metallic engine structure in a high thermal differential environment

APPROACH
- Utilize CMC experience gained through other programs
- Examine processing concerns and thermal shock capability using test specimens
- Explore various concepts during the preliminary design phase - integration of airfoils with platform, Trailing Edge, etc.
- Final design, fabricate and rig test most promising design concept

MAJOR MILESTONES
- Coupon thermal and mechanical tests (9/1999)
- Design of nozzle for rig test (6/2000)
- Component rig test, partial engine set (6/2001)

CONTRIBUTION to TECHNICAL EFFORT OBJECTIVE(S)
- Significant increase in T4.1
- Weight reduction (~50%)
- Reduced engine cooling requirements (10% less for nozzle)

NAVY BAA 6.2 CMC HPT Nozzle
- 3D preform
- Flame testing
Navy IR Survivability Assessment

- 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
  - March 1998 - February 2000
  - $650K

- Phase II - Fabricate one flight worthy suppressor unit for ground test demonstration using production materials and processes.
  - March 1999 - April 2000
  - $1.15M

  Ground Demo with CMC nozzle
  - Sept. 00 (CMC MANTECH PROGRAM)

- Phase III - Flight Test production suppressor
  - April 2000 - December 2001
  - $1.5M
MANTECH: CERAMCO
(Official Kickoff: Jan. 20, 2000)

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.

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

SH60B SEAHAWK

Sikorsky
A United Technologies Company

Bell Helicopter TEXTRON

AEROMAT 2000
MANTECH: CERAMCO (TEAM 1)

- **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 exhuast temp = 1200F.
- **Benefit:** Acquisition Cost Avoidance, Weight savings.
- **System Impacted:** H-60 Helicopter Platform, Nozzles for Advanced IR suppressor system.

**Program Status**

- **Material System:** Oxide-Oxide (sol gel alumino-silicate), Nextel 610, 8HS. Max operating temp = 1800F.
- **Completed Manufacturing/Producibility 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.**

AEROMAT 2000
MANTECH: CERAMCO
(TEAM 2)

- **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

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**AH-1Z ENGINE / SUPPRESSOR INSTALLATION(U)**

**Stage 1**
- Inner
- Outer

**Stage 2**
- Blocker

**Stage 3**

**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

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**Bell Helicopter TEXTRON**

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**AEROMAT 2000**
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
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.

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.

Pegasus F402-RR-406 engine

AV8 Harrier

HPT2 vane doubllet removed from service

CMC insert

AEROMAT 2000
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.
**SBIR**

**REPAIR OF CMC's FOR EXHAUST WASHED STRUCTURES**

<table>
<thead>
<tr>
<th>BACKGROUND</th>
<th>APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Existing AV-8B Metallic Blastshield Degrades Under Extreme Thermo-Acoustic Environment Creating Significant Maintenance Burden</td>
<td>• Issue Phase I SBIR For The Development of Repair Procedures</td>
</tr>
<tr>
<td>• NGC Has Demonstrated Prototype Nicalon/Blackglas Blastshields</td>
<td>• Phase II SBIR Will Demonstrate Repair Approach By Testing a Repaired Blastshield Under Thermo-Acoustic Conditions</td>
</tr>
<tr>
<td>• Prior To Fleet Introduction, Repair Approaches Are Required To Be Developed</td>
<td>• Team With AFRL For Acoustic Testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STATUS</th>
<th>PROGRAM INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Preliminary Repair Designs Have Been Developed</td>
<td>• Sponsor: AV-8B Program Office</td>
</tr>
<tr>
<td>• Phase I Option Currently Evaluating Matrix Re-Impregnation Approach</td>
<td>• Contractor: Materials Research &amp; Design Kent Buesking (610) 526-9540</td>
</tr>
<tr>
<td>• Phase II Program Expected To Start May 2000</td>
<td>• NAVAIR TPOC: Jerry Rubinsky - NAVAIR Structures (301)-342-9355</td>
</tr>
</tbody>
</table>

**NORTHROP GRUMMAN**

**SOUTHERN RESEARCH INSTITUTE**

**AEROMAT 2000**
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.

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

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.

Honeywell

AEROMAT 2000
RT Flex Strength = 1051 MPa
Weibull Modulus = 20-30
Fracture Tough. = 8.25 Mpa * m\(^{1/2}\)
Density = 3.2 g/cc
Elastic Modulus = 300 GPa
Hardness = 1460 GPa
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.

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