HIGH TEMPERATURE MATERIALS NEEDS IN NASA'S ADVANCED SPACE PROPULSION PROGRAMS, Andrew J. Eckel, NASA Glenn Research Center, Cleveland, OH 44135

In recent years, NASA has embarked on several new and exciting efforts in the exploration and use of space. The successful accomplishment of many planned missions and projects is dependent upon the development and deployment of previously unproven propulsion systems. Key to many of the propulsion systems is the use of emergent materials systems, particularly high temperature structural composites.

A review of the general missions and benefits of utilizing high temperature materials will be presented. The design parameters and operating conditions will be presented for both specific missions/vehicles and classes of components. Key technical challenges and opportunities are identified along with suggested paths for addressing them.
High Temperature Materials Needs in NASA’s Advanced Space Transportation Programs

Andrew J. Eckel
Glenn Research Center
Cleveland, Ohio, USA

David E. Glass
Langley Research Center
Hampton, VA USA
Outline

♦ Introduction

♦ Airframe
  • Hot & Integrated Structures
  • Tanks
  • TPS

♦ Propulsion
  • Rotating Components and Seals
  • Flowpath Components

♦ Concluding Remarks
Advanced Space Transportation Program(s) - ASTP

Materials enable NASA missions!
<table>
<thead>
<tr>
<th>Rockets</th>
<th>Airbreathers</th>
</tr>
</thead>
</table>
| **Don’t like the atmosphere**  
  - Accelerate only  
  - Get out quick  
  - Tend toward vertical launch  
  - Low ISP  | **Like the atmosphere**  
  - Accelerate and cruise in atmosphere  
  - Tend toward horizontal launch  
  - High ISP  |
| **Drag**  
  - High drag not a problem on ascent, desirable on descent for deceleration  
  - Blunt leading edges  | **Drag**  
  - Optimize for low drag  
  - Thin, slender body, low thickness/chord  |
| **Weight critical**  
  - Mass fraction ~ 10% of GTOW  
  - Requirement to be weight sensitive  | **Volume critical**  
  - Mass fraction ~ 30% of GTOW  
  - Requirement to be volume sensitive, volume drives drag  |
| **Engine in back**  
  - Weight drives components to be clustered near engine  
  - Tail heavy  
  - Hard to get forward cg  
  - Highly compressive loaded structure  | **Engine in mid-body**  
  - Stability easier  
  - Easier to control cg  
  - Can split LOX for cg control |
# Rockets vs. Airbreathers Effect on Airframe

<table>
<thead>
<tr>
<th>Rockets</th>
<th>Airbreathers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TPS</strong></td>
<td><strong>TPS</strong></td>
</tr>
<tr>
<td>• Driven by descent</td>
<td>• Driven by ascent</td>
</tr>
<tr>
<td>• Low heat load due to short ascent</td>
<td>• High heat load due to long ascent time</td>
</tr>
<tr>
<td><strong>Leading edges</strong></td>
<td><strong>Leading edges</strong></td>
</tr>
<tr>
<td>• Blunt due to desire for descent drag</td>
<td>• Sharp due to low drag, low t/c</td>
</tr>
<tr>
<td>• Low heat flux</td>
<td>• High heat flux</td>
</tr>
<tr>
<td><strong>Tanks</strong></td>
<td><strong>Tanks</strong></td>
</tr>
<tr>
<td>• Cylindrical since weight sensitive and volume insensitive</td>
<td>• Conformal since volume and drag critical</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td><strong>Structure</strong></td>
</tr>
<tr>
<td>• Lightly loaded wings</td>
<td>• Highly loaded wings (some air breathers)</td>
</tr>
<tr>
<td>• Propulsion and airframe not highly integrated</td>
<td>• Hot wings and control surfaces due to thin cross sections and high heat flux/load</td>
</tr>
<tr>
<td><strong>Landing gear</strong></td>
<td><strong>Landing gear</strong></td>
</tr>
<tr>
<td>• Sized for empty descent (vertical takeoff)</td>
<td>• Sized for fully loaded ascent</td>
</tr>
<tr>
<td>• Lightly loaded</td>
<td>• Highly loaded</td>
</tr>
<tr>
<td>• Light weight</td>
<td>• Significant weight</td>
</tr>
</tbody>
</table>
Key Drivers for Utilizing Higher Temperature Capable Advanced Materials

• **Weight:**
  - High Thrust-to-Weight for Launch Vehicles
  - Lower Propulsion System Mass for Satellite and Planetary Missions

• **Enabling:** High Temperature Capability and/or Oxidation Resistance Enabling for Many Propulsion Concepts

• **Performance:** Increased operational margin -- translates to enhanced range, life and/or system payload (e.g., E-T-O propulsion systems, satellites, deep space probes)

• **Simplicity:** Higher temperature capability may reduce or eliminate coolant system requirements (e.g., on re-entry)

• **Cost:** Reduced System Operational Costs (e.g., less inspections, rebuilds)
ASTP High Temperature Materials Needs

What are we working today?

♦ **Airframe**
  - Hot Structures/Control Surfaces
  - Tanks
  - TPS

♦ **Propulsion**
  - Rotating Components and Seals
  - Flowpath Components
CMC Control Surfaces

- **Objective**
  - Develop hot structure control surfaces with multi-use mission life that are reliable, durable, and lightweight.

- **Materials**
  - Carbon/Carbon (C/C)
  - Carbon/Silicon Carbide (C/SiC)
  - Oxidation protection systems
  - C/SiC joining technology
  - Comingled SiC and C fibers to reduce microcracks
  - Tow-spreading to increase performance

- **Design and Analysis**
  - CMC body flap design (design tools development)
  - Life/oxidation modeling development and stressed oxidation tests

- **Advanced Fabrication**
  - Advanced fabrication demonstration, integrally fabricated flaperon (WPAFB-AFRL)

- **Validation and Testing**
  - Body flap subcomponent test (DFRC)
  - CMC control surface seal validation arcjet test (GRC/ARC/JSC/LaRC)
  - Vibration and vibroacoustic tests (LaRC)
C/SiC Body Flap

- Half-scale X-37 body flap was fabricated and tested at NASA Dryden under combined heating and loading to 2050°F and 100% design limit load (report available)
- Acoustic / vibration testing at NASA Langley upcoming
- Design methodology task performed by SRI (report available)
- Follow-on tasks to enhance control surface performance
  - Oxidation resistance
  - Fastener improvement
  - Failure testing
  - Integrated fabrication

C/SiC Flaperon Advanced Fabrication Demonstration (Integrated Fabrication)

Half-Scale X-37 Body Flap

GE PSC

X-37 C/SiC Flaperon Subcomponent Utilizes NGLT Lessons Learned
Carbon-Carbon Control Surface

♦ CMC Control Surface Development
  Thermostructural Testing (DFRC)

♦ Accomplishments
  • Developed test setup and test techniques required to test a CMC body flap through the thermal-structural testing of the C/C control surface
  • Performed combined thermal and mechanical testing of a hot structure test component
  • Demonstrated the ability to measure strains on a hot structure at 1650°F using fiber optic strain sensors
Metallic Materials for Hot Structures

**Objective**
- Develop metallic material systems and processing/fabrication technology for production of reliable, durable, lightweight hot structure and TPS components

**Fabrication**
- Fabrication of appropriate shapes and product forms
- Joining
- Fabrication of structural elements/subcomponents

**Materials Development**
($\gamma$TiAl, adv. Ni and Fe alloys, MMC’s)
- Correlate and optimize microstructure, properties, and processing
- MMC fiber-matrix compatibility (chemical, mechanical)
- MMC laminate fabrication

**Compatibility with Service Environments**
- Assess environmental service limits of candidate materials
- Develop coatings for environmental protection and thermal control
- Assess impact resistance and durability of candidate materials and structural elements
High Temperature PMC's

- **Objective**
  - Develop non-autoclave processable polymeric resins, composites, and adhesives suitable for use in airframe components at temperatures from -150°F to 700°F

- **Determine failure modes that affect durability of advanced high temperature polymeric materials**
  - Produce adequate amounts of materials for important properties of the high temperature polymeric materials.
  - Understand the effects of complex loads and environments on materials durability and life.

- **Fully characterize properties of high temperature resistant structural materials**
  - Develop high temperature resistant / clay nanocomposites that have improved thermo-oxidative stability.

- **Develop and demonstrate high temperature resistant structural materials**
  - Develop materials with proper combination of high and low temperature mechanical properties.
  - Optimize processability and properties.

Photographed structure not developed as part of NGLT.
Objective
- Develop high temperature and multi-parameter (cryogenic) fiber optic sensors

High temperature sensors for use up to 3000°F
- Develop techniques to bond sapphire optical fiber to CMC materials for use at 2500°F and 3000°F
- Evaluate the performance of silica and sapphire based FO sensors through CMC coupon testing to maximum use temperature

C/SiC

Fiber Optic Strain Sensor

1850°F Test of Fiber Optic Strain Sensor on C/SiC Hot Structure
Tanks

♦ Hot & Integrated Structures
  • CMC Control Surfaces
  • Metallic Materials for Hot Structures
  • High Temperature PMC’s
  • Fiber Optic Sensors

♦ Tanks
  • Composite Tanks
  • Metallic Tanks
  • Cryoinsulation

♦ TPS
  • Acreage
    – CMC Acreage TPS
    – Metallic TPS
    – Ablators
    – Blankets
    – Tiles
  • Leading Edges
    – 3000°F Passive Leading Edges
    – 3600°F Passive Leading Edges
    – Heat-Pipe-Cooled Leading Edges
  • Control Surface Seals
NGIT

NEXT GENERATION LAUNCH TECHNOLOGY

Composite Tanks

- **Materials**
  - Validated life prediction tools including permeation
  - Develop 450°F to 550°F non-autoclave processable composites and adhesives
  - Cryo-biaxial life cycling of sandwich panels with in-situ permeation

- **Objective**
  - Develop the technology required to design and fabricate full scale, reusable, composite cryogenic tanks

- **Design and Analysis**
  - Web joint structural member scaled to reference vehicle
  - Composite fracture control & residual life tools
  - Conformal tank design trades

- **Fabrication**
  - Heat-pipe heat blanket for composite repair
  - Non-autoclave, tow placement fabrication of a 10.5 ft diameter half tank, including post test coupon testing and NDE.

- **Verification**
  - > 40 LH2 cryo-structural cycles on NG subscale tank
  - Curved panel test data
  - Cryo-structural testing of conformal tank web joint
  - Complete cryo testing of Y-joints
Conformal Tank Joint Concepts – 4 Selected

- Conformal Tanks Require Internal Members for Shape Retention

2 Linear Web Attach Concepts

1 – Linear Flat Vee

2 – Linear Box Beam

2 Discrete Truss Attach Concepts

3 – Discrete Disk

4 – Discrete Ashtray

Baseline Orbiter

Baseline Booster

Mid LH2 Fuel Tank Selected

3rd Gen RLV Booster - Mach 8

Candidate Shape Retention Joint Attachments to Composite Sandwich Tank
Metallic Tanks

Materials

- Understanding Al alloy delaminations
  - What induces delams?
  - Design around them?
- Alternative alloys
  - System payoffs?

Objective

- Develop the technology required to design and fabricate full scale, reusable, metallic cryogenic tanks

Design and Analysis

- Maturing tank life verification strategies
  - NDE based statistical approach?
  - Proof test method?

Find The Flaws
Self Reacting-Friction Stir Welding

- Successful completion of full-scale circumferential FSW

- Successful SR-FSW of three gore dome welds
  - Final confidence panels welded – strength properties box shifted to the "colder side", pin tool RPM and travel speed must be slightly reduced

- Self-Reacting FSW is an enabling technology for (1) Reusability (near zero defect joints) and (2) Low Cost (self-reacting eliminates much tooling costs)
Objective
- Develop a reusable high use temperature (450°F) cryoinsulation that can be applied to complex structures by spray techniques or secondary bonding.

Reusable polyimide foam insulation which eliminates cryopumping
- Develop a process cycle which allows greater than 80% closed cells for a polyimide foam having a density of 2.0 pcf to 4.5 pcf.
- Develop a process cycle which allows foam filled honeycomb to be fabricated without causing degradation to organic honeycomb core.
- Develop a process to fabricate curved polyimide foam and foam filled honeycomb structures.

Develop Spray on Polyimide Foam Technique
- Develop a spray on polyimide foam process cycle which allows application to complex structure.
- Optimize process cycle to produce polyimide foam with more than 80% closed cells having a density of 2.0 pcf to 4.5 pcf.
- Fully characterize physical properties of polyimide foams produced by spray on process.

Optimize the secondary bonding procedure and characterizing the reusable polyimide foam
- Develop a process to form strong adhesive bonds between the foam and structure without damaging either.
Foam Filled Honeycomb Cryo-Insulation

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam</td>
<td>PDL-1034 Polyurethane Foam (adjacent to tank wall)</td>
<td>Cryogenic insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contribute to structure thermal protection</td>
</tr>
<tr>
<td>Foam</td>
<td>TEEK Polyimide Foam (adjacent to TPS)</td>
<td>Cryogenic insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contribute to structure thermal protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provide higher temperature capability/minimize TPS weight</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>Nomex Aramid Fiber/Phenolic Resin (3/8-in cell)</td>
<td>Provide additional strength to the foam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provide further strain compatibility with the metallic cryotank</td>
</tr>
<tr>
<td>Fabric/Film Laminate</td>
<td>BMI 2550 Supported Film Adhesive</td>
<td>Provide uniform surface for TPS bonding</td>
</tr>
</tbody>
</table>
Thermal Protection Systems

♦ Hot & Integrated Structures
  • CMC Control Surfaces
  • Metallic Materials for Hot Structures
  • High Temperature PMC’s
  • Fiber Optic Sensors

♦ Tanks
  • Composite Tanks
  • Metallic Tanks
  • Cryoinsulation

♦ TPS
  • Acreage
    • CMC Acreage TPS
    • Metallic TPS
    • Ablators
    • Blankets
    • Tiles
  • Leading Edges
    • 3000°F Passive Leading Edges
    • 3600°F Passive Leading Edges
    • Heat-Pipe-Cooled Leading Edges
    • Actively Cooled Leading Edges
  • Control Surface Seals
Objective
- Develop and demonstrate a ceramic matrix composite (CMC) TPS for multi-use on RLV's

Analysis
- Loads and material properties: Identify design loads and requirements, assemble candidate material thermal/structural properties
- Thermal/structural sizing of candidate concepts: Preliminary mass estimates, investigate critical design issues

Concept development
- Identify candidate concepts: Attachments, seals, panel size and configuration, insulation packaging
- Fabricate prototypes of promising concepts/constituents: Investigate attachment concepts, seal configuration, panel removal, etc.
**Objective**
- Develop and demonstrate a metallic TPS for multi-use on RLV's

**Effects of Thermal Bowing**
- Analytical predictions
  - Entry thermal bowing history

- Wind tunnel verification
  - Effect of bowed shapes on boundary layer transition

**Verification**
- Radiant pressure tests
  - Combined elevated temperatures and pressure

- 8 Ft HTT tests
  - Combined elevated temperatures, acoustics, pressure, and hot gas flow
Metallic Thermal Protection Systems

- Improved durability to micro-meteoroid and orbital debris (MMOD) and foreign object damage (FOD) compared to ceramic systems

- Does not require chemical waterproofing or re-waterproofing

- Highly modular design with mechanical attachment

- Reduced maintenance and repair turnaround

- Capable of flight through most weather conditions

POC: Marty Agrella, Oceaneering, (281) 228-5580
Curved MTPS

♦ Primary Components

- Metallic OML Panel
- Perimeter Water Seals
- OML Fasteners
- Standoffs to IML
- Insulation Packages
Durable Acreage TPS Technologies

Conformal Reusable Insulation (CRI)
- Durable, Low Cost Acreage TPS applicable to windward and leeward surfaces where $T_{\text{max}} < 2400^\circ\text{F}$
- New class of improved ceramic TPS for windward surfaces based on heritage flexible blanket and CMC technology

Higher Temperature Flexible Reusable Surface Insulation (HTFRSI)
- Durable, Low Cost Acreage TPS applicable to surfaces where $T_{\text{max}} < 900^\circ\text{F}$
- Higher Temperature fibrous polymer Felt TPS based on heritage nomex FRSI
CRI Performs Similarly to Tough Tile in Hypervelocity Testing

Testing at WSTF
6.8 ±0.2 km/s
45° Angle of Attack
0.555 cm Al-2017 T4 particles
~1 inch thick samples
Multiple CRI blankets were impacted with hypervelocity particles to simulate various on-orbit damages. These samples were then tested in an arc-jet to evaluate survivability & thermal performance during a single reentry heating cycle.

Comparing CRI to Tile with similar impact conditions:

All tests were successful showing no loss of material or excessive thermal heating to the substructure.
3000°F Passive Leading Edges

- **Objective**
  - Provide a C/C material system (substrate and coating) for lightly loaded leading edges with a multi-use temperature of ~ 3000°F

- Investigate rapid processing and non CVD coating techniques

- Investigate coating and sealant chemistries for higher temperature durability

- Investigate high and low conductivity fiber systems
X-37 Wing Leading Edge TPS Accomplishments/Future Work

Completed
♦ NASA Ames tested WLE materials 2003
♦ Down selected to TUFROC material 2003

Future Work
♦ BRI-20 process qualification
♦ HETC on BRI-20 process reproducibility at NASA Ames
♦ Nose cap arc jet testing at Ames
♦ 10x10x6 inch BRI-20 arc-jet test article production
♦ WLE Swept configuration arc jet test at NASA Ames

♦ ROCCI process reproducibility at NASA Ames
♦ HETC on ROCCI process reproducibility at NASA Ames
♦ Process reproducibility of TUFROC System
♦ WLE component part Certification and arc jet test
♦ WLE TPS qualification and certification complete
Objective
- Develop a composite material system (substrate and coating) for lightly loaded leading edges with a multi-use temperature > 3600°F

- Develop carbon fiber reinforce ceramic matrix composites and coatings

- Develop coatings for C/C.

- Develop and verify analytic tools for design and analysis of C/C fiber architectures for leading-edge applications.
X-43 Mach 10 Leading Edge and Coating Testing

- Flight conditions simulated during AEDC arc-jet test
  - Mach 10, 105,000 ft
  - Enthalpy = 2000 Btu/lb
  - $P_{t2} = 1.15$ atm
  - $q_{\text{cold wall}} \sim 1300$ Btu/ft$^2$-s
  - 130 sec
- Each survived all tests
- Several use BFG K321 5:1 C/C substrate

<table>
<thead>
<tr>
<th>Coating</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ir/HfO$_2$</td>
<td>(Engelhard)</td>
</tr>
<tr>
<td>HfC-based</td>
<td>(RCI)</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>(Synterials)</td>
</tr>
<tr>
<td>HfC/HfB$_2$</td>
<td>(GA)</td>
</tr>
<tr>
<td>SiC/HfC</td>
<td>(MER)</td>
</tr>
</tbody>
</table>

Photograph during test

Post-test photographs
Heat-Pipe-Cooled Leading Edges

- Heat pipes offer a light weight option for intermediate heat fluxes

- Heat pipes "smooth out" regions of high heat flux

- Leading edges are an ideal application for heat pipes
Heat-Pipe Wing Leading-Edge Test Articles

- Shuttle - heavy
  - Hastelloy-X container/wick
  - Na working fluid
  - Circular heat pipes

- Advanced systems - significant weight savings (Designed for NASP)
  - Mo-Re container/wick embedded in C/C
  - Li working fluid
  - D-shaped heat pipes

- Advanced STS
  - Hastelloy-X container/wick
  - Na working fluid
  - Rectangular heat pipes
C/C Heat-Pipe-Cooled Component

- Heat-pipe container:
  0.010-in. arc cast Mo-41Re
    - High strength
    - High use temperature
    - Ductile at room temperature
    - Weldable

- Heat-pipe working fluid:
  Lithium
    - Compatible with refractory metals

- Refractory-composite structure:
  0.040-in. 3-D C/C or C/SiC
    - High use temperature
    - Lightweight

- Heat pipes maintained “cool” surface with $q_{inc} > 500$ Btu/ft²-s (passive surface would have been > 5500°F)

C/C heat-pipe temperature distribution
Control Surface Seals

- Objective
  - Develop robust, reusable, resilient, high temperature control surface seal concepts and verify performance in simulated environments

- Arc jet tests
  - Flow
  - Control Surface Seals

- Future CMC body flap

- CMC control surface seals

- Current seal SOA
  - Issue: Loss of Resiliency

- Seal preloader development
  - (e.g. ceramic, refractory metal)
X-38 Rudder/Fin Control Surface Seals

- X-38 rudder/fin control surface seal drawn from Shuttle thermal barrier technology; designed for < 1500°F use
- GRC/JSC tests showed that seal could only be used for single mission
  - Compression of seal at anticipated 1900°F operating temperature caused loss of resiliency due to permanent set of Inconel X-750 spring tube
  - Loss of seal resiliency required redesign of adjacent sealing surface to prevent gap openings during flight
  - Rough sealing surfaces damaged seals during actuation and scrubbing

Limitations of existing seal technology led to NGLT support of advanced control surface seal development
Thermal Barrier for Solid Rocket Motor Nozzle Joints

- Thiokol redesigned Shuttle RSRM nozzle joints with GRC carbon fiber rope (CFR) thermal barrier to prevent hot (5500°F) gas from affecting downstream O-rings. Currently assembling RSRM’s with thermal barrier for future flights.

- Based on success in Shuttle RSRM’s, Aerojet using three thermal barriers in nozzle-to-case joint of Atlas V SRM’s to protect O-rings from hot (5500°F) gases.

Control Surface Seals

♦ GRC has developed a unique, high temperature, flexible ceramic wafer seal.

♦ Operating temperature limited only to the limit of wafer material
  • $\text{Si}_3\text{N}_4$: 2550°F long term, 3000°F short term
  • SiC: 3000°F long term

♦ Silicon nitride wafer seals on top of silicon nitride compression springs show promise as durable, resilient sealing system.

♦ Wafer seal flow rates are up to 32 times lower than those for best braided rope seals

♦ Preliminary test results: Wafers survived 1000 scrub cycles at 1600°F with no signs of damage. Future scrub tests planned at higher temperatures

♦ Silicon nitride compression springs provided resiliency and kept seal in contact with sealing surface at high temperatures
ASTP High Temperature Materials Needs

♦ **Airframe**
  - Hot Structures/Control Surfaces
  - Tanks
  - TPS

♦ **Propulsion**
  - Rotating Components and Seals
  - Flowpath Components
High Temp/High Specific Strength Materials

♦ Objective
Assess potential of TiAl alloy, Gamma Met PX, for application in RTA as a compressor component and/or potential structural material.

♦ Approach
Determine effect of microstructure and high temperature exposure on mechanical properties of Gamma Met PX.

♦ Benefits
- Reduce weight of compressor components by 30% compared to Ni-base superalloys.
- Reduce weight of backstructure by 40% compared to Ni-base superalloys.

Advanced TiAl Alloy Shown to have Similar Mechanical Properties as Ni-base Superalloys, plus 50% Lower Density
High Temp/High Specific Strength Materials

♦ Objective:
  • Achieve weight reduction in TBCC engine through development of turbine blade-to-disk bonding techniques.

♦ Approach:
  • Bond state-of-art single crystal turbine blades to powder metallurgy disk materials.
  • Screen candidate braze alloys microstructurally and mechanically.

♦ Accomplishments:
  • 17 Ni-base braze alloys evaluated microstructurally after processing and simulated mission testing.
  • Several promising braze alloys produced good bonds. Mechanical evaluation to follow.
Objective
Develop and demonstrate actively-cooled ceramic matrix composites heat exchanger designs that can meet a range of potential thermal and structural requirements for future reusable launch vehicles.

Approach
Various programs have pursued multiple concepts and materials since NASP:

Concepts
- Inserted metal tubes in composite
- Co-processed metallic tubes
- Intimate contact metallic tubes
- All composite heat exchanger

Materials
- Carbon/Carbon (C/C)
- Carbon/Silicon Carbide (C/SiC)
- Silicon Carbide/Silicon Carbide (SiC/SiC)

♦ Current focus is on all-composite systems

Inserted Metal Tubes in Composite
Co-processed Metallic Tubes
Intimate Contact Metallic Tubes
All Composite Structures

6" x 30" Panel
# Actively-Cooled Ceramic Composites

<table>
<thead>
<tr>
<th>Year</th>
<th>Projects and Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990's</td>
<td>Inserted Metal Tubes in Composite, Coprocessed Metallic Tubes, Intimate Contact Metallic Tubes</td>
</tr>
<tr>
<td>2000</td>
<td>X-33/RLV Nozzle Ramp, 3rd Gen Cooled Composites</td>
</tr>
<tr>
<td>2001</td>
<td>P&amp;W Maintainable Cooled Composite Panels</td>
</tr>
<tr>
<td>2002</td>
<td>IHRPRPT Nozzle Ramp, RLV Actively Cooled Thrust Cells</td>
</tr>
<tr>
<td>2003</td>
<td>AFRL Advanced Combustion Chamber Concepts, IHRPRPT Actively-Cooled Nozzle Programs</td>
</tr>
<tr>
<td>2004</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td></td>
</tr>
</tbody>
</table>

**Materials:**
- Carbon/Carbon (C/C)
- Carbon/Silicon Carbide (C/SiC)
- Silicon Carbide/Silicon Carbide (SiC/SiC)
Example of Composite Heat Exchanger Weight Benefits (ref: P&W)

Note: Based on GTX Analysis

Results in a 5% to 10% Reduction In Vehicle Gross Take-Off Weight

HEX Weight

Metal Design

Composite Hot Face with Metal Tubes

All Composite Design
Lightweight High Temperature Structures

♦ Objective:
Develop low melt viscosity polymers for RTM, VARTM or RFI processing of high temperature propulsion components
  - Melt viscosities below 20Poise
  - \( T_g \) and stability suitable for use from 550°F to 750°F

♦ Approach:
Modify oligomer chemistry to reduce viscosity with minimal effect on \( T_g \) and stability
  - Molecular morphology – branching, twists, asymmetry
  - Formulated molecular weight
  - Endcap chemistry

♦ Partners:
Boeing, Clark Atlanta U, Maverick, NASA LaRC, Triton Systems, Tuskegee U

RTM = Resin Transfer Molding
RFI = Resin Film Infusion
VARTM = Vacuum Assisted Resin Transfer Molding
Lightweight High Temperature Structures

**GPRA Milestone:** Develop RTM processable polymer for use at temperatures up to 550°F (288°C)

**67% Retention of RT Properties at 650°F**

![Bar graph showing Interlaminar Shear Strength at 650°F](image)

**Complex Structures Made by RFI**

![Example complex structure](image)

**Milestone Successfully completed!**

New high temperature polyimide, HFPE, developed:
- Processable by Resin Film Infusion (RTM variant) into a variety of complex shapes
- Outstanding retention of mechanical properties at temperatures up to 650°F
  - Exceeds milestone target by 100°F and state-of-the-art by 200°F

- Use of HFPE in flow path component backing structures will reduce component weight by 20-30% vs. metallic backing structures

- Further development planned in NGLT
  - Durability studies with Cornell and Syracuse Universities under Propulsion URETI
High Conductivity Materials

Objective: Determine feasibility of ultrahigh conductivity metals and composites for high heat flux applications.

♦ Approach: Examine 3 concepts
  • Cu alloys beyond GRCop-84
  • MMC's made with diamond reinforced copper
  • Nickel Aluminide bimetallics

♦ Benefits:
  • Higher temperature capability improves rocket performance;
  • Reduces cooling requirements
  • Improves life

♦ Accomplishments:
  • First ever diamond reinforced copper matrix (D/Cu) metal matrix composites (MMCs) for actively cooled propulsion structures

![Cast D/Cu Plate]

Diamond/Copper MMCs Successfully Produced
High Conductivity Materials

First Ever Particulate Diamond Reinforced Copper Matrix MMCs Tensile Strength Tested

- Composites show good bonding between copper and diamond particulates
- Material can be machined using conventional techniques
- Samples currently being tested for higher thermal conductivity and greater strength than current SOA Cu alloy
  - Properties can be tailored for particular design applications
    - Specimens have fair but not exceptional strength
      - (Yield = 15.5 ksi and UTS = 25.8 ksi)
    - Reproducibility & high ductility indicate good consolidation

20-40 μm Mo Coated Diamond

Cu Matrix

SEM Micrograph of Cast D/Cu Plate
High Conductivity Materials

**Objective:**
- Determine feasibility of high-temperature coatings to protect Cu-base materials in aggressive environments

**Accomplishments:**
- Candidate coatings evaluated in simulated combustion environments
- NiCrAlY confirmed as blanching resistant (in cyclic oxidation-reduction simulations)

**Significance:**
- Coatings can extend temperature capability and life of Cu-base materials at lower risk.

Excellent durability of NiCrAlY in combustion environments

Blue curve shows continuous growth of oxide scale, making NiCrAlY resist degradation even in reducing environment.
Summary

- In spite of the current vehicular uncertainty in accomplishing NASA’s exploration goals, increasingly higher temperature, lighter weight materials will continue to be key to the success of future NASA missions.

- NASA’s current research efforts on high temperature materials are broadly based across material classes (e.g., metallics, polymers, ceramics, composites) but focused on addressing specific issues to enable proposed vehicles.