# Fabrication and Testing of Ceramic Matrix Composite Rocket Propulsion Components


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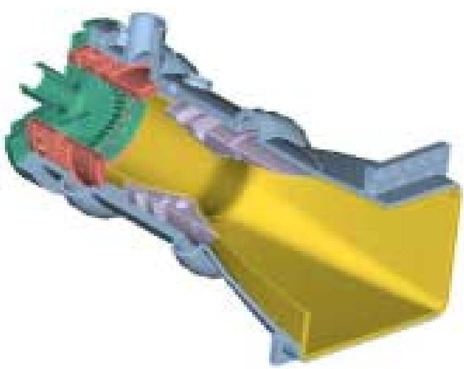

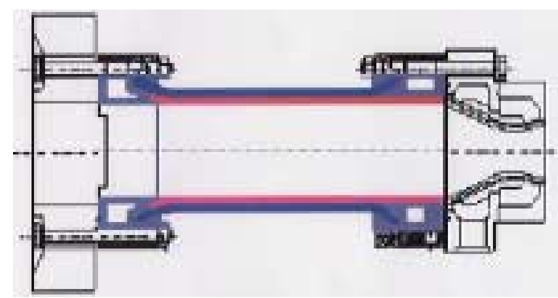

# Acknowledgements

- The authors are very grateful for the outstanding expertise the following colleagues and organizations contributed to make this presentation possible:
  - CMC Blisk program members:
    - Shayne Swint (Program Manager), Kathy Mims (Program Coordinator), Eric Earhart, Wayne Gregg, Don Harris, Jose Roman, Ward Overton, Ricky Wilbanks, Ron Beshears, Mike Effinger, Gary Genge, John Forbes, Matt Marsh--all MSFC, & Doug Kiser--GRC
    - Participating Organizations: Southern Research Institute, Honeywell Advanced Composites Inc., White Sands Test Facility, Argonne National Laboratory, Oak Ridge National Laboratory, Test Devices, Lockheed Martin Corporation, University of Alabama at Huntsville, Louisiana Tech University, University of Illinois at Urbana Champaign
  - Gas Generator program members
    - Janos Borsody (Program Manager), Jerry Lang, Andy Eckel, Jay Singh, Roy Sullivan, Ted Kovacevich--GRC, Jay Dennis, Andy Hissam, Hai Nguyen, Leigh Ann Perkins, Rene Ortega, Doug Fox, Jeff Lackey--MSFC
    - Participating Organizations: Honeywell Advanced Composites Inc., Rocketdyne Division of Boeing, Materials Research and Design
  - Nozzle Ramp program members
    - Corky Clinton--MSFC, Andy Eckel--GRC, David Glass--LaRC
    - Participating Organizations: Rockwell Science Center, Honeywell Advanced Composites Inc., Refractory Composites Inc., Snecma/SEP, Rocketdyne Division of Boeing
  - Thrust Cell program members
    - Sandy Elam, Mike Effinger, Pete Valentine--MSFC, and Martha Jaskowiak, Andy Eckel--GRC
    - Participating Organizations: Rocketdyne Division of Boeing, Hyper-Therm, Inc., Ceramic Composites, Inc.

# Presentation Agenda

- NASA's Goals
- Benefits of CMCs
- Simplex CMC Blisk Testing
  - Simplex CMC Blisk Follow-on
- CMC Cooled Nozzle Ramp Program
- Cooled Thrust Chambers
- C/SiC Gas Generator
- Summary

# Enterprise Goals


## GOALS: Earth-to-Orbit

- Within 10 years,
  - Increase the safety by two orders of magnitude
  - Reduce the cost to NASA transportation of placing payloads in orbit by one order of magnitude.
- Within 25 years,
  - Increase the safety by four orders of magnitude.
  - Reduce the cost of placing payloads in orbit by two orders of magnitude.

## GOALS: In-Space Transportation

- Within 15 years,
  - A factor of ten reduction in the cost of Earth orbital transportation.
  - A factor of two to three reduction in propulsion system mass and travel time required for planetary missions.
- Within 25 Years,
  - Enable bold new missions to the edge of the solar system and beyond by reducing travel times by one to two orders of magnitude.

# Generations of Reusable Launch Vehicles

**Today: Space Shuttle**
**1st Generation RLV**

- Orbital Scientific Platform
- Satellite Retrieval and Repair
- Satellite Deployment

**2010: 2nd Generation RLV**

- Space Transportation
- Rendezvous, Docking, Crew Transfer
- Other on-orbit operations
- ISS Orbital Scientific Platform
- 10x Cheaper
- 100x Safer


**2025: 3rd Generation RLV**

- New Markets Enabled
- Multiple Platforms / Destinations
- 100x Cheaper
- 10,000x Safer

**2040: 4th Generation RLV**

- Routine Passenger Space Travel
- 1,000x Cheaper
- 20,000x Safer

# Advanced Space Transportation Investment Areas

| | Pillar 3 | | | | | |
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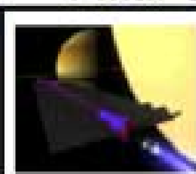
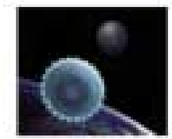
| |  |  |  |  |  |  |
| **Goal** | Earth-to-Orbit | Earth-to-Orbit | In-Space | In-Space | Earth-to-Orbit | Earth-to-Orbit & In-Space |
| **Investment Area** | Small Payload Focused | RLV Focused | In Space Focused | Interstellar Precursor | Space Systems Base | Space Transportation Research |
| **Projects** | Fastrac<br>Bantam | Propulsion<br>Airframe | Low Cost Upper Stages<br>Electric<br>Advanced Cryo<br>Tehthers<br>Non-toxic | Sails<br>Electric | Propulsion<br>Airframe<br>TPS<br>IVHM<br>Operations & Range<br>Vehicle Systems | 4th Generation Launch<br>Omniplanetary<br>Interstellar |

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- Provide the basic building blocks of propulsion, airframe, TPS, IVHM and operations technologies to meet space transportation system goals
- Mature technologies toward flight demonstration and advanced development
- Provide technology focus for future generations of space transportation systems
- Develop breakthrough concepts to enable missions that are currently not technically or economically feasible

# Benefits of CMC Components for Space Transportation Propulsion Applications

- Ceramic matrix composite (CMC) components are being developed by NASA to ***enable significant increases*** in engine performance and safety, and to reduce costs.
- CMC components provide opportunities for pursuing ‘Revolutionary Propulsion Concepts,’ enabling new, higher efficiency systems that can operate at higher temperatures with increased safety.
- CMC components can enable the achievement of safety and cost goals as follows:
  - CMC components can increase the safety margin due to higher temperature capability and higher damping capacity, while minimizing system complexity (e.g.--elimination of need for cooling, fewer parts) and component and system weight.
  - Low density of CMCs can allow increased thrust to weight and minimizes effects on stability when material is lost from rotating components.
  - CMC components can decrease costs via higher temperature capability, low part count (example--integrally bladed disk), and increased component life.

# Potential Space Transportation Propulsion Applications of CMCs

- **Turbopump and Combustion Components:** Blisks, stator/nozzles, gas path ducting, tip seals, combustors, inserted blades, and housings

- **Actively-cooled Components:** Nozzles (ramps, bells, extensions), combustion chambers (hot gas flow path), thrust cells, manifolds, and heat exchangers.

- **Uncooled Thin Wall Structures:** Nozzles (radiation cooled), combustion chambers, and manifolds/ducts.

**The use of CMC components & systems is projected to be the only way, aside from design and system engineering, to *significantly* increase safety & reduce cost simultaneously, largely due to increasing temperature margins and operational temperature at the same time, *while* decreasing weight.**

**No other material can do this.**

# Simplex Turbopump C/SiC Blisk Program

## Program Description

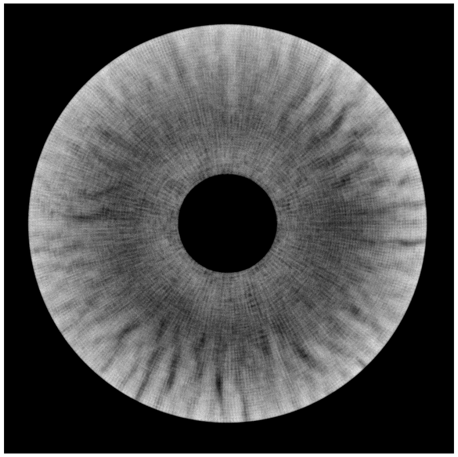
### Goals

- Identify and solve issues related to using Ceramic Matrix Composites in Rocket Turbomachinery
- Take technology to TRL Level 6
- Transfer knowledge gained from the program to industry

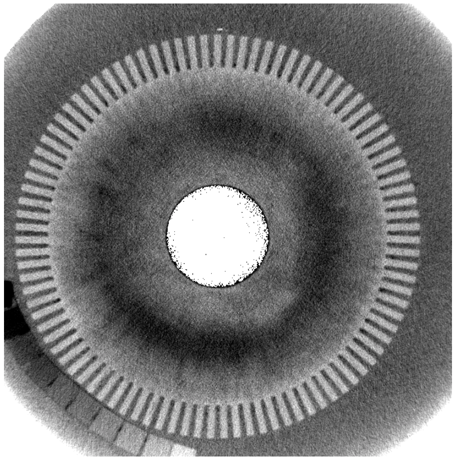
### Challenges

- Fabricate a disk 8″ in diameter
- Demonstrate that the material could withstand the vibrational loads seen in a transonic turbine
  - Thermal issues not addressed in this program

# Simplex C/SiC Blisk Images



Computed Tomography image of polar CMC disk at mid-process



Computed Tomography image of polar CMC Simplex blisk

Nominal appearance of C/SiC blisk surface (Honeywell Advanced Composites, Inc.)

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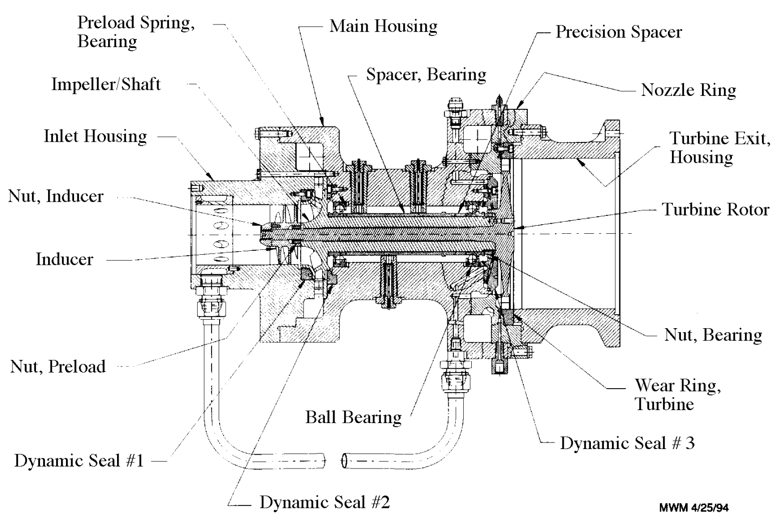
# Simplex Turbopump C/SiC Blisk Program

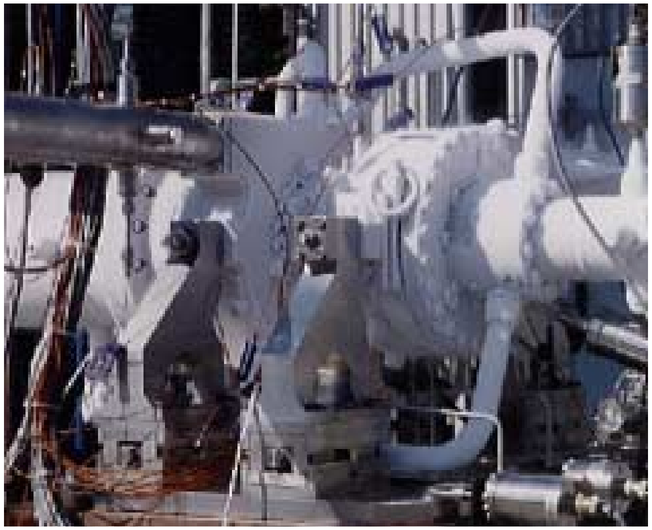



Simplex Turbopump in original baseline configuration

- Turbine Rotor replaced with C/SiC bladed disks (blisks).
- Two weave configurations tested
  - Polar Woven
  - Quasi-isotropic Lay-up

## Simplex operating conditions

| **Parameter** | **Simplex Inlet** |
|---|---|
| Temperature (F) | -250 |
| Pressure (psia) | 700 |
| Flowrate (lbm/sec) | 13 |
| Speed (RPM) | 25,100 |
| Blisk Diameter (in) | 7.6 |
| Turbine Tip Speed (ft/Sec) | 832 |



Simplex Turbopump Test Bed at NASA MSFC during chill down prior to testing.

# Simplex Turbopump C/SiC Blisk Testing Results

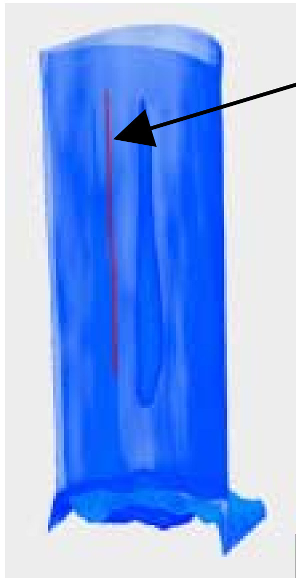
## Polar Blisk Test Summary

| Test | Time (sec) > 24,000 rpm | Time (sec) > 20,000 rpm | Max Speed (rpm) |
|---|---|---|---|
| 1 $LN_2$ | 0 | 0 | 0 |
| 2 | 0 | 57 | 20600 |
| 3 | 0 | 93 | 19400 |
| 4 | 0 | 136 | 20920 |
| 5 | 11 | 89 | 25390 |
| 6 | 169 | 279 | 25130 |
| 7 | 25 | 125 | 24700 |
| 8 LOX | 183 | 297 | 24510 |
| 9 | 0 | 9 | 20140 |
| 10 | 197 | 293 | 24080 |
| 11 | 175 | 288 | 24090 |
| 12 | 187 | 285 | 24060 |
| 13 | 192 | 301 | 24100 |
| 13 | 1139 | 2252 | |

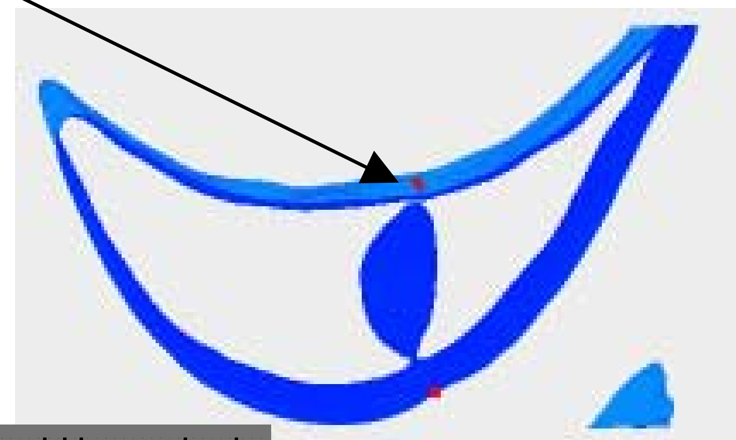
Worst Case Damage on Polar Blisk

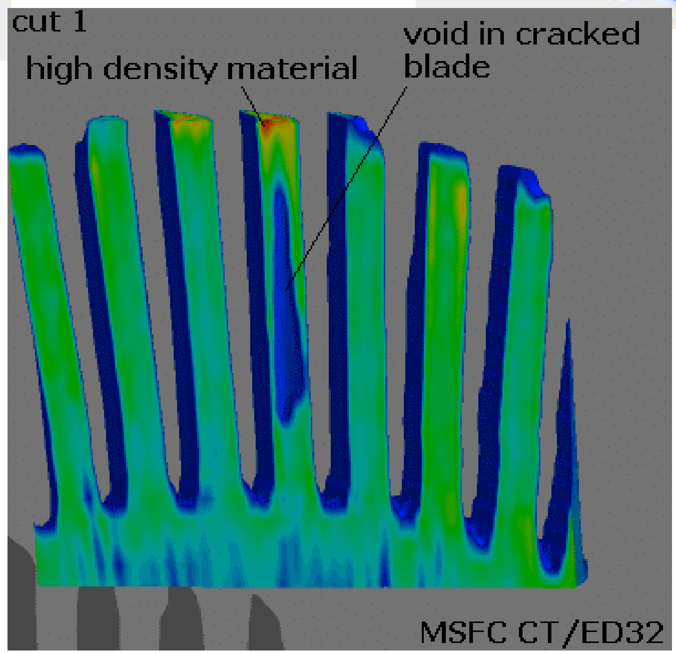
# Images of C/SiC Simplex Blisk Results

Cracked Polar Blade



Portion of cracked polar blade discernable by computed tomography.





# Simplex Turbopump C/SiC Blisk Testing Results

## Quasi-Isotropic Blisk Test Summary

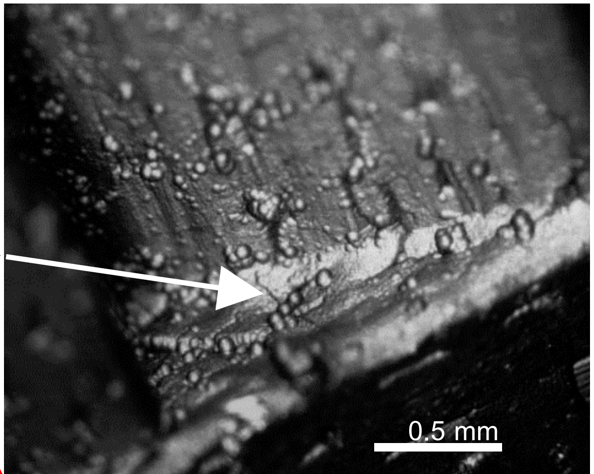
| Test | Time (sec) > 24,000 rpm | Time (sec) > 20,000 rpm | Max Speed (rpm) |
|---|---|---|---|
| 1 LN2 | 44 | 126.5 | 25490 |
| 2 | 169 | 260 | 25150 |
| 3 | 196 | 278 | 25180 |
| 4 | 189 | 266 | 25150 |
| 5 | 186 | 270 | 24920 |
| 6 | 199 | 278 | 25220 |
| 7 LOX | 43.1 | 116 | 24690 |
| 8 | 226 | 300 | 24100 |
| 9 | 221 | 296 | 24080 |
| 10 | 244 | 309 | 24190 |
| 10 | 1717.1 | 2499.5 | |

- No through cracks found in Quasi-isotropic Blisk
- Damage to leading and trailing edges is extensive
  - 57 of 95 blades showed some damage visible by boroscope
  - Some leading edges show impact damage
  - 9 trailing edges almost completely gone

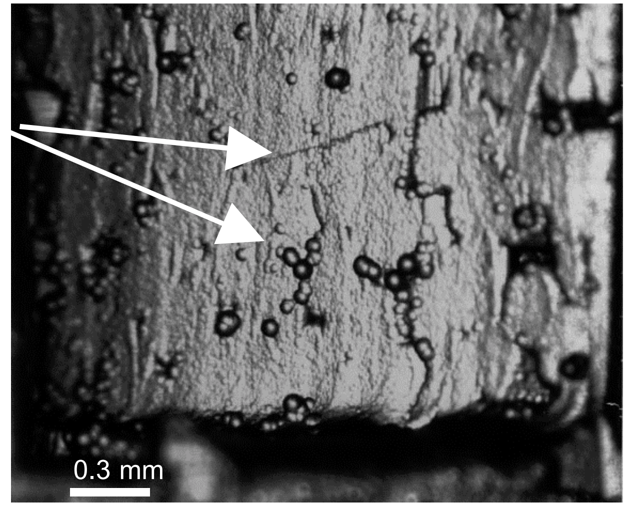
FOD impact pattern on Quasi-isotropic CMC blisk

**Mike Effinger**
Fabrication and Testing of Ceramic Matrix Composite Rocket Propulsion Components
**4th Conference on Aerospace Materials, Processes, and Environmental Technology**
**Huntsville, Alabama, September 18–20, 2000**

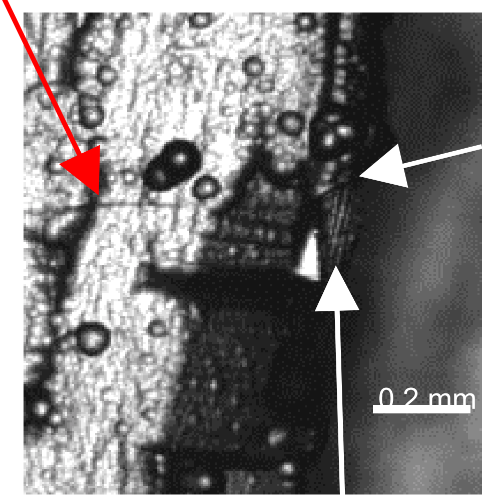
# Images of C/SiC Simplex Blisk Results



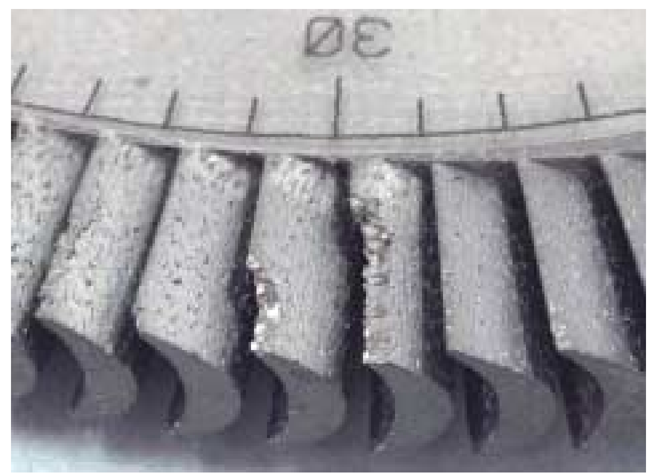
Crack at the blade root



Crack on the suction side



Typical spalling damage on the blade edges


Typical trailing edge damage on the quasi-isotropic blisk

# Simplex Turbopump CMC Blisk Program Accomplishments

- Manufactured 4 state-of-the-art C/SiC blisks
- 1st CMC blisk tested in a turbopump for a rocket engine
  - ~40 minutes test time and 5 million cycles for each C/SiC blisk, thus demonstrating the ability to withstand vibratory loading seen in turbopump
- CMC blisk operated nominally with loss of blade material and other less than desirable *a priori* conditions
- Successfully sustained FOD
- CMC computed tomography benchmarked at mid-process
  - Led to preforming improvements
- Blisk exposure to only mechanical and dynamic loads, and not thermal loads
  - Demonstrated value of Building Block Approach
  - Led to critical identification of mechanical and/or physical spalls and cracks which could limit lifetime
- 1st to acquire and publish CMC blisk damping data
- Nondestructive Characterization Life Prediction concept developed and established as a possibility (subject of AMPET Conference Paper in September)
- Executed an interagency cooperative effort with the Air Force through IHPRPT
- Benchmarked MSFC's structural & material analyses & component testing of a CMC component

# Likely Future CMC Development Path

- Approaches to Technology development:
  - Building Block Approach (BLA)--a stepwise process for development of materials and processes based on general requirements, materials property testing, subelement testing, and then full-scale testing.
  - Build and Bust Approach (BUA)--design and build a part with a new material, test the component with little knowledge of the material that was being tested.
- Grounds for Successful CMC Technology Development: Combine the Build and Bust Approach with the Building Block Approach
  - Least costly in the long-term.
  - Most effective, efficient approach to technology development.
  - Avoids developing a material that may not be usable in the actual system configuration.
  - Avoids building and testing components and systems that fail, with little or no knowledge of what was actually being tested.
  - Apparent down side to **Combined Approach**: Need up front, long-term and substantial commitment (**8 to 10 years**) from Congress, management, and engineers.
    - Greater than the 2-6 year terms of Politicians and longer than most managers and engineers want to spend in one job nowadays.
  - Actual up side to Combined Approach: **Avoid** most likely what would happen is a BUA (2-4 yrs), followed by a 1.5 BLA (12-15 yrs) in series to yield a total (**14-19 year effort**).

# Simplex Follow-On

- Objectives
  - Obtain additional data for correlation of natural frequency and damping changes to material degradation.
    - Coupon tests to be subjected to known load and cycles followed by Damping/Natural Frequency testing and subsequent tensile testing / microscopic inspection
    - Polar blisk to be run in the Simplex Turbopump for approximately 26 more tests. At midpoint of testing and at the completion of testing, Damping/Natural Frequency testing will be performed.
    - Blisk to be sectioned to determine damage accumulated and for comparison to tensile test coupon baseline material for correlation of NDE to material condition.
  - Demonstrate that the C/SiC blisk is capable of surviving the turbine conditions for the planned cycles.
  - Determine the impact on rotor stability of having material damping in the rotating system

# NASA's High Risk, High Payoff Cooled Composite Nozzle Ramp

- **Objective:** Develop and demonstrate lightweight actively cooled composite material systems for potential use as nozzle ramps for the Aerospike engine.
- **Benefits**
  - Reduced weight relative to cooled metallic designs.
  - Higher operating temperature capability minimizes or may eliminate re-entry cooling requirements offering potential for additional weight reduction.
- **Schedule** -- 44 month project
  - 1st 12 months - Concept Development/Definition; 4 vendors.
  - Months 13-44 - single vendor to produce increasingly larger, more complex structures subjected to battery of thermal, mechanical, aeroconvective and acoustic tests.
  - Culminates in test of ~30"x60" test article in an aerospike test stand.

# NASA's High Risk, High Payoff Cooled Composite Nozzle Ramp

## Baseline Requirements and Environments

| | |
|---|---|
| ◆ **Cold Wall Heat Flux (optional arrangement)** | **Hot Wall (3000°F) heat flux** |
| ✦ Maximum: 15 Btu/in$^2$-sec | • Maximum: 7 Btu/in$^2$-sec |
| ✦ Average: 7 Btu/in$^2$-sec | • Average: 4 Btu/in$^2$-sec |
| ◆ **Stagnation Gas Temperature** | **6000°F** |
| ◆ **Maximum static gas pressure** | **50 psia** |
| ◆ **Maximum shear load** | **5 psi** |
| ◆ **$LH_2$ Coolant Inlet Pressure** | **Above 4000 psi** |
| ◆ **Coolant Inlet to Exit Pressure Drop** | **Approximately 350 psid** |
| ◆ **$LH_2$ Coolant Inlet Temperature** | **Below -300°F** |
| ◆ **Coolant Flow Rate** | **0.8 lbm/sec per linear inch of ramp width** |
| ◆ **Inside ramp surface operating temperature** | **Thermal insulation may be required** |

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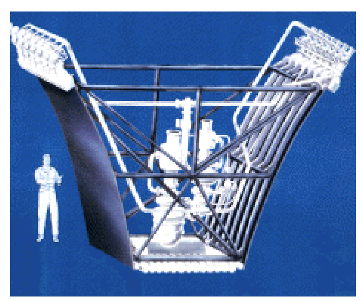
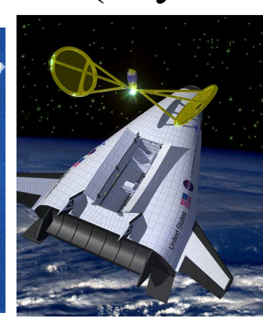
# NASA's High Risk, High Payoff Cooled Composite Nozzle Ramp

- **Key technology challenges**
  - Heat exchanger weight:
    - Project Requirement is 2.0 lb/ft$^2$ (Project Goal is 1.5 lb/ft$^2$)
  - Manifolding of coolant channels
  - Hermeticity of coolant channels
  - Severe thermal gradients and thermal strain mismatches between hot surface and cryogenic coolant tubes
  - Lightweight attachment schemes for panels to support structure
  - Manufacturing scale-up to Large Scale Test Article (LSTA) 30" x 60" size
  - Subsequent scale-up to full scale Aerospike engine nozzle (beyond project scope)
    - Baseline ramp length: ~180"
    - Baseline ramp width: ~90"
    - Radius of curvature: 90" maximum

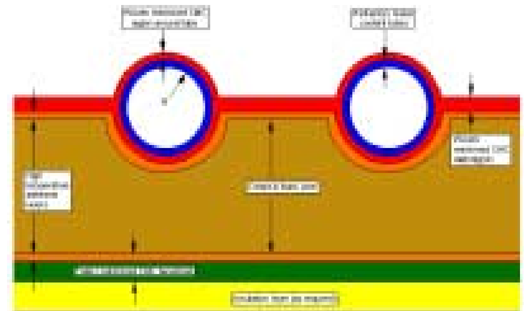

Refractory Composites Inc.



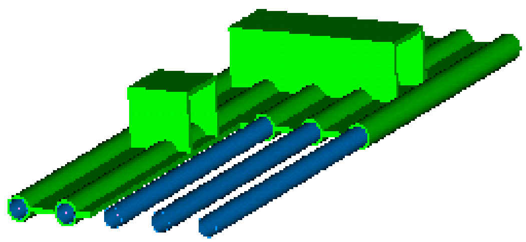


# NASA's High Risk, High Payoff Cooled Composite Nozzle Ramp

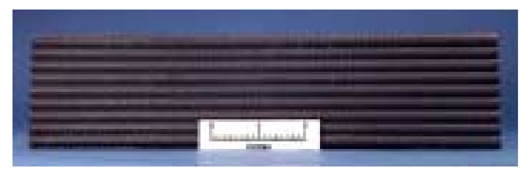
## ◆ Selected Vendors/Concepts

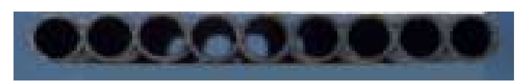


- ✦ Honeywell Advanced Composites

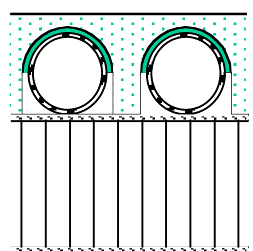


- ✦ Refractory Composites Inc.





- ✦ Rockwell Science Center



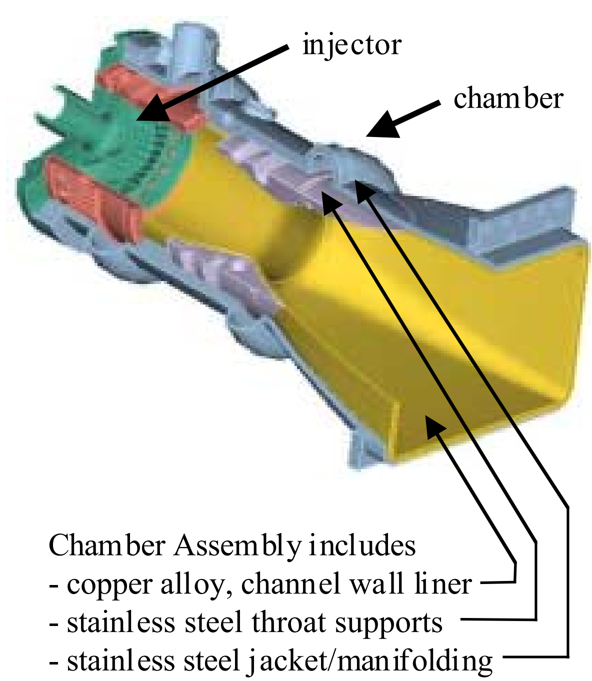
- ✦ Snecma/SEP

# Actively Cooled Thrust Chambers

- **Objective:** Reduce weight, increase operating temperatures of current thrust chamber designs

- **Approach**
  - Address material & fabrication issues for baseline design
  - Develop potential actively cooled CMC materials with small fabrication units
  - Test each CMC unit in appropriate conditions Hot-fire testing planned at NASA-GRC:
    - GOX/$GH_2$ at Pc = 1000 psi (MR=6)
    - Durations = 5-250 sec
    - Coolant = $LH_2$

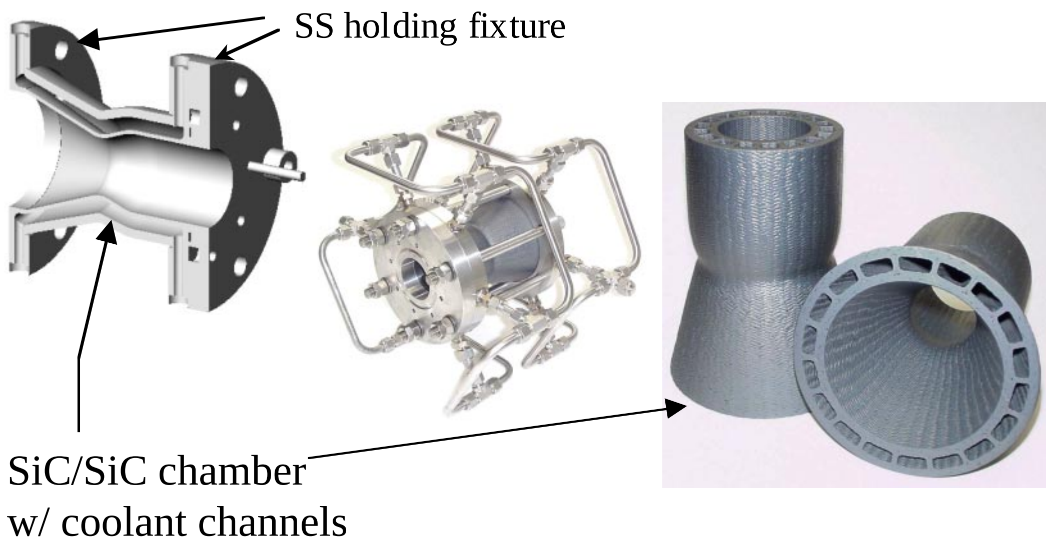
Baseline Design: X33 Thrust Cell




- **Challenges**
  - Acceptable permeability to contain hydrogen coolant
  - Appropriate manifolding for coolant supply
  - Oxidation resistance in hot thermal environment
- **CMC has Highest Weight, Cost, and Safety Payoff**
  - Replaces liner, throat supports, AND jacket/manifolds

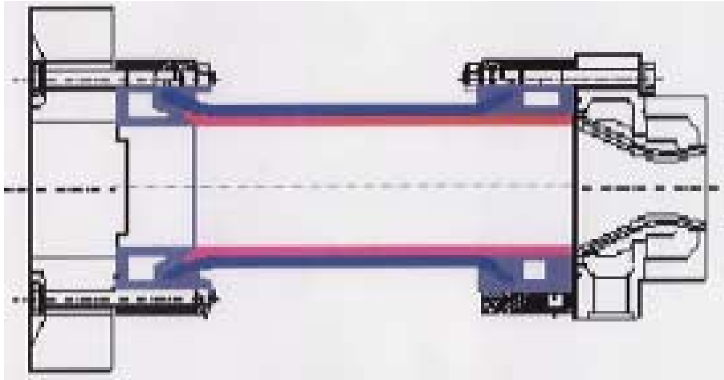
# Actively Cooled Thrust Chambers

- **Status**
  - Hyper-Therm, Inc.: SiC/SiC chamber with annular ring of woven coolant channels
    - Work initiated: July ‘99
    - Est. Completion Date: Sept ‘00
    - 3 complete preforms densified
    - Permeability testing planned
    - Leak checks & proof testing will be performed before delivery




  - Ceramic Composites, Inc.: C/C chamber surrounded by copper tubing
    - Work initiated: July ‘99
    - Delivery Date: Sept ‘00
    - 3 chambers delivered
    - Oxidation protection coatings
      - HfC/SiC coatings
    - Copper tubing for $LH_2$ coolant relieves permeability concerns

# Light-Weight Gas Generator



- **Objective:** Develop and demonstrate uncooled, hot gas impermeable ceramic composite structure
- **Approach:** Hot-Fire testing of sub-element
- **Challenges:**
  - CMC Architecture / Metal-Ceramic joint integrity
  - Gas impermeability
- **Status**:
  - Conceptual design selected - 8/99
  - Sub-element defined - 2/00 (Fabrication - 50% completion)
  - Hot-Fire testing target date - 12/00

# Summary

- NASA has established goals for Second and Third Generation Reusable Launch Vehicles. Emphasis has been placed on significantly improving safety and decreasing the cost of transporting payloads to orbit.
- CMC components are being developed by NASA to ***enable significant*** increases in safety and engine performance, while reducing costs.
- The development of the following CMC components is being pursued by NASA: Simplex CMC Blisk, Cooled CMC Nozzle Ramps, Cooled CMC Thrust Chambers, and CMC Gas Generator.
- These development efforts are application oriented, but have a strong underpinning of fundamental understanding of processing-microstructure-property relationships relative to structural analyses, nondestructive characterization, and material behavior analysis at the coupon and component and system operation levels.
- As each effort matures, emphasis will be placed on optimizing and demonstrating material/component durability, ideally using a combined Building Block Approach and Build and Bust Approach.

# Web Addresses

- NASA's Space Transportation: http://std.msfc.nasa.gov/
- NASA MSFC's Materials, Processes, & Manufacturing Department: http://mpm.msfc.nasa.gov/
- NASA GRC's Materials Division: http://www.lerc.nasa.gov/WWW/MDWeb/
- AMPET Home Page (4th Conference on Aerospace Materials, Processes, and Environmental Technology): http://AMPET.MSFC.NASA.GOV/