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GTX Project Summary

Space Transportation Day
October 11-12, 2000

Space Transportation Technology Workshop

537825
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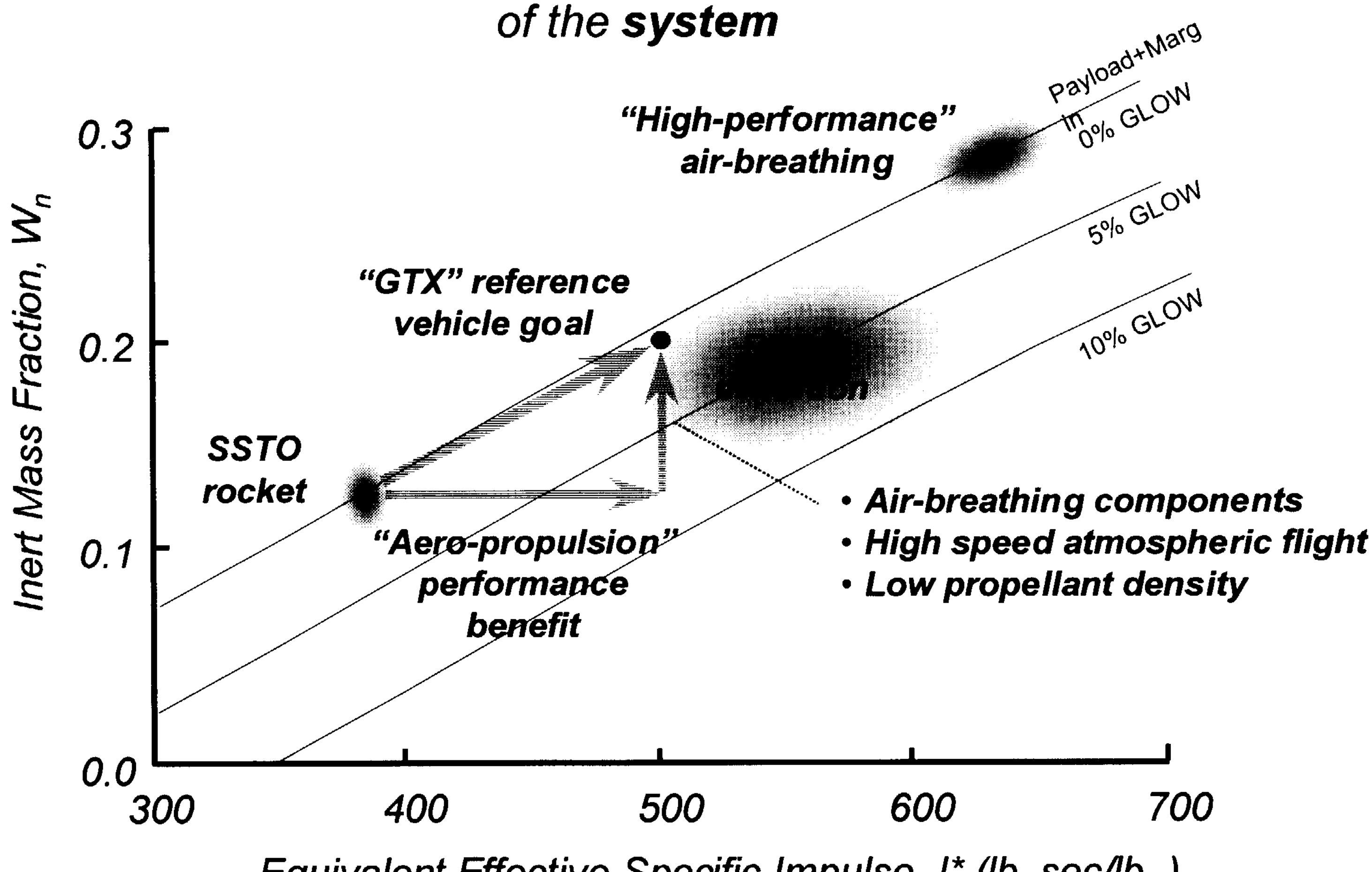
GTX Project Objectives

- Determine whether or not air-breathing propulsion can enable reusable SSTO
- Provide validated system performance data, and a baseline system design
- Develop technologies applicable to high-speed air-breathing propulsion

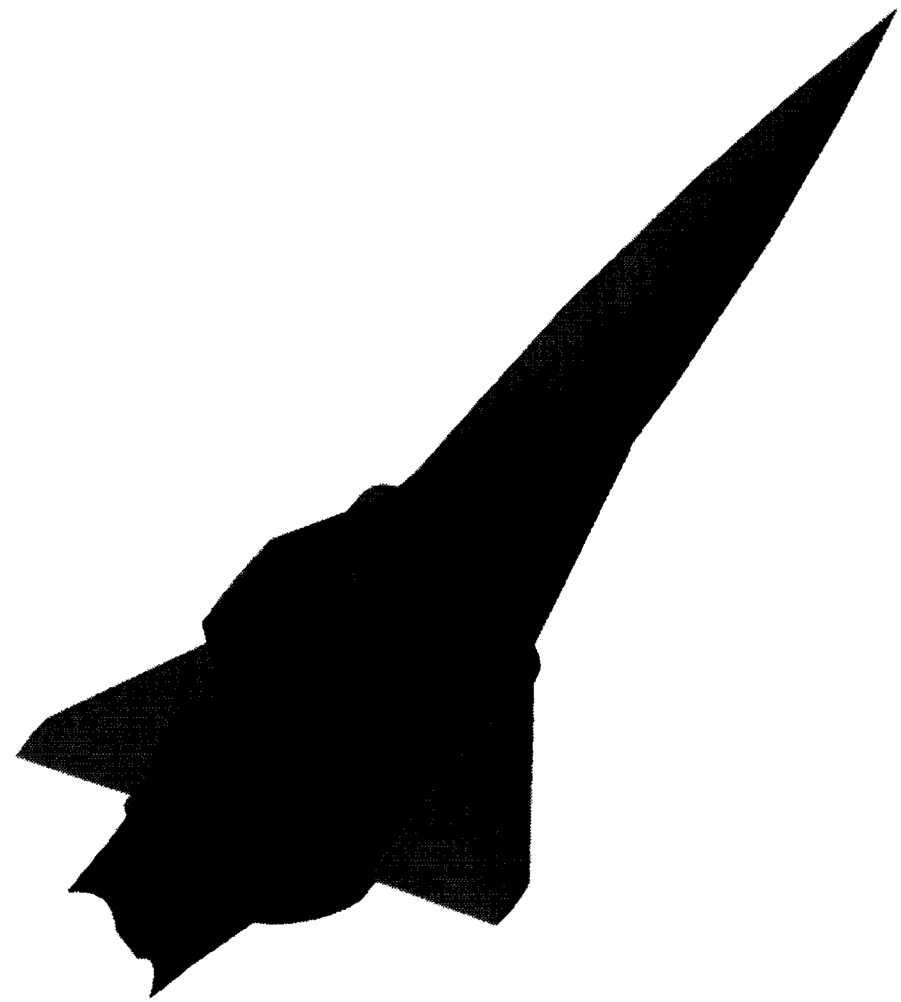
Reusable SSTO Performance Axes

*The net benefit of air-breathing propulsion depends on the aero-propulsion and structural performance of the **system***

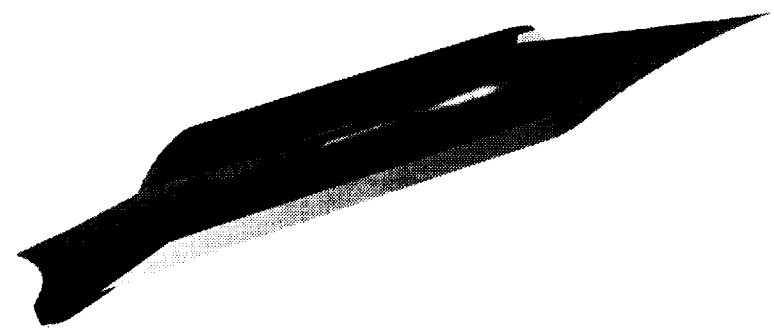


GTX Reference Vehicle Description

- Reusable, Single-Stage-to-Orbit
- Vertical Lift-Off / Horizontal Landing
- RBCC Propulsion System Operates in 4 Modes
- 500 sec Minimum I* at Max A/B Mach 11
- 238,000 lb Gross Lift-Off Weight
- LOX/LH2 Propellants
- 300# Payload

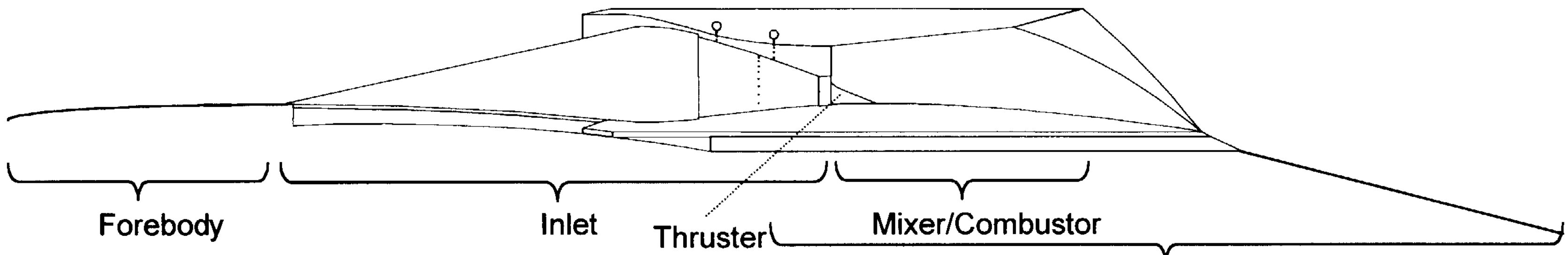


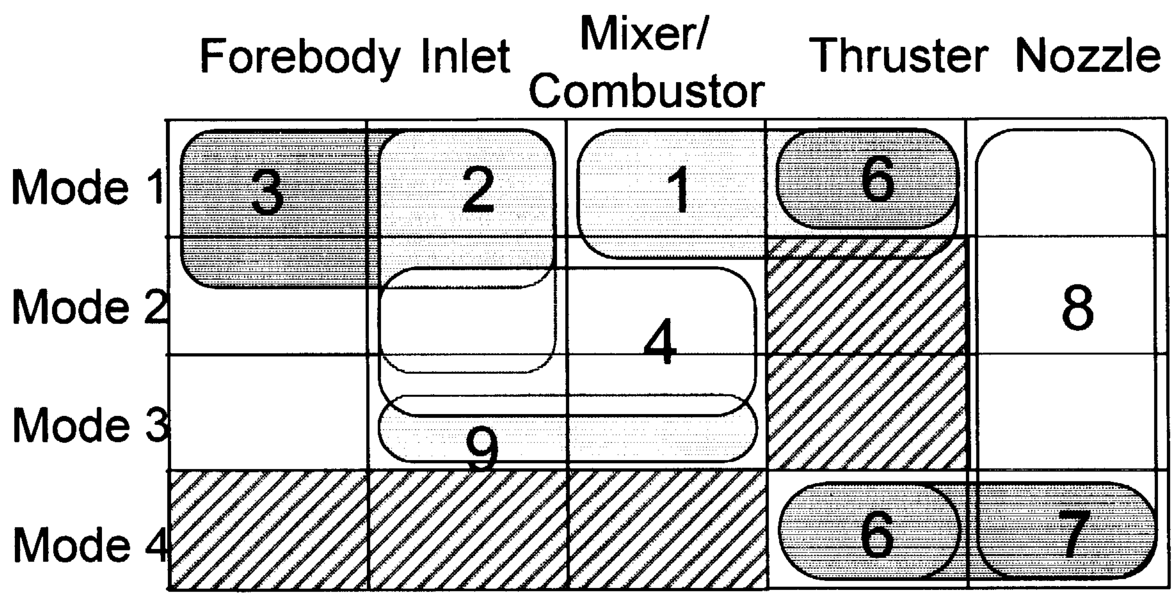
- Independent Ramjet Stream and Simultaneous Mixing and Combustion (SMC) Ejector-Ramjet Cycles Under Consideration
  - Lower risk, nearer-term than more complex concepts (e.g. SERJ, LACE)
  - Adequate performance for 500 sec I^* goal at moderate rocket re-ignition Mach number
  - Shorter and lighter than the diffusion and afterburning (DAB) scheme
  - More compatible with rocket mode than other cycles
- Axi-symmetric Flowpath Configuration
  - More structurally efficient than 2-D rectangular
  - Reduced design and analysis risk
- Mixed-Compression, Translating Centerbody Inlets
  - Provides required throat area variation, and flowpath close-off for rocket mode
  - Existing design database
  - Minimal sealing issues

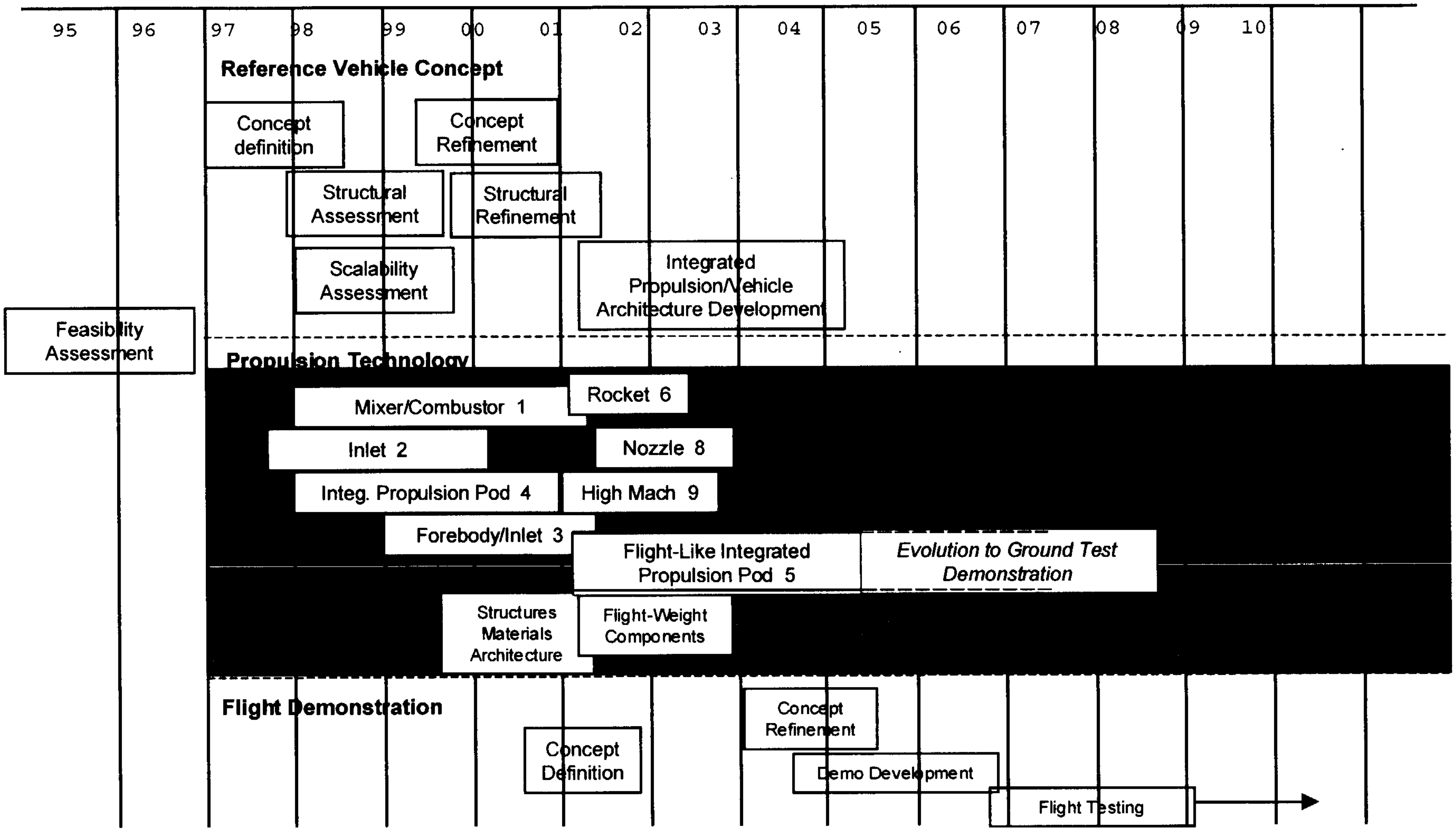


GTX RBCC Propulsion System Features

Planned Flowpath Development Test Rigs







Numbers refer to GTX rig numbers

Space Transportation Technology Workshop

GTX Project Plan Overview

For More Information on GTX

Come to the GTX Session
at the
JANNAF 25th Airbreathing Propulsion
Subcommittee Meeting
November 13-17, 2000
Monterey, California

Process and Material Development for Fabrication of CMC Blisks

J. Kiser, 216-433-3247, James.D.Kiser@grc.nasa.gov

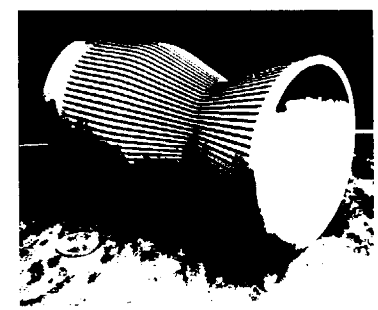
CMC Blisk

FY 01: CMC Blisk Project outlined and initiated
FY 03: Provide simple shape CMC disks to CCT
FY 06: Smooth blade surface technology demonstrated
FY 06: Demonstrate 12" diameter, 3" thick high strength disks

High Conductivity Materials

D. Ellis, 216-433-8736, David.L.Ellis@grc.nasa.gov

Thrust Cell Liner



FY 01: Complete experimental design for Cu-alloy development
FY 02: Complete screening of advanced copper alloys
FY 03: Determine feasibility of very high conductivity Metal Matrix Composites
FY 05: Determine mechanical and thermal properties of MMC's
FY 06: Demonstrate advanced alloy coating combination via hot fire testing

Tasks and Milestones

CMC Cooled Components

M. Jaskowiak, 216-433-5515

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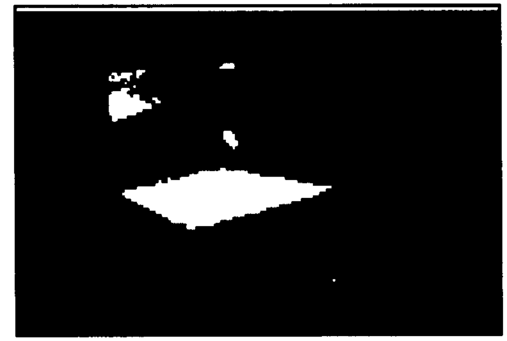
Actively-Cooled CMC Panel



FY 01: Heat exchanger concepts and uncooled concepts selected

FY 03: Thermal performance tests of first concepts

FY 05: Aeroconvective tests of first concepts

Polymers and PMC's for High Temperature Propulsion Applications

M. Meador, 216-433-9518, Michael.A.Meador@grc.nasa.gov

FY 02: Demonstrate RTM processable polymer for use at 550F

FY 03: Demonstrate high temperature polymer nanocomposites with improved mechanical properties and reduced gas permeability

FY 04: Develop and demonstrate polymers and PMCs with durability at 750°F

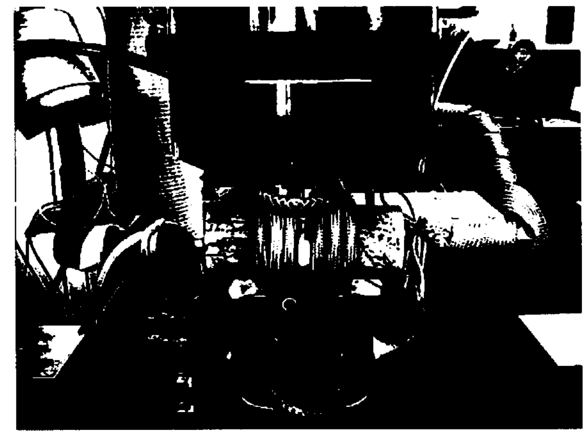
FY 05: Demonstrate enhanced cyrogenic toughness and durability of high temperature PMCs

FY 06: Demonstrate affordable PMC for 750°F applications

Tasks and Milestones

CMC's for Static Propulsion Components

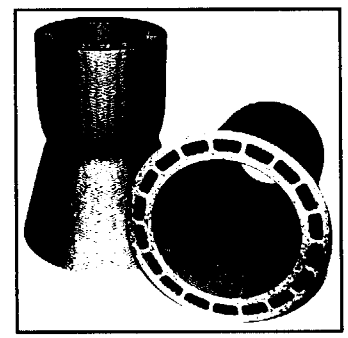
M. Freedman, 216-433-3284
Marc.R.Freedman@grc.nasa.gov



FY 01: Baseline materials characterized
FY 03: Screening capabilities updated
FY 05: Fiber architecture model verified
FY 07: Knowledgebase established

Ceramic Composite Thrust Chamber Development

J. Lang, 216-433-6675, Jerry.Lang@grc.nasa.gov

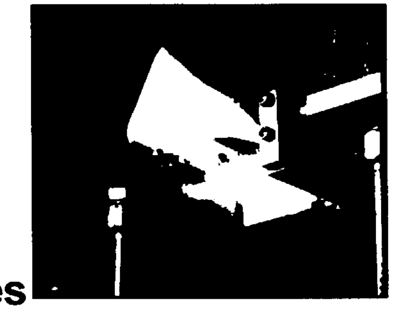


FY 01: Define and characterize CMC thrust chamber subelements
FY 03: Screen uncooled concepts for thrust chambers (RCS Scale)
FY 05: Screen regeneratively cooled concepts for thrust chambers

Tasks and Milestones

Cooled Leading Edge Concepts

D. Glass, 757-864-5423, d.e.glass@larc.nasa.gov



- FY 01: Complete survey of Gen 3 vehicle needs for leading edges
- FY 02: Fabricate subcomponent test articles for leading edges
- FY 03: Test leading edge subcomponents in challenging aerothermal environment
- FY 04: Identify leading edge with 2X life compared with FY 00
- FY 06: Identify leading edge with 5X life compared with FY 00

National Durability Test Apparatus

L. Greenbauer-Seng, 216-433-6781,
Leslie.A.Greenbauer-Seng@grc.nasa.gov

- FY 01: Examine industry critical materials needs based on selected Gen 3 engines
- FY 01: Initiate design of quick access test rig
- FY 01: Initiate construction of low cost, low fidelity test rig
- FY 03: Construct higher fidelity quick access rig
- FY 04: Operate Quick Access rig for government and industry materials evaluation

Tasks and Milestones

RLV 3rd Generation Supplemental Slides

The following slides provide additional information on select RLV 3rd Generation Long Life, Light Weight Materials Tasks

Goals and Objectives:

- Improve the durability, reliability, performance and affordability of polymer matrix composite propulsion components for space transportation systems

Background

- Current high temperature PMCs have poor long-term stability at temperatures above 650°F, poor durability at cryogenic temperatures and high manufacturing costs

Current Status/Major Accomplishments:

Recent work at GRC has led to:

- Solvent based low cost manufacturing (saRTM) for use with 650 -700°F PMCs
- RTM processable PMCs for use at temperatures up to 500°F
- High temperature clay/polymer nanocomposites
- Improved understanding on the durability of braided PMC structures

Near Term Milestones:

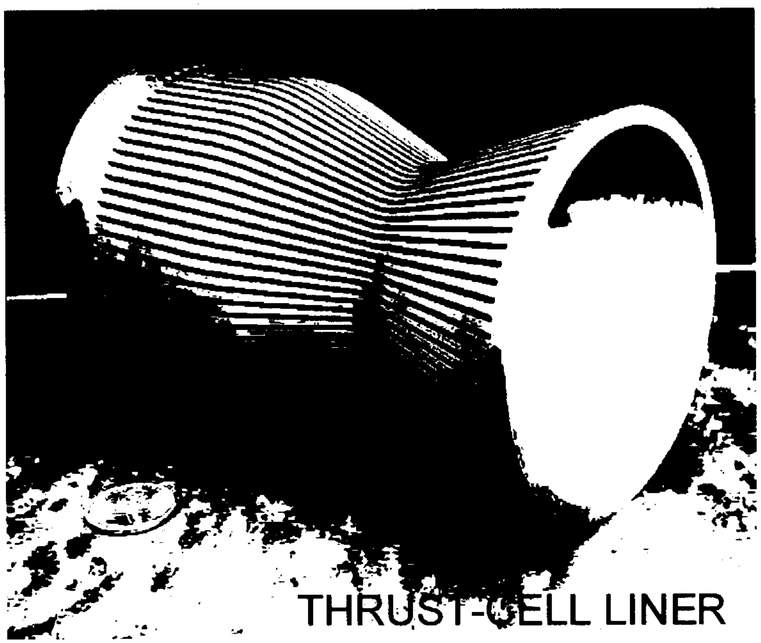
- Demonstrate RTM processable 550°F polymer for propulsion applications (*FY02*)
- Develop/demonstrate high temperature polymer nanocomposite with improved mechanical properties and reduced gas permeability (*FY03*)
- Develop/demonstrate polymers and PMCs with durability at 750°F (*FY04*)
- Demonstate enhanced cryogenic toughness and durability of high temp PMCs (*FY05*)
- Demonstrate affordable 750°F PMC (*FY06*)

Point of Contact:

Michael A. Meador, (216) 433-9518, Michael.A.Meador@grc.nasa.gov

Polymers and Polymer Matrix Composites for Propulsion Components

BLANCHING : Generation of Interconnected Porosity from Cycles Between Oxidizing & Reducing Environments


THRUST-CELL LINER

COATINGS SYSTEMS FOR BLANCHING PROTECTION

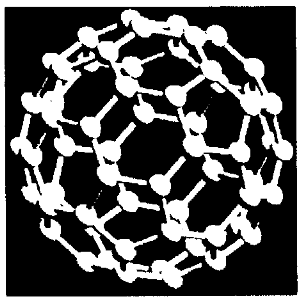
- **CURRENT**: NiCrAlY SYSTEMS
- **GEN-2:** Cu-Cr SYSTEMS
- **GEN-3:** NON-Cr_2O_3-FORMING SYSTEMS

- **Coatings can prevent environmental attacks such as blanching**
- **Advanced coatings can reduce hot wall temperature**
- **Both increase liner life and decrease operating expenses**

Coatings For Thrust Cell Liners

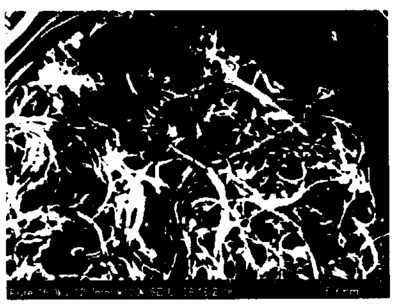
Diamond

- Thermal Conductivity – 2000 W/mK
- Hardest known substance



Buckyballs

- Unknown thermophysical properties
- Potentially very hard/strong
- May be chemically modified



Carbon Nanotubes

- Similar structure and properties to Buckyballs
- Long range potential to make fiber reinforced composites

Combined with a copper matrix, these particulates/fibers could produce low thermal expansion, ultra-high conductivity, high strength composites

Space Transportation Technology Workshop

Advanced Copper Matrix MMCs

Safe Life Propulsion Design Technologies

(3rd Generation Propulsion Research & Technology)

Rod Ellis
NASA Glenn Research Center

2nd Annual Space Transportation Day, October 11-12, 2000
Marshall Space Flight Center, Huntsville, Alabama

Task Titles

- Ceramic matrix composite (CMC) life prediction methods.
- Life Prediction methods for ultra high temperature polymer matrix composites for RLV airframe and engine application.
- Enabling design and life prediction technology for cost effective large-scale utilization of MMCs and innovative metallic material concepts.
- Probabilistic analysis methods for brittle materials and structures.
- Damage assessment in CMC propulsion components using nondestructive characterization (NDC) techniques.
- High temperature structural seals for RLV application.

Ceramic Matrix Composite (CMC) Life Prediction Methods (P-5-Ellis-2-t)
POC: Rod Ellis/5900, Stan Levine/5100

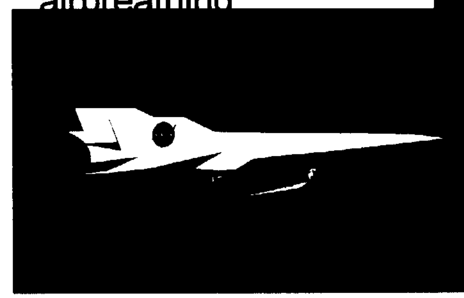
Goals/Objectives

To advance current empirically based life models to allow for the
- Ability to account for environmental effect on life.
- Ability to predict life for combined loads.
- Ability to predict component life.

Technical Challenges

- Understanding the physics of mechanical and environmental damage mechanisms leading to eventual material failure.
- Integrating environmental, micro-mechanics and macro-level damage models into a unified engineering design tool.

CMC are enabling for aerospike, advanced turbopumps, airbreathing



propulsion concepts, and airframe TPS and hot structure applications.

Approach

- Coordinated effort with sub-tasks addressing:
- Probabilistically based, macro-level, residual strength life model.
- Engineering mechanics model at the fiber/matrix level.
- Identification and modeling of governing chemistry of environmental attack and life extension methods.
- Generation of a robust lifting database characterizing the effect of environmental state variables (temperature, oxygen, and steam) on material strength degradation.

Milestones

Initiate procurement of CMCs (C/SiC, SiC/SiC) panels for coupon-level tests supporting development of life prediction methods, 1QFY01.
- Complete initial series of mechanical/thermomechanical tests supporting development of life prediction models, 4QFY02.
- Complete development of models characterizing key damage mechanisms in CMCs under oxidizing and steam-rich environments, 4QFY03.
- Complete development of CMC life prediction models including the combined effects of thermal/mechanical loading and environmental property degradation, 4QFY04.
- Complete development of life enhancing environmental coatings and thermal barrier coatings and publish results, 4QFY05.
- Complete subcomponent tests and use results to verify/validate the performance of CMC lifing methods in predicting behavior under complex stress states and service environments 4QFY06.

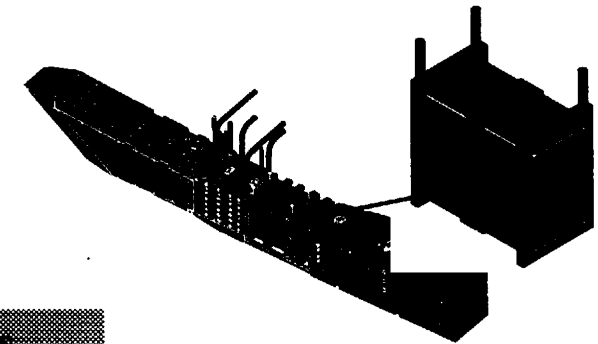
Life Prediction Methods For Ultra High Temperature (UHT) Polymer Matrix Composites (PMC) For RLV AirFrame and Engine Application (P-5-Ellis-1-t)

POC: Rod Ellis/5900, Mike Meador/5100

Goals/Objectives/Benefits

- Develop physics-based life prediction methods: Successful development is **enabling** given the need for safe, reliable, cost-effective **Reusable Launch Vehicles**.
- Support development of low-cost PMC: Fully **optimized** and **tailored** PMC materials will lead to highly efficient airframe and propulsion components.
- Develop comprehensive data bases for candidate UHT PMC: Data bases determined with Design of Experiments (DOE) methodology will lead to increased reliability and will support probabilistic analysis.
- Support development of advanced UHT PMC incorporating **nanotechnology**: Revolutionary gains in performance and reliability expected from this new class of materials.
- Develop new NDE techniques for UHT PMC incorporating nanotechnology: Successful development of NDE technology is key to assuring quality.
- Perform subcomponent tests to verify methodologies: Test will be conducted on composites in **scaled-up form** produced using **low-cost** manufacturing methods.

RBCC Manifolds & Support Structure



Technical Challenges

- Low Cost Manufacture
- Complex Environmental Issues
- Complex Deformation / Damage Mechanisms
- Uncertainties Associated With Nanotechnologies

Approach

- **Critical screening tests** will be conducted at **GRC** and **AFRL/WPAFB** on candidate PMC to evaluate material integrity and reusability under extreme thermo-mechanical loading conditions. Particular attention will be given to the role of heat rates, water, steam, and other limiting RLV environments.
- **Comprehensive data bases** will be generated for down selected materials at **GRC** and **under contract** focusing on standard mechanical properties. Also, nonstandard properties such as stiffness retention and residual strength will be determined in support of life prediction model development.
- **Physics-based life prediction models** will be developed which accurately model the damage mechanisms and failure mechanisms observed in the experimental studies. The analytical modeling effort will be pursued at **GRC** and at **Georgia Tech**.
- **Subcomponents** will be fabricated using low-cost manufacturing methods by well-established contractors and tested under prototypical loading conditions at **MSFC**. The analytical predictions of subcomponent deformation and fatigue behavior will be made at **GRC** using the advanced life prediction methods fully implemented into finite element codes.

Milestones

- Complete screening study of UHT PMCs with optimized 3D fiber architectures with the focus on moisture absorption and behavior under rapid thermal transients, 4QFY01.
- Complete development of continuum damage mechanics (CDM) model accounting for viscoelasticity and microcracking and publish results, 2QFY02.
- Complete initial series of coupon-level mechanical/thermomechanical tests supporting development of life prediction methods, 4QFY02.
- Complete development of PMC life prediction models including the combined effects of thermal/mechanical loading and environmental property degradation, 4QFY03.
- Complete initial screening tests on UHT PMCs with properties enhanced using nanocomposite technology, 4QFY04.
- Complete subcomponent test and use results to verify/validate the performance of PMC lifing methods in predicting behavior under multiaxial stress states and service environments 4QFY06.

Enabling Design and Life Prediction Technology for Cost Effective Large-Scale Utilization of MMCs and Innovative Metallic Concepts

(P-5-Arnold-1-t)

POC: Steve Arnold (5900), Mike Nathal (5100)

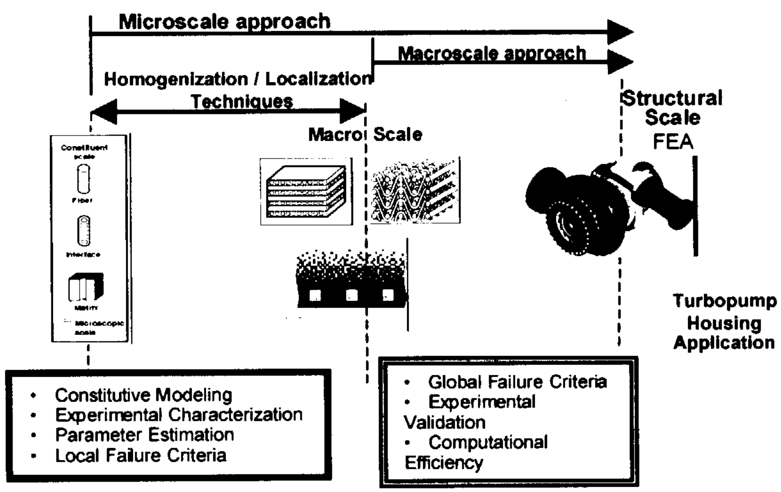
Goals/Objectives

- Develop/mature the accurate multi-scale structural analysis and life prediction technology required to **enable full deployment of MMCs** and other advanced metallic concepts in 3rd generation RLVs
  - → Significantly improve component safety and reliability
  - → Dramatically decrease costs associated with both design/ development and component life-cycles
- Empower materials scientists to **design *the* advanced metallic materials** systematically for cost-effective implementation in RLV applications
- Empower structural engineers to **design *with* the advanced metallic materials** on all relevant scales to exploit the full potential of these materials

Technical Challenges

- **Deformation Modeling:** Enhance physically-based multi-mechanism models and include environmental effects
- **Damage Modeling:** Identify/develop accurate strength and stiffness reduction continuum damage models
- **Thermomechanical Testing:** Obtain quality materials and develop appropriate test methods for both characterization and verification
- **Material Parameter Estimation:** Mature/verify technology for rapid parameter estimation with minimal testing
- **Homogenization/Localization Techniques:** Develop/verify techniques with improved accuracy and functionality
- **Local/Global Failure Analysis:** Identify/develop multi-scale life prediction methodologies for actual component thermomechanical environments
- **Model Synthesis:** Enable design/analysis on all scales (constituent → structure) while optimizing computational efficiency

Approach: Multi-scale Modeling of MMC's



Milestones

- Identify & procure "model" discontinuous reinforced metallic composite material & associated matrix material, 2QFY01.
- Release enhanced version of MAC/GMC incorporation among other things the new multi-mechanism viscoelastoplastic deformation & damage model, 3QFY01.
- Perform series of exploratory coupon level tests to identify key deformation & damage mechanisms in discontinuous reinforced metallic material, 4QFY01.
- Develop & incorporate into MAC/GMC a high fidelity micromechanics-based formulation accounting for shear-coupling, 4QFY02.
- Perform coupon level deformation Y life tests under biaxial loading, 4QFY03.
- Perform a multiscale analysis of a fiber/particulate reinforced subcomponent incorporating appropriate local/global failure criteria, 4QFY05.
- Perform subcomponent testing under complex multiaxial states of stress, 4QFY06

Probabilistic Analysis Methods for RLV Propulsion Materials & Structures

(P-5-Nemeth/Pai-1-t)

POC: Rod Ellis (5900), Stan Levine (5100)

Goals/Objectives

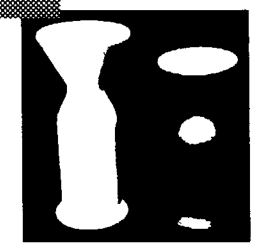
- Develop advanced probabilistic design and analysis methods for "brittle" materials and structures with the focus on:
- Reliable analysis methods for micro-electromechanical (MEMs) devices and systems
- Efficient methods for optimizing and tailoring composite materials
- More efficient structural design processes resulting in improved component reliability and reduced cost

Technical Challenges

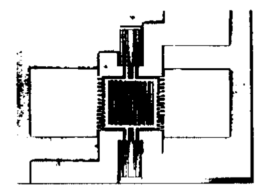
- Account for the highly stochastic nature of damage accumulation and failure in brittle materials and structures and account for demanding service environments including:
- Foreign object damage (FOD)
- Complex environmental effects
- Extreme thermomechanical loading conditions
- Complex dynamic loading conditions

Candidate RLV Components

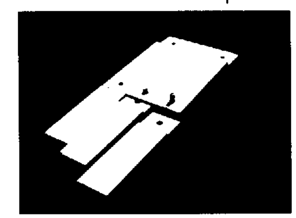
- Propulsion components including:
  - nozzle injectors
  - exit cones
  - throats
- Thermal protection system
  - sharp leading edges
- Engine sensors
  - Microelectromechanical Systems



Silicon Nitride Rocket Thruster



MEMS Sensors



Ultra-High-Temperature Ceramic for RLV Leading Edges

Approach: Multi-scale Modeling of MMC's

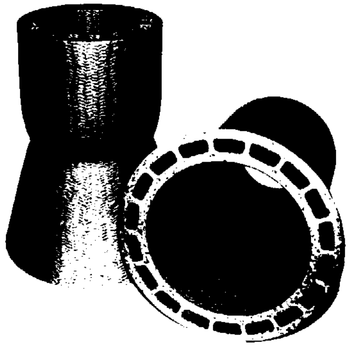
- Extend probabilistic analysis methods developed at GRC for aeronautics applications (CARES/LIFE, NESSUS) to RLV applications and materials.
- Team from the outset with industry partners to ensure the design tools developed fully meet the needs of the space propulsion design community.
- Ensure that the probabilistic life prediction methods developed are physics-based and take proper account of environmental effects.
- Ensure that the probabilistic analysis methods developed are computationally efficient and are fully compatible with "industry standard" finite element analysis codes.

Milestones

- Complete beta testing of ANSYS version 5.7 with probabilistic design system (PDS) options [4QFY01]
- Modify CARES/Life to simulate geometry/material property variations using ANSYS (PDS) and establish effect on life prediction [4QFY02]
- Complete extension of probabilistic residual strength model for CMCs (C/SiC, SiC/SiC) to multiaxial stress states and variable amplitude loading [4QFY03]
- Complete probabilistic modeling of MEMS and electronic structures under prototypical loading conditions and harsh environments [4QFY04]
- Complete integration of probabilistic life prediction models with propulsion health monitoring system [4QFY06]

CMC Life Determination Using Nondestructive Characterization Techniques

P-5-Effinger-FTP-1

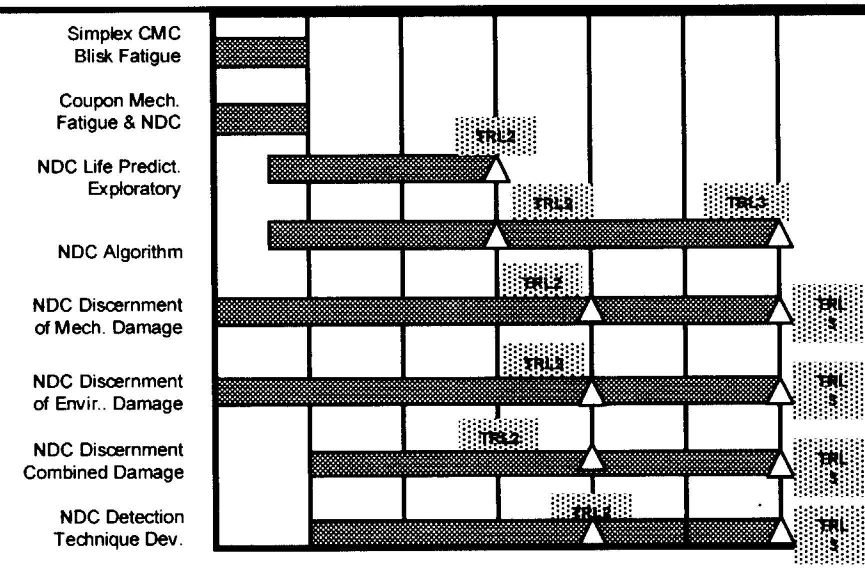


Milestones/Activities

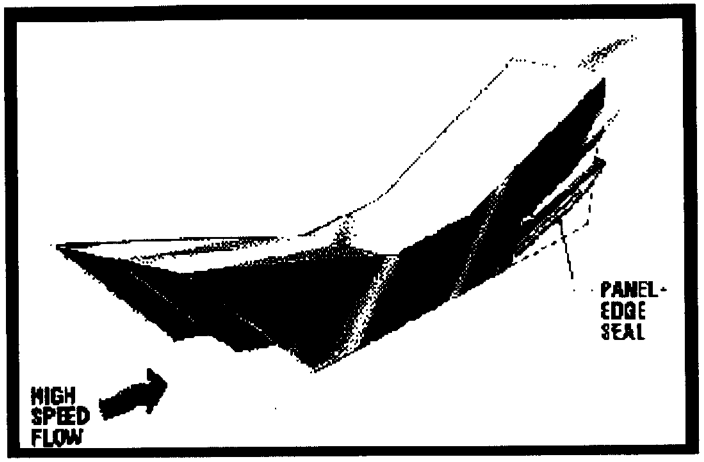
- FY'01 Milestones
  - Complete Simplex blisk fatigue testing
  - Establish correlation of NDC data of fatigued coupons to NDC data of fatigued CMC blisk
- FY'02 Milestones
  - University and industry contracts awarded
  - Synergistic NDC Life Prediction plan with AF, DOE, and NASA generated
- Prioritized list of Activities
  - Synergistic plan with Foundation's P-5-Kiser-1
  - Multi-axial & attachment testing data

Implementation/Metrics

- Current State of the Art
  - physics base life *prediction* with no real-time life *determination* potential
- Performance Metrics
  - Feasibility path defined, milestones met
- Risks
  - Environmental degradation determination by NDC, development of tools/mode to predict CMC life with NDC determined properties, NDC discernment of different aspects of material degradation.
- Participants
  - NASA: GRC, MSFC, Industry: Honeywell, SoRI, Univ. of HI, IL @ Chicago, OAI, Cleveland State, others



Advanced Structural Seals for Propulsion Systems



RBCC or TBCC Inlet/Nozzle Ramp Seals

Products / Benefits

- Milestones

1. Preliminary seal concepts identified	FY01
2. Unique performance test fixture fabrication complete	FY02
3. Seal thermal structural analyses complete	FY02
4. Hot resiliency/scrub critical function tests comp. (Gen 1 seals)	FY03
5. Hot resiliency/scrub critical function tests comp. (Gen 2 seals)	FY04
6. Rocket heating/ Thermal Survival Tests Complete	FY05
7. Thermal/acoustic tests complete	FY06

- Prioritized list of Activities

Define requirements and seal concepts; Perform seal thermal-structural analyses

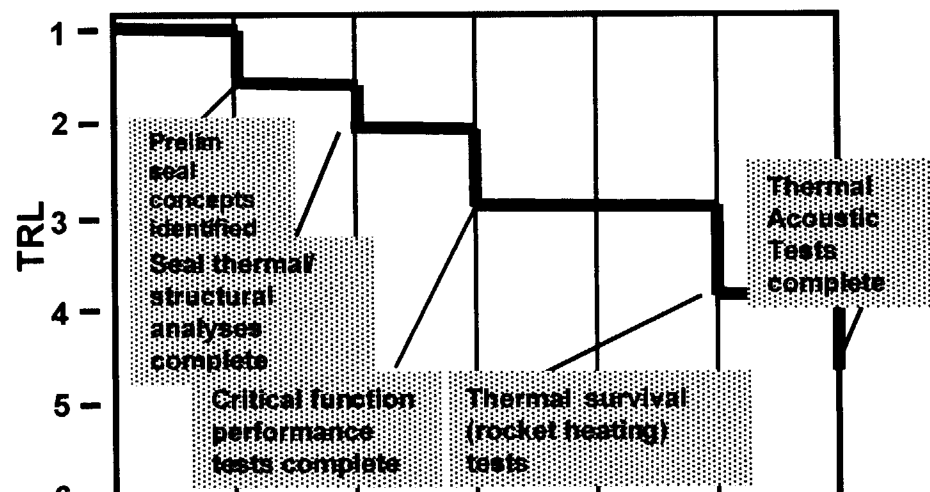
Design/fabricate test apparatus to measure seal performance

Conduct perf. tests: flow, compression, rocket heating, thermal/acoustic (as applicable)

Document seal design guidelines

Implementation / Metrics

- Current State of the Art
  - Limited NASP engine seals & database
  - No known 2000-2500°F dynamic re-usable structural seals
- Performance Metric
  - Re-usable seals tested under relevant env.
- Risks
  - Facility availability for hot thermal/mechanical/acoustic tests
  - Materials with inadequate perf. capabilities
- USG Participants:GRC Lead.
- POC: Dr. Bruce M. Steinetz NASA GRC
  bruce.steinetz@grc.nasa.gov (216) 433-3302



Space Transportation Technology Workshop

Safe Life / Foundation Technologies

STATUS/FUTURE WORK

- Ceramic Matrix Composite (CMC) Life Prediction Methods
  - Initiate procurement of CMCs (C/SiC, SiC/SiC) panels for coupon-level tests supporting development of life prediction methods, [1QFY01].
  - Complete initial series of mechanical/thermomechanical tests supporting development of life prediction models, [4QFY02].
- Life Prediction Methods for Ultra High Temperature (UHT) Polymer Matrix Composites for RLV Airframe and Engine Application
  - Complete screening study of UHT PMCs with optimized 3D fiber architectures with the focus on moisture adsorption and behavior under rapid thermal transients, [4QFY01].
  - Complete development of continuum damage mechanics (CDM) model accounting for viscoelasticity and microcracking and publish results, [2QFY02].
- Enabling design and life prediction technology for cost effective large-scale utilization of MMCs and innovative metallic material concepts.
  - Initiate procurement of advanced metallics including particulate and fiber reinforced composite materials, [1QFY01].
  - Release enhanced version of MAC/GMC incorporating latest multi-mechanism viscoelastoplastic deformation and damage model, [3QFY01].

STATUS/FUTURE WORK

4. Probabilistic analysis methods for brittle materials and structures.
    - Complete beta testing of ANSYS version 5.7 with probabilistic design system (PDS) options, [4QFY01].
    - Modify CARES/Life to simulate geometry/material property variations using ANSYS (PDS) and establish effect on life prediction, [4QFY02].

5. Damage assessment in CMC propulsion components using nondestructive characterization (NDC) techniques.
    - Complete simplex blisk fatigue testing, [4QFY01].
    - Establish correlation of NDC data of fatigued coupons to NDC data of fatigued CMC blisk, [4QFY01].

- High temperature structural seals for RLV application.
    - Preliminary seal concepts identified, [4QFY01].
    - Complete fabrication of unique performance test fixture, [4QFY02].