PRIMARY ISSUE PROS: 11/16

236 pg

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ASTP Organization

"ST Day 2000: Reducing Risk for the Next Generations" - ASTP

In-Space Investment Area
Les Johnson, *Manager*

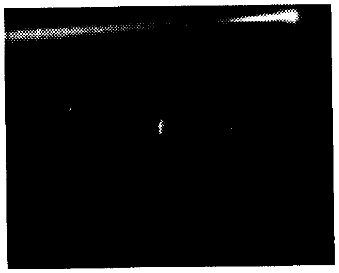
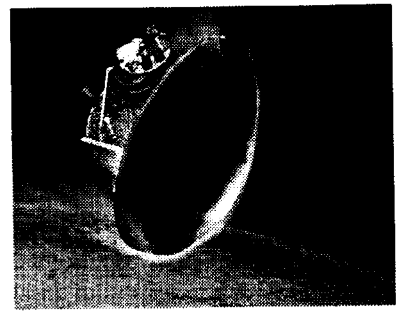
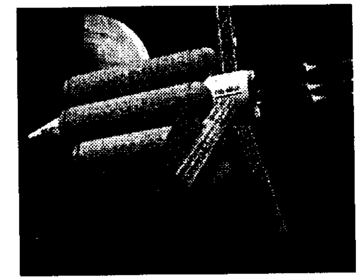
- Saroj Patel, *Exploration Space Transportation Lead at JSC*
- Bonnie James, *Special Assistant for Exploration*

Space Transfer Technology Project
Leslie Curtis, *Manager (MSFC)*

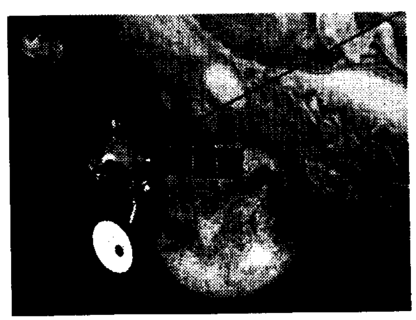
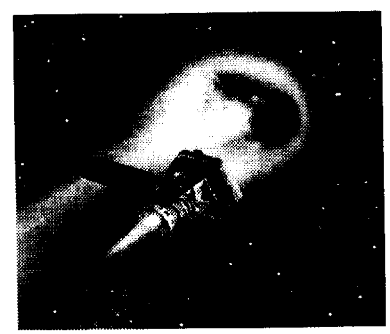
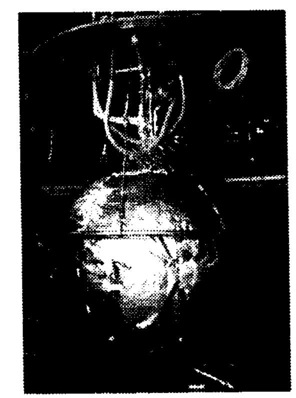
- Rae Ann Meyer, *Assist. Manager*
- Judy Ballance, *Lead Engineer - ProSEDS*
- Kelly Looney, *ProSEDS Systems Engineer*
- Tommy Harris, *ProSEDS Systems Engineer*
- Lee Jones, *In-Space IPA*

Propellantless Propulsion Project
Randy Baggett, *Manager (MSFC)*

- Bonnie James, *Assist. Manager*
- Melody Herrmann, *Lead/Systems Engineer*

- Achieve within 15 years a factor of 10 reduction in the cost of Earth orbital transportation and a factor of 2 to 3 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 1 to 2 orders of magnitude.

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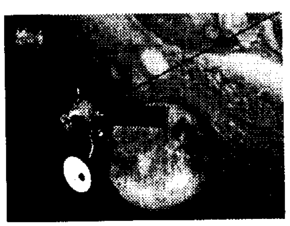
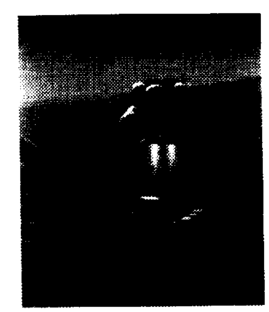
In-Space Transportation Goals

- High percentage of projected launches to Low-earth Orbit (LEO) will require upper stages.
  - More than 70% go to Geosynchronous Orbit (GEO) or higher.
- Under current total mission cost caps, more ambitious science missions require improvements in propulsion technologies.
  - DS-1 enabled by NSTAR solar electric ion propulsion.
  - Future planned missions require 2 to 3 times more Delta V.
  - Rendezvous and return missions will require similar investments in chemical propulsion systems and aerocapture technologies.
- Per current studies, human exploration missions to Mars, in-space transportation costs are projected to be higher than earth-to-orbit costs.
  - Affordable in-space transportation is enabling for human exploration missions (lighter weight systems, shorter trip time).
  - In-situ propellants offer significant potential to reduce mission costs.
- New opportunities to explore beyond the outer planets will require unparalleled technology advancement and invention.



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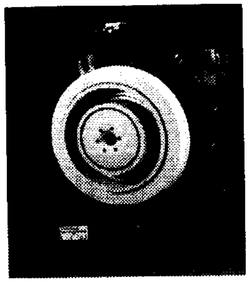
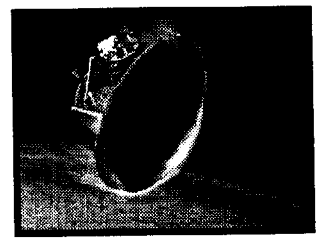
In-Space Investment Rationale



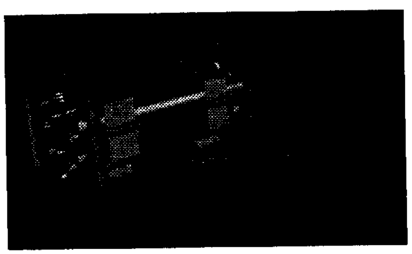
Electric Propulsion
Advance EP systems to reduce mass & cost of orbital transfer and to enable interplanetary missions

Sails
Solar and magnetic sails to enable exciting new mission concepts and by reducing mass and overall trip time for interplanetary missions.

Cryogenic Fluid Management
Advance CFM systems to enable long term storage of cryogens in space

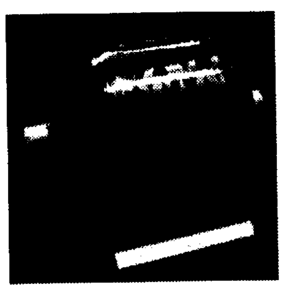


Aeroassist
Utilize aerocapture and aeroassist transportation systems to significantly reduce mass -- by using planetary environments for orbit capture and deceleration



Fission
Develop fission technology to enable rapid, affordable access to any point in the solar system

Tethers
Develop reusable electrodynamic and momentum transfer tethers to reduce transportation system mass and cost



Light Weight Components
Develop light weight components to reduce the dry mass of spacecraft propulsion systems

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In-Space Transportation Technology Elements

Electric Propulsion

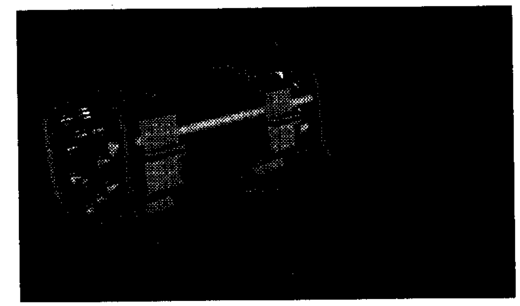
Advance EP systems to reduce mass & cost of orbital transfer and Enable interplanetary missions

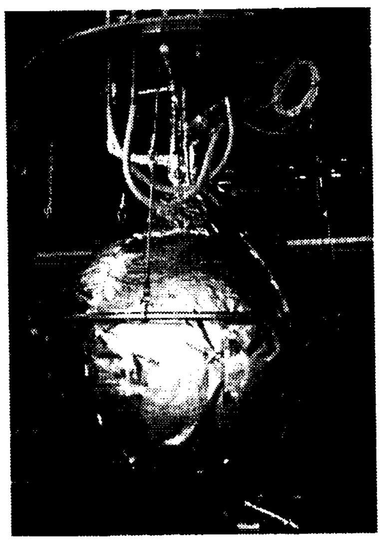
- GRC – Hall, Ion, MPD, PIT technologies
- JPL – MPD (lithium), DS-1 tests, ion optics
- JSC – VASIMR Technologies
- MSFC- PIT (switch and ckt design)

Fission

Develop Fission Technology to enable rapid, Affordable access to any point in the solar system

- GRC – Energy Conversion, Fuels, LANTR
- JSC – Two phase systems and technologies
- KSC – Operational and range requirements
- MSFC – Fuels, SAFE, System studies, non nuclear testing

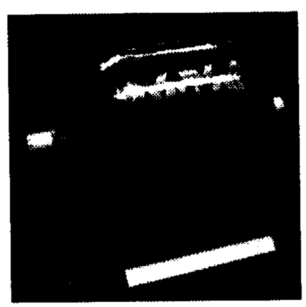




Cryogenic Fluid Management

Advance CFM systems to enable long term Storage of cryogens in space

- ARC- Cryocooler & Refrigerator development, insulation
- GRC- Subscale/Component test, analytical modeling
- JPL - technology requirements
- JSC - In-situ propellant production
- KSC - GSE, quick-disconnects, insulation
- MSFC- System/Large scale test, analytical modeling



Light Weight Components

Develop light weight components to reduce the dry mass of spacecraft propulsion systems

- Center Roles are still being established

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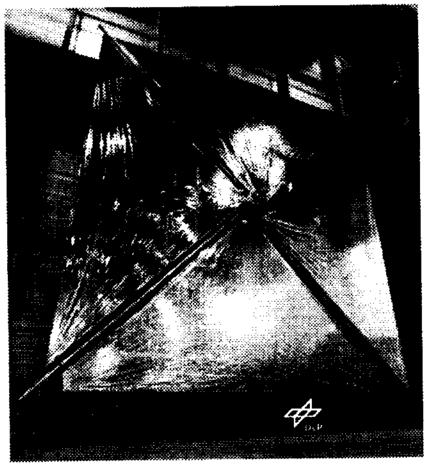
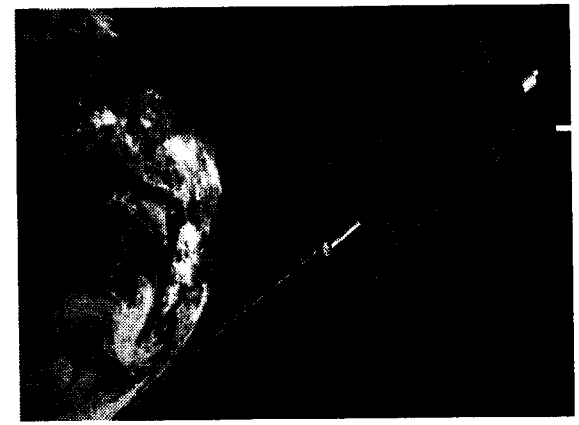
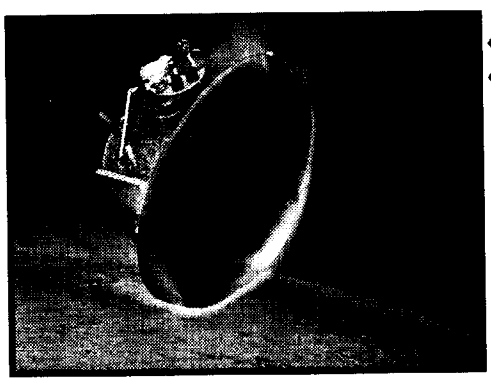
Space Transfer Technology Project Elements



- Sails
  - Solar
  - Magnetic
- Center Roles:
  - JPL: TWG lead; system design; GN&C; Mechanical systems; Large structures; I&T
  - LaRC: materials & Lt. weight structures; mechanical system
  - MSFC: Prop. Physics;M2P2; mt'l & light weight structures
  - JSC: Large Structure environ.





- Aeroassist
- Center Roles:
  - LaRC: TWG Lead; system design/performance; Aero/ Aerothermal analysis; structures; GN&C simulations
  - ARC,JSC,JPL,LaRC,MSFC: Vehicle design/system analysis
  - ARC: TPS; TPS Aerothermal sensors; Aerothermal analysis
  - JSC: GN&C; deceleration systems; Adv.. TPS materials
  - MSFC: Environmental models

- Tethers
  - Electrodynamics
  - Momentum Transfer Tethers
- Center Roles:
  - MSFC: TWG Lead; system design/performance; integrated test; tether survivability; deployer; GN&C; deployment test facilities; orbital tracking & collision avoidance
  - JSC: orbital tracking & collision avoidance

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Propellantless Propulsion Technology Project Elements

GTX Project Summary

Space Transportation Day
October 11-12, 2000

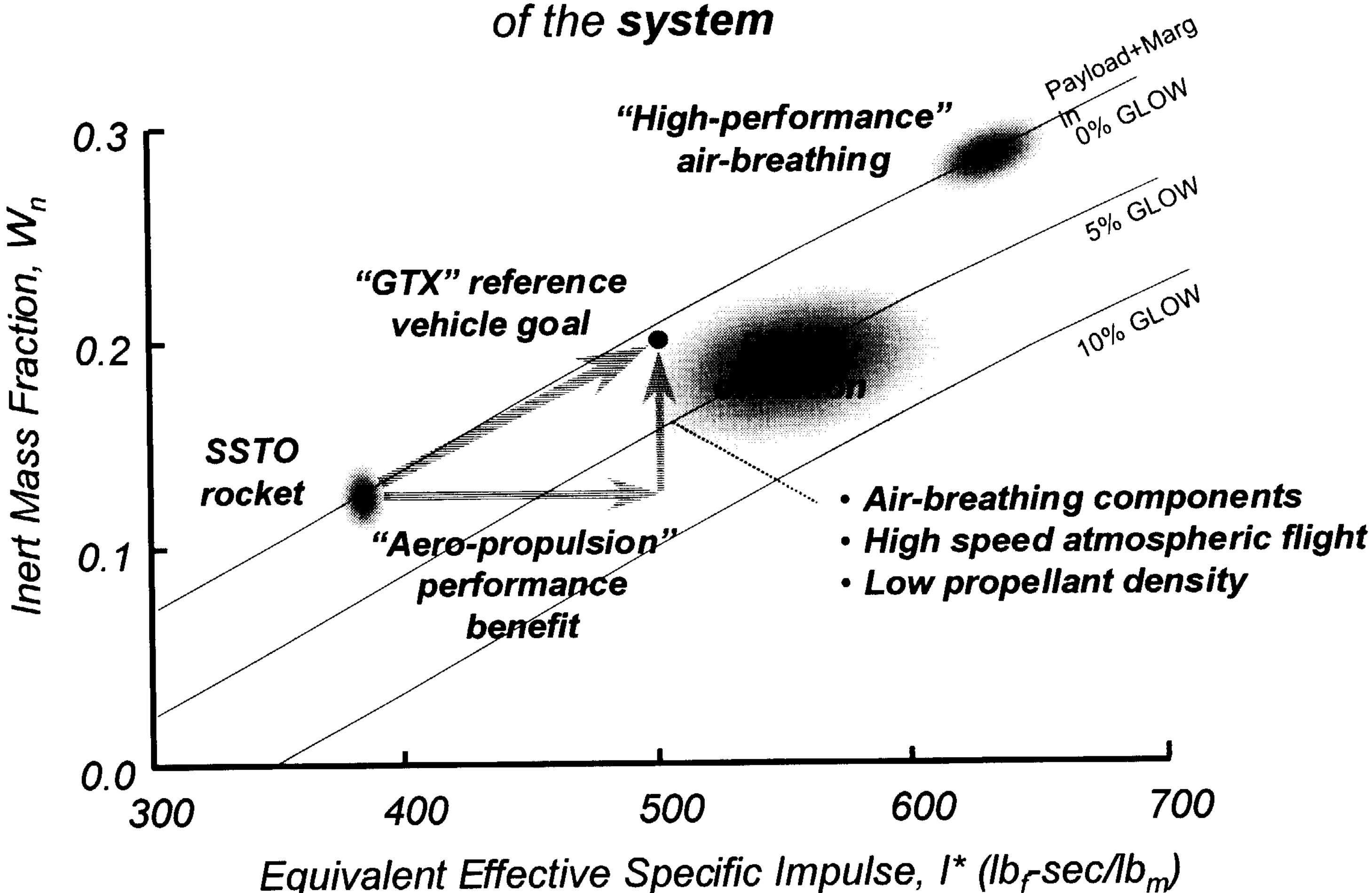
Space Transportation Technology Workshop

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***

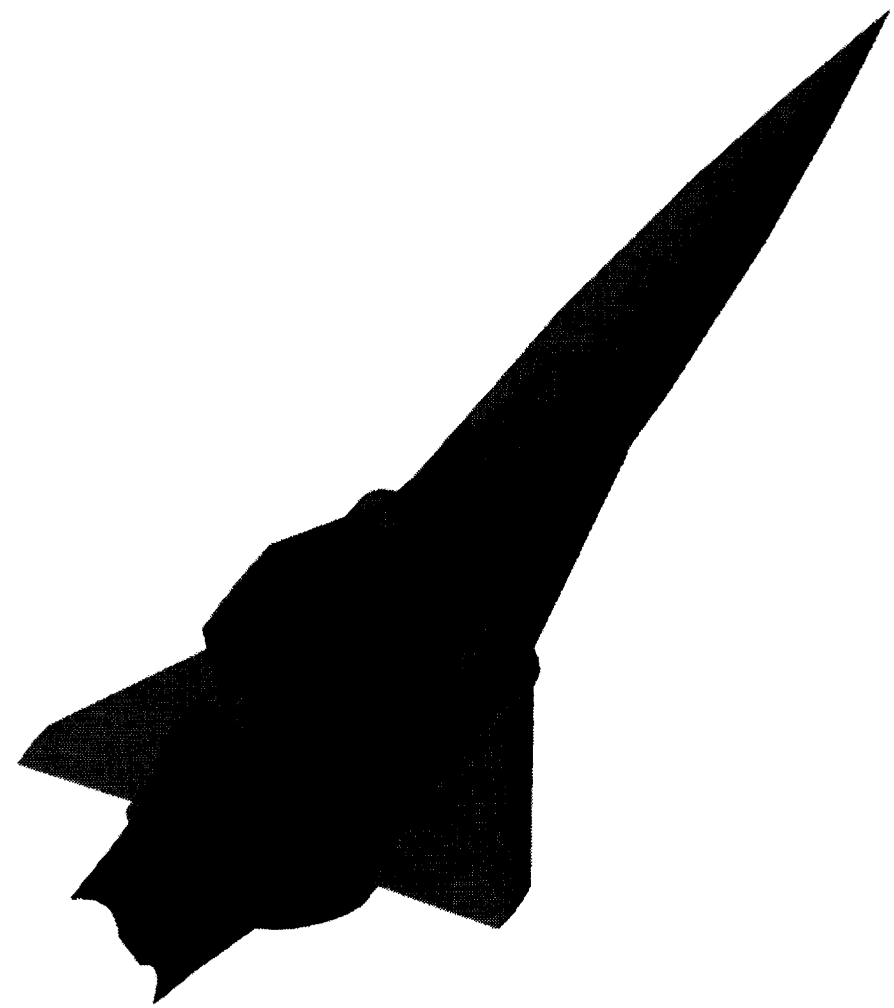


Space Transportation Technology Workshop

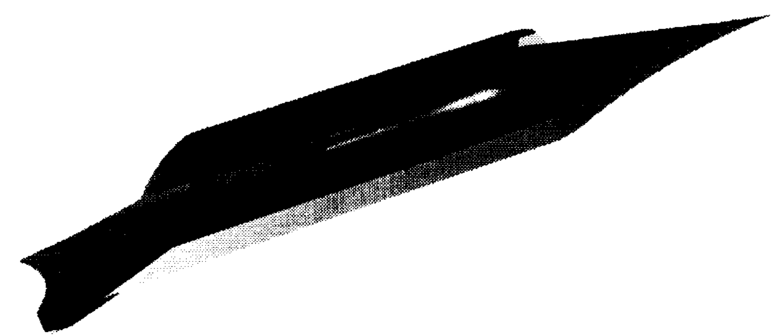
GTX Project

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

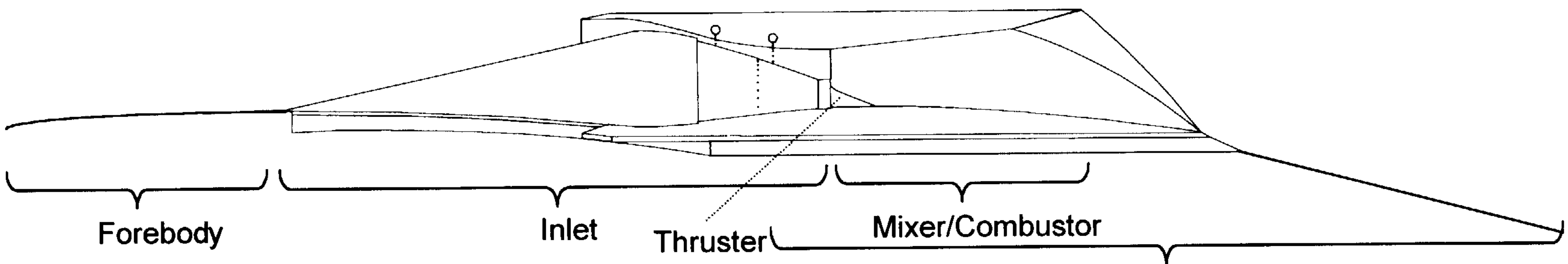


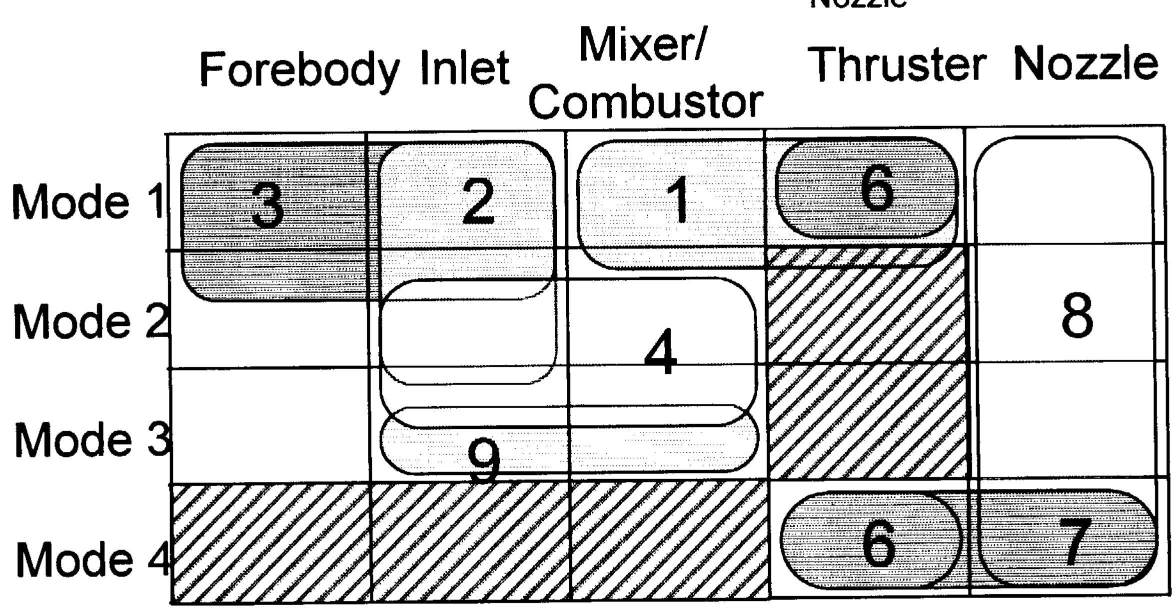
- Independent Ramjet Stream and Simultaneous Mixing and Combustion (SMC) Ejector-Ramjet Cycles Under Consideration
  - Lower risk, nearer-term than more complex concepts (e.g. SERJ, LACE)
  - Adequate performance for 500 sec I^* goal at moderate rocket re-ignition Mach number
  - Shorter and lighter 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



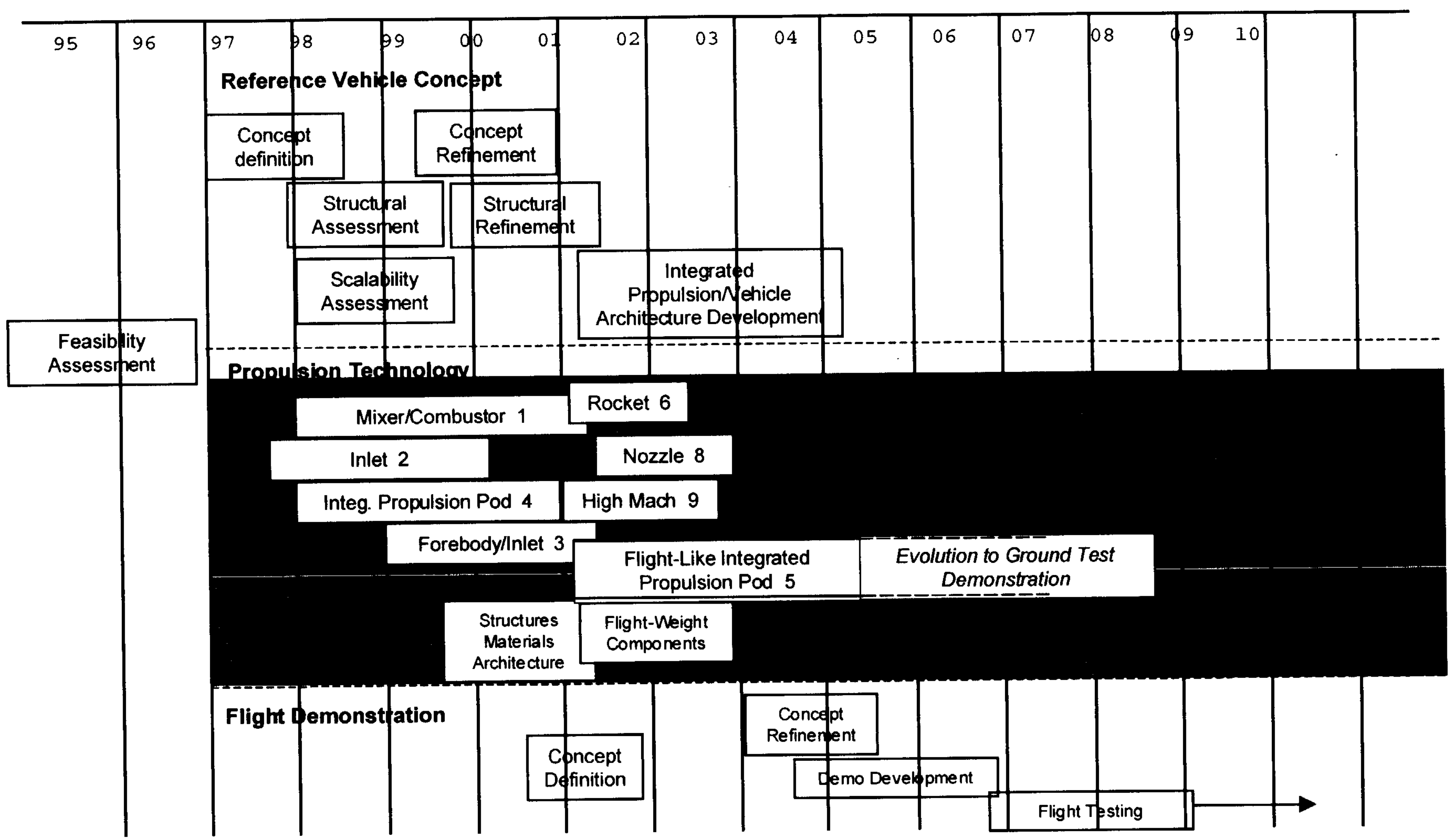
GTX RBCC Propulsion System Features

Planned Flowpath Development Test Rigs





GTX Project Plan Overview



Numbers refer to GTX rig numbers

Space Transportation Technology Workshop

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

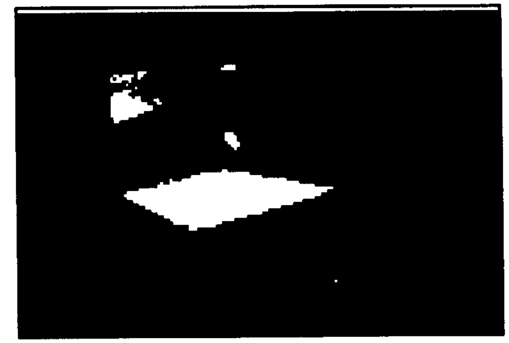
FY 01: Complete experimental design for Cu-alloy development
FY 02: Complete screening of advanced copper alloys
FY 03: Determine feasibility of very high conductivity Metal Matrix Composites
FY 05: Determine mechanical and thermal properties of MMC's
FY 06: Demonstrate advanced alloy coating combination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

Tasks and Milestones

CMC Cooled Components

M. Jaskowiak, 216-433-5515
Martha.H.Jaskowiak@grc.nasa.gov

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

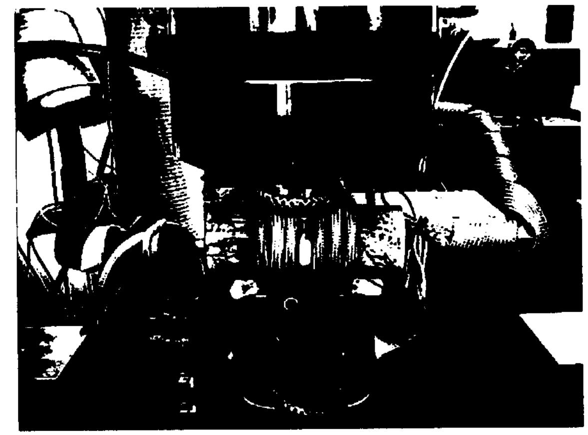
Polymers and PMC's for High Temperature Propulsion Applications

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

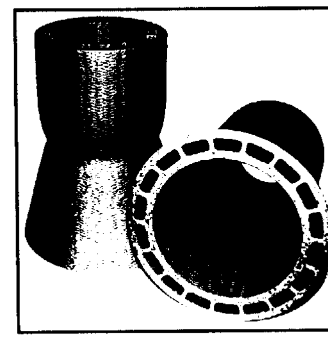
Tasks and Milestones

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

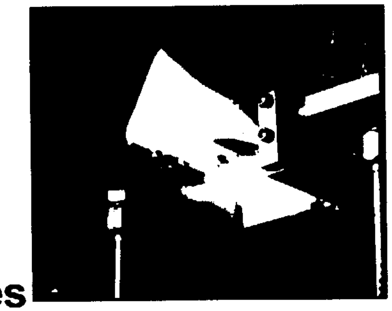


FY 01: Define and characterize CMC thrust chamber subelements
FY 03: Screen uncooled concepts for thrust chambers (RCS Scale)
FY 05: Screen regeneratively cooled concepts for thrust chambers

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

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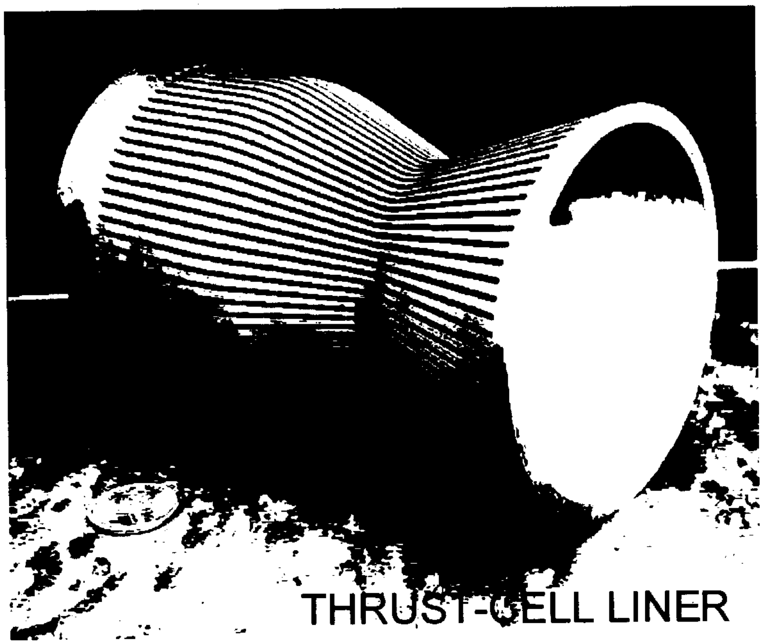
Polymers and Polymer Matrix Composites for Propulsion Components

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



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**

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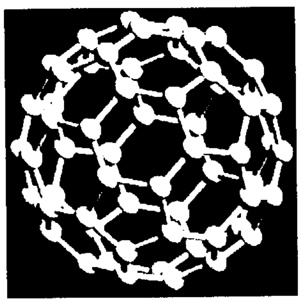
Coatings For Thrust Cell Liners

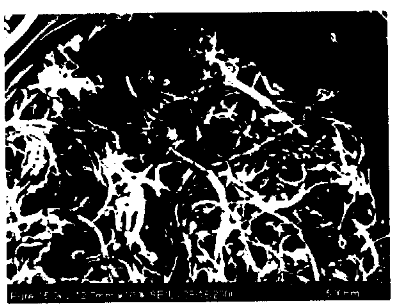
Diamond

- 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

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

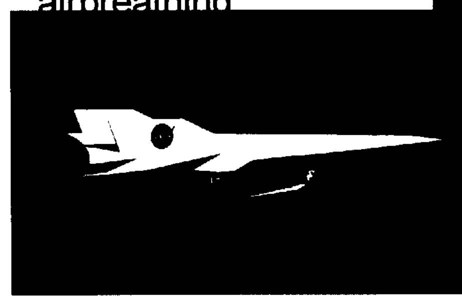
Goals/Objectives

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.

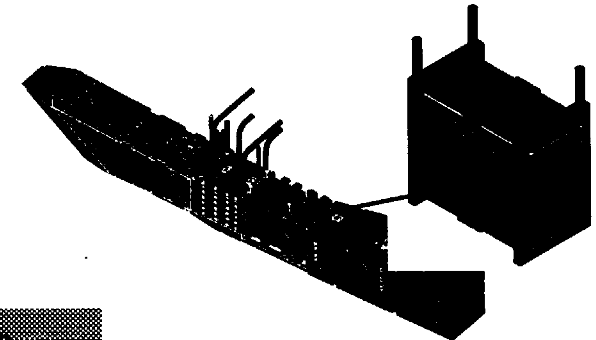
Life Prediction Methods For Ultra High Temperature (UHT) Polymer Matrix Composites (PMC) For RLV AirFrame and Engine Application (P-5-Ellis-1-t)

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)

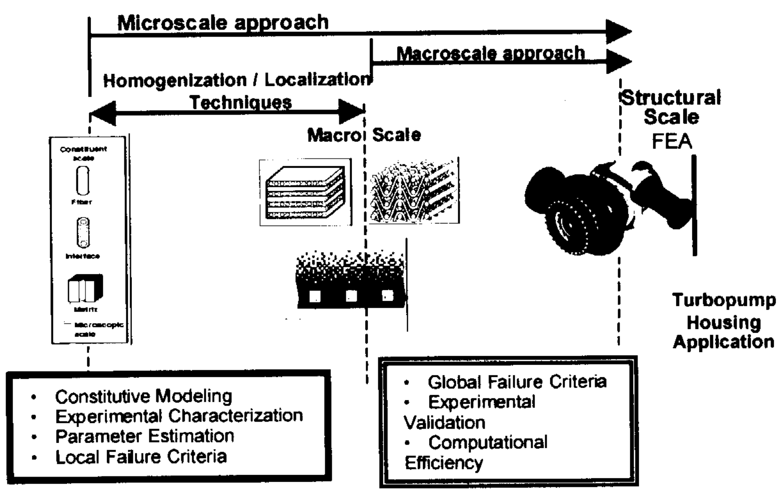
Goals/Objectives

- 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

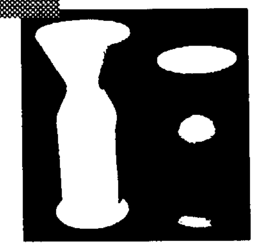
- Develop advanced probabilistic design and analysis methods for "brittle" materials and structures with the focus on:
- Reliable analysis methods for micro-electromechanical (MEMs) devices and systems
- Efficient methods for optimizing and tailoring composite materials
- More efficient structural design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

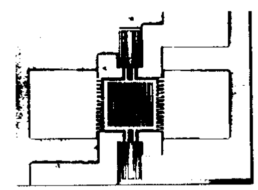
Candidate RLV Components

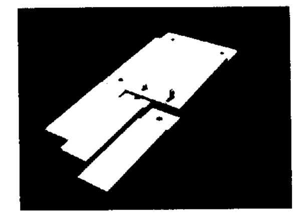
- Propulsion components including:
  - nozzle injectors
  - exit cones
  - throats
- Thermal protection system
  - sharp leading edges
- Engine sensors
  - Microelectromechanical Systems



Silicon Nitride Rocket Thruster

MEMS Sensors





Ultra-High-Temperature Ceramic for RLV Leading Edges

Approach: Multi-scale Modeling of MMC's

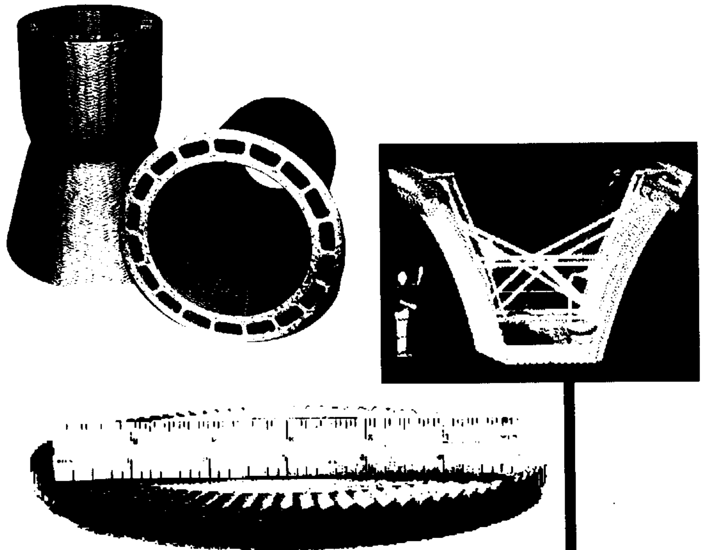
- Extend probabilistic analysis methods developed at GRC for aeronautics applications (CARES/LIFE, NESSUS) to RLV applications and materials.
- Team from the outset with industry partners to ensure the design tools developed fully meet the needs of the space propulsion design community.
- Ensure that 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

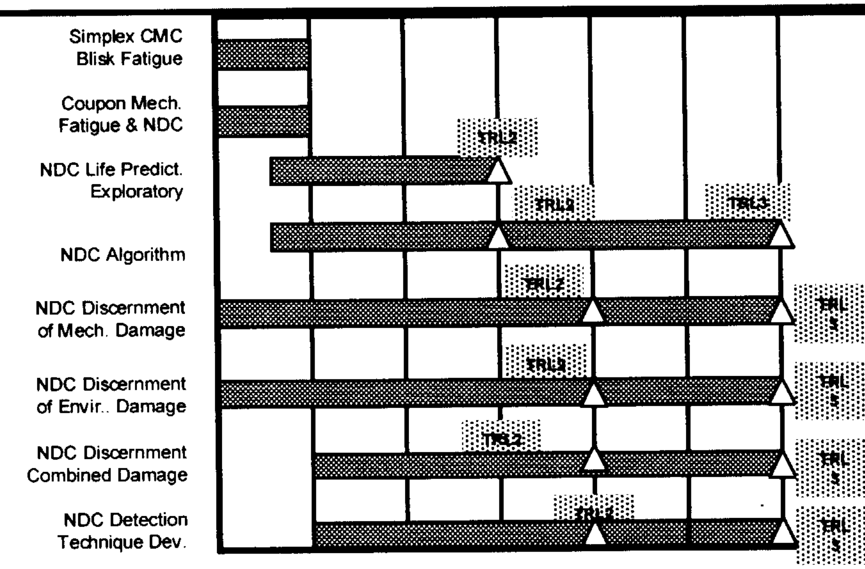


Milestones/Activities

- 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

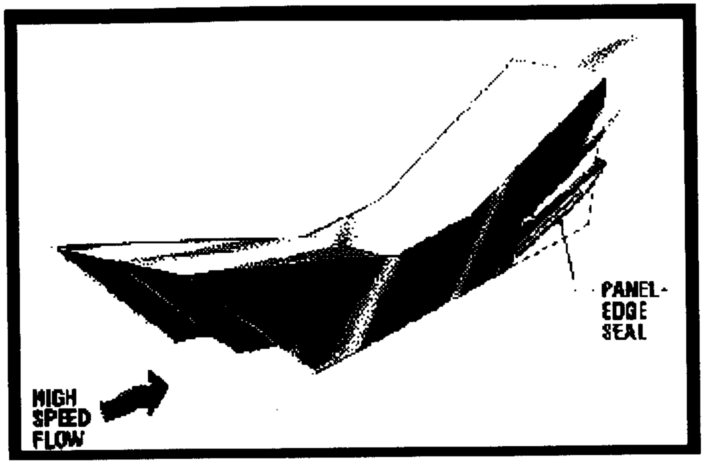
- Current State of the Art
  - physics base life *prediction* with no real-time life *determination* potential
- Performance Metrics
  - Feasibility path defined, milestones met
- Risks
  - Environmental degradation determination by NDC, development of tools/mode to predict CMC life with NDC determined 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



Space Transportation Technology Workshop

Safe Life Propulsion Technologies

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

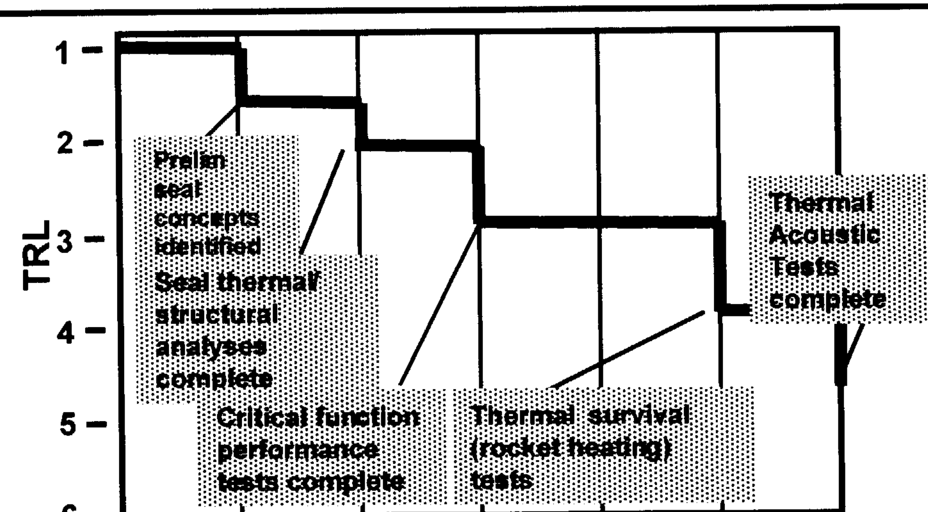
Design/fabricate test apparatus to measure seal performance

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].

IN/24

Light Weight Long Life Materials and Structures

Tom Glasgow
Oct. 12, 2000

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Long Life Light Weight Propulsion Materials and Structures

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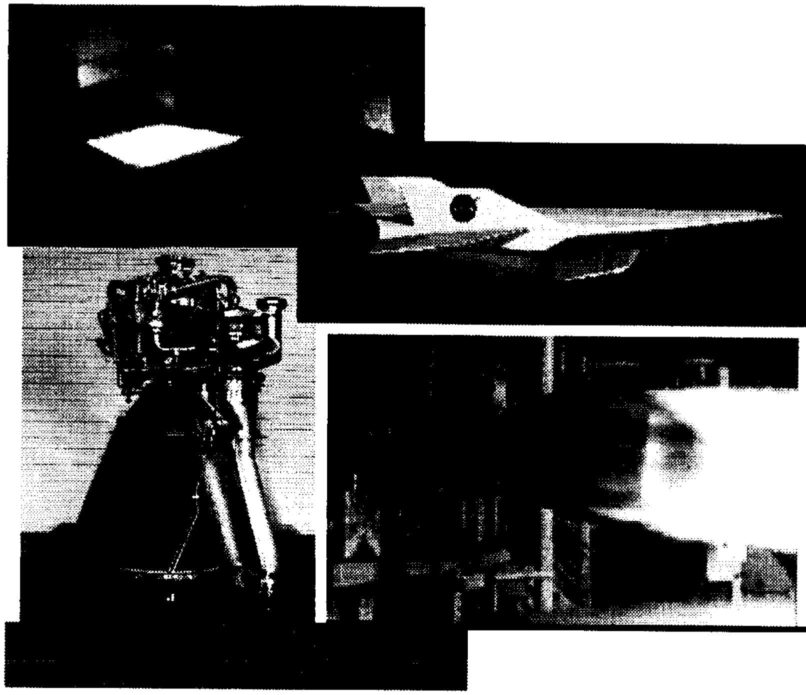
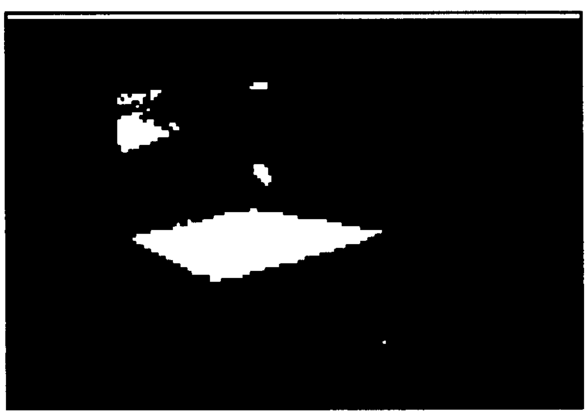


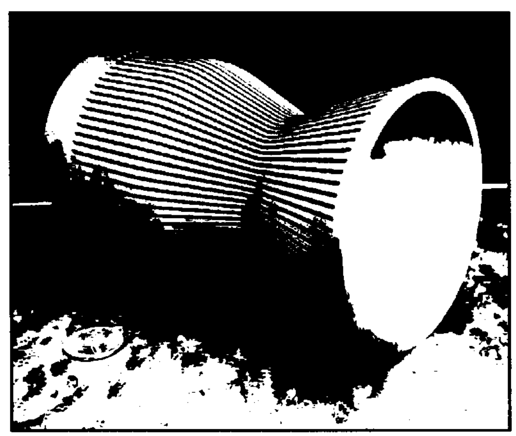
- Basic work to be performed at GRC, MSFC, LaRC
- Contracts for CMC Panels, Blisks and Thrust Chambers, for Copper Alloy Fabrication and Polymer Production , will be arranged with materials Specialty Companies
- Academia will be involved in Polymers and Copper Alloy Development Opportunities to participate will also be advertised through SBIR

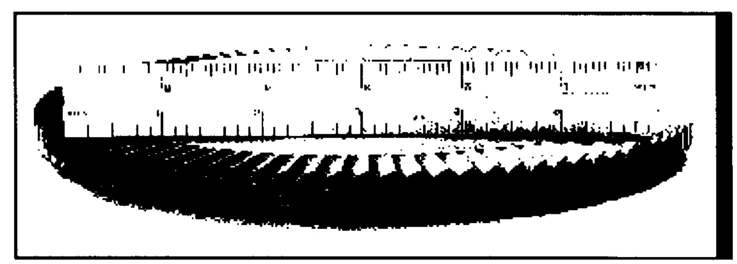
- FY'01 Milestones
  - Complete experimental design for high conductivity alloy development
  - Define and characterize prototype CMC Nozzle Sub-elements
  - Complete survey of Gen 3 Vehicle Needs for leading edges
  - Initiate Design of High Fidelity Quick Access Rocket Exhaust Exposure Rig
- FY'02 Milestones
  - Demonstrate Reaction Transfer Molded PMC with 550°F use Temp Complete Screening of Advanced Copper Alloys
  - Determine thermal performance of First Concept Cooled CMC Panels
  - Screen regeneratively cooled concepts for CMC Thrust Chambers
- Prioritized list of Activities, e.g.:
  - Establish Low Fidelity Materials Exposure Rig
  - Establish contacts for supply of CMC test pieces
  - Select Polymer concepts for 550°F use temp.

- Extensive use of GRC Cell 22 Rocket Test Facility will be required in out years but not FY01
- No use of Industry facilities is anticipated

- High performance materials are enabling or enhancing for numerous engine/vehicle concepts and are critical to meeting safety, cost and performance goals.
- Subproject covers polymeric, metallic and ceramic high temperature materials for rocket propulsion systems.
- Current TRL's average 2.5. Most will attain 5 or 6 by 2006. Project also includes a wide variety of efforts with some fundamental work with late maturity dates.







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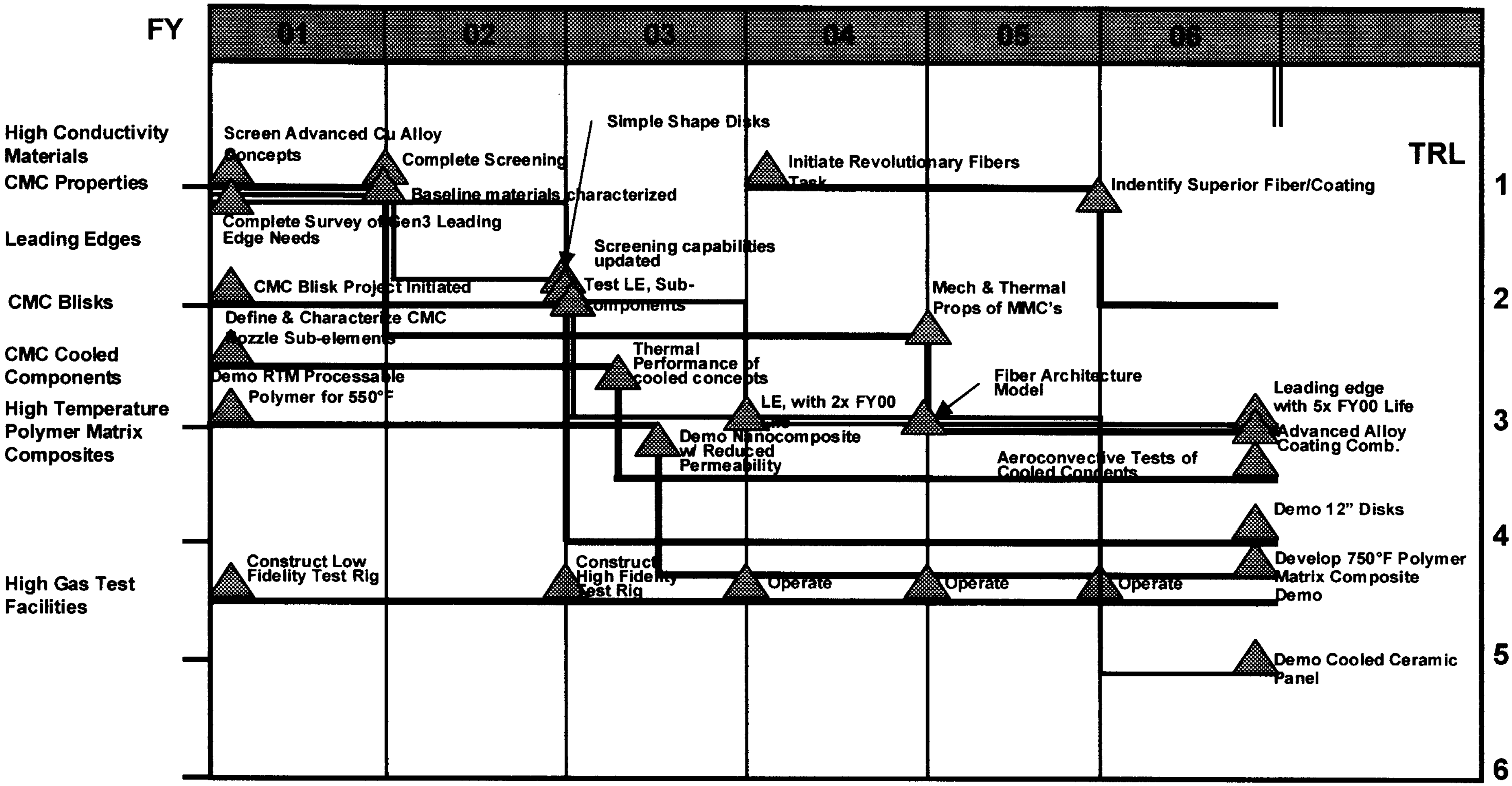
Long Life, Light Weight Propulsion Materials and Structures



Space Transportation Technology Workshop - Propulsion:

Space Transportation Technology Workshop

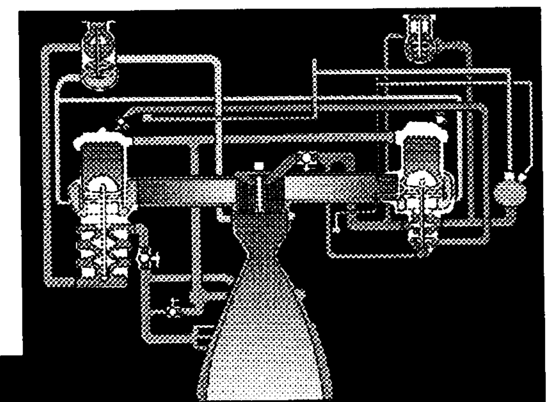
Long Life, Light Weight Propulsion Materials and Structures

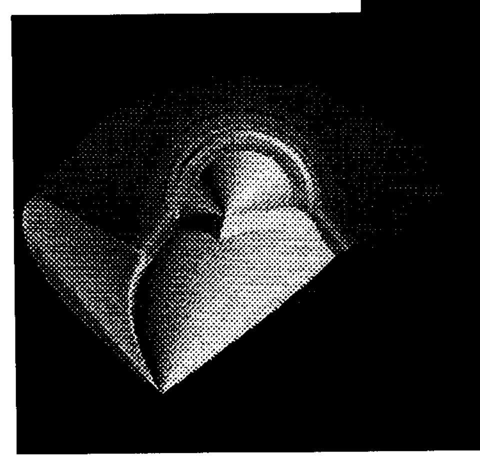
S3/CP//N/20

Numerical Propulsion System Simulation for Space Transportation

Karl Owen, GRC, 216-433-5895

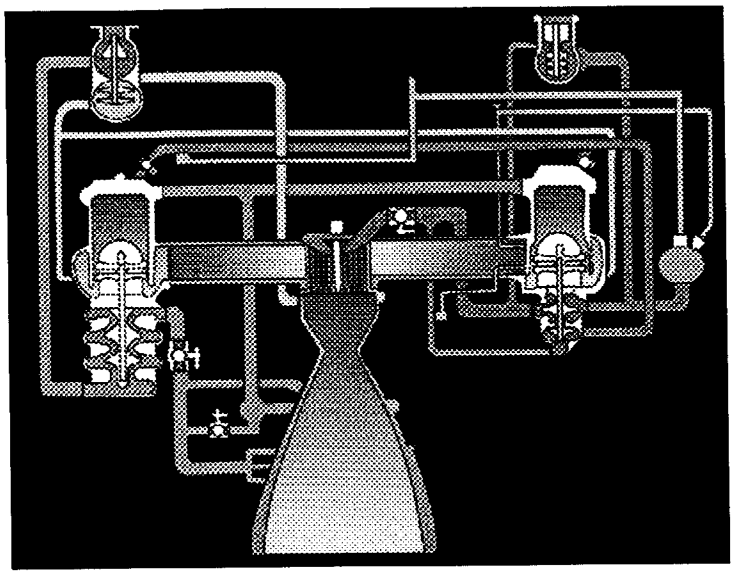
New project to Develop Advanced System Simulations for 3rd Generation Engine Design and Analysis





Numerical Propulsion System Simulation

Space Transportation Technology Workshop



Milestones / Activities

FY01 *MAJOR* Milestones

- Incremental Release Rocket System Simulation (GRC)
- Rotor-Stator Pump CFD Analysis Initial Capability (MSFC)

FY02 *MAJOR* Milestones

- Production RBCC Rocket System Simulation (GRC)
- Initial Cavitating Pump Element Design Code (MSFC)

Prioritized Activities

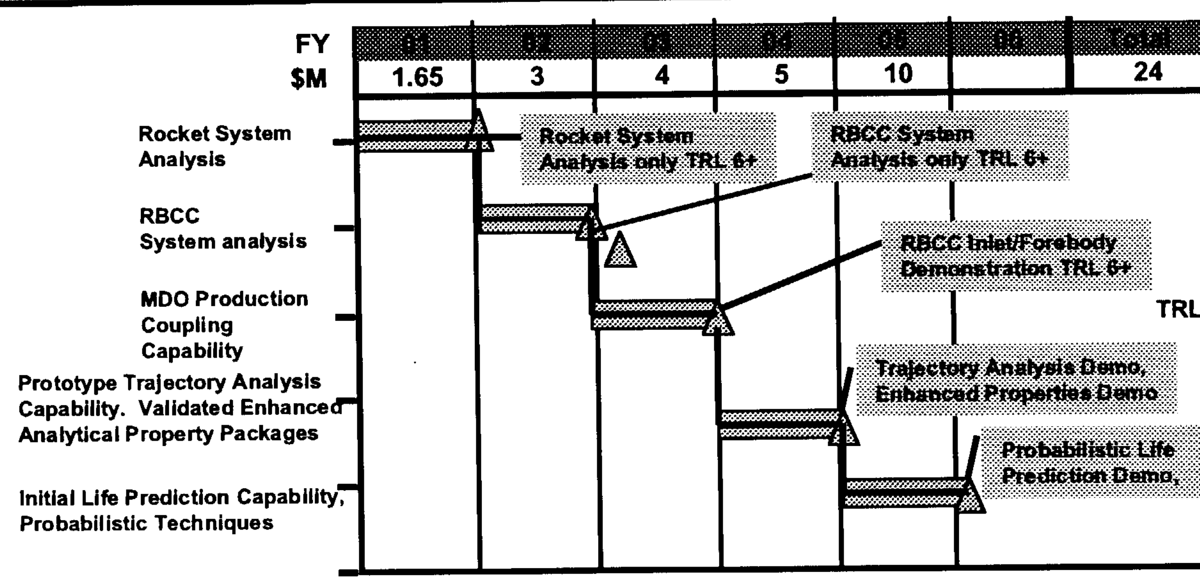
- Development of Rocket System Modules for Simulation FY01
- Development of RBCC System Modules for Simulation FY02

FY01 Acquisition Plan

- Contracting with appropriate support organizations

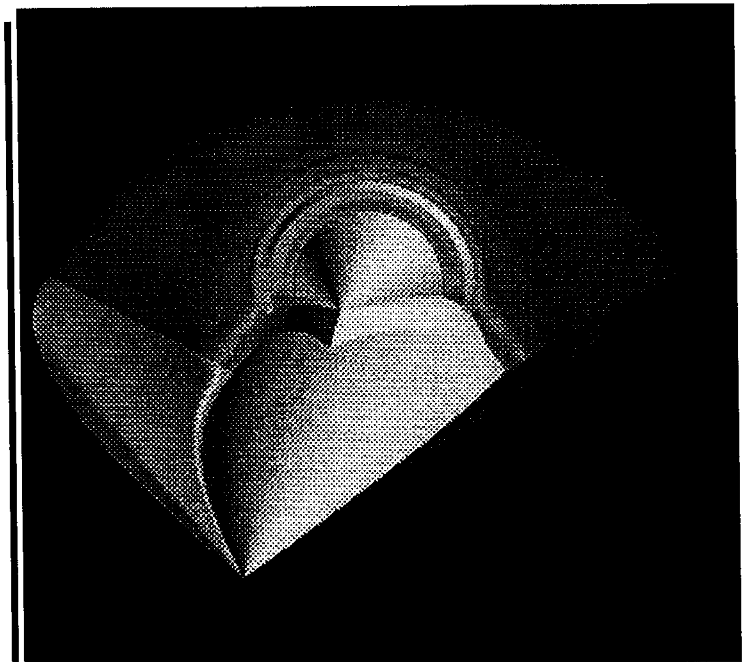
Facility Requirements

- COSMO Supercomputing Facility at ARC
- SHARK and AEROSHARK Computing Facilities at GRC



Implementation / Metrics

- Current State of the Art
  - Current System Simulations are mature, difficult to modify, and poorly documented.
  - Multidisciplinary couplings are one way and fabricated for specific applications.
  - Probabilistic life prediction techniques for space applications are in their early application.
  - Many parts of the full system, variable fidelity simulation have been demonstrated individually or technology is available from aeronautical applications
- Benefits of Technology (Cost, Safety, Performance, etc)
  - An anticipated 20% reduction it time to design with improvements in performance and risk reduction.
- Risks/Technical Challenges with Mitigation Plans:
  - All GRC software implementation will be V&V'd against data or other V&V'd software.
  - GRC Software development will proceed as occurred with similar development efforts in Aeronautical simulations.
  - Similar Aeronautical Systems are at TRL 8
  - Where appropriate, parallel efforts will be encouraged/ tracked in high risk areas until success is assured.



•Participants/University

NASA Centers: GRC, MSFC, LaRC, ARC (Subtask in outyears)

Industry: TBD Partners

Universities: OAI, TBD

HBCU/HMCU/SDB's: TBD

•Public Briefings Scheduled for FY01

Annual NPSS Industry Review in October, 2001

Space Transportation Technology Workshop

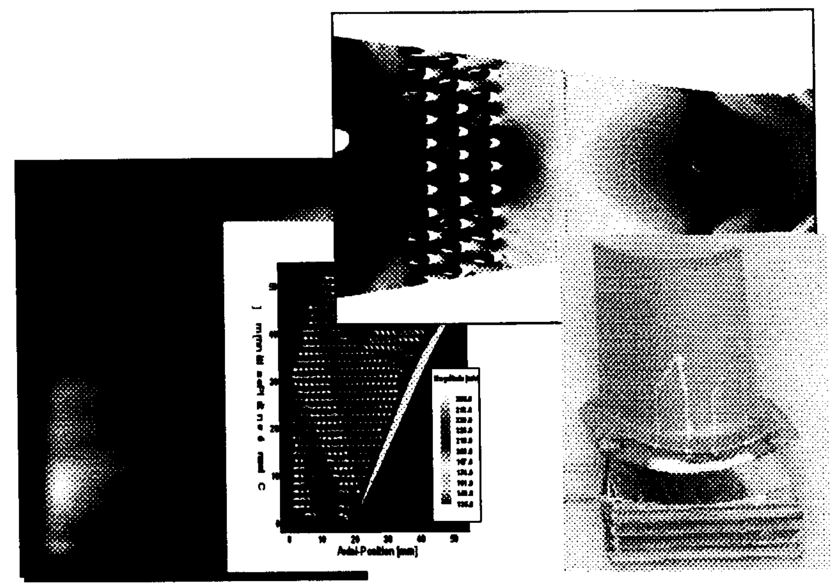
Numerical Propulsion System Simulation

54/CP/IN/35

Information Rich Test Instrumentation

Carolyn Mercer, GRC 216-433-3411
Gary Hunter, GRC, 216-433-6459

New project to
Develop ground test
instrumentation for 3rd
Generation Engine tests



Participants in Planning Process

Technical Working Group:

Carolyn Mercer, Instrumentation, GRC
Gary Hunter, Sensors, GRC
Kevin Breisacher, Combustion, GRC
Gerry Nissen, Sensors, Boeing
Joel McManus, Sensors, Boeing
Dick Greenhalgh, Rockets, P&W
W.T. Powers, Instrumentation, MSFC
Bob Truesdale, Solid Rockets, AEDC

Gregory A. Hall, Space Transportation, KSC
Don Gardner, Instrumentation, AEDC
William Mouyos, Sensors, Lockheed Sanders
Bill St. Cyr, SSC

Proposals by:

Mike Marcolini, Instrumentation, LaRC
Glenn Diskin, Hypersonics, LaRC
Bob Rogowski, NDE, LaRC
Jih-Fen Lei, Instrumentation, GRC

W.T. Powers, Avionics, MSFC
Ravi Mehta, Instrumentation, ARC

GOALS

- Increase safety by understanding operating conditions and component capabilities
- Reduce development and operating costs by:
    - Reducing testing and design cycle times and
    - Reducing engine weight and increasing component life

OBJECTIVES

- Determine cooling system effectiveness
- Determine structural loads

•TECHNICAL CHALLENGES

- 2000 deg F surfaces; 8000 deg F flows; up to Mach 11
- Remote signal extraction
- Ultra-low intrusive measurements

Information Rich Test Instrumentation

Technologies targeted
and selected to address objectives

Objectives	Thin Films/MEMS	Phosphor Paints	Spectroscopy	Velocimetry
Cooling System				
Surface Temp	O	O		
Surface Heat Flux	O			
Gas Temp			O	
Combustion	O		O	
Weight				
Surface strain	O			
CFD validation				
Velocity				O
Temperature	O	O	O	

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Information Rich Test Instrumentation

Tasks awarded for FY01:

–Micro-fabricated multifunctional smart sensor system for harsh environments *(surface heat flux, temperature, strain, vibration) GRC*

–High temperature surface measurements using thermographic phosphors
(surface temperature, heat flux) GRC + Oak Ridge National Labs

–Flow temperature profiling using smart particles imaging technology
(gas temperature) LaRC + GRC

–Embedded, integrated, high frequency response, multi-plane velocimetric system for aeropropulsion systems *(gas velocity) LaRC + GRC*

Information Rich Test Instrumentation

Milestones/Activities

- Surface point techniques:
  - **FY01 Feasibility test of inorganic binders at 1000C**
  - **FY02 Multi-functional thin film sensor array demo**
- Planar optical techniques:
  - **FY03 Temperature sensing "smart" particle demo at 1000C**
  - **FY04 Multiplexed fiber optic velocimetry demo**
- Prioritized list of Activities
  - **Develop and demonstrate surface heat flux measurements**
  - **Develop and demonstrate surface temperature measurements**
  - **Develop and demonstrate gas velocity measurements**

55/CP/1M/37

Turbine Based Combined / Combination Cycle / RTA Project Overview

Paul A. Bartolotta	NASA/GRC
Brian F. Quigley	NASA/GRC

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Brian F. Quigley 216-433-8672 Brian.F.Quigley@grc.nasa.gov

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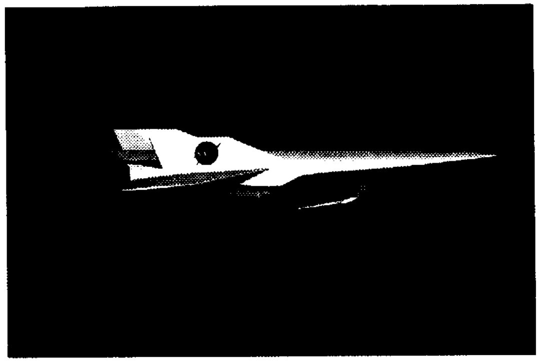
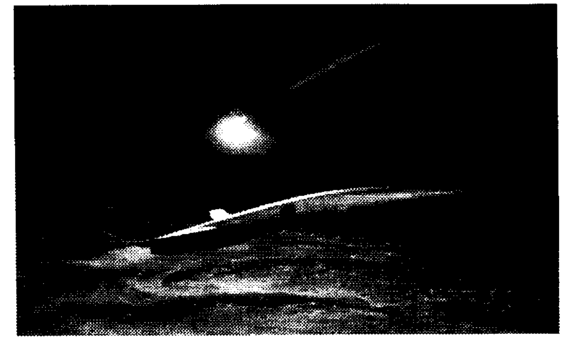


- Single Stage To Orbit (SSTO)
  - Turbine Accelerator Integrated with Dual Mode Scram Jet in Combined Flow Path
  - Over/under Configuration
  - Hyper-X type vehicle (Baseline)

- Technology Challenges
  - Turbine Accelerator
  - Shared Inlet
  - Dual Fuel (H/C & H2) in Single Vehicle
  - Transition Mode
  - Shared Mixer Ejector & Nozzle
  - Thermal Management
  - PAI



- Two Stage To Orbit (TSTO)
  - First Stage:
    Turbine Accelerator with Afterburner or Ram Jet
  - Second Stage:
    RBCC and/or Rockets

- Technology Challenges
  - Turbine Accelerator
  - Inlet Performance
  - Staging Separation
  - Thermal Management
  - PAI

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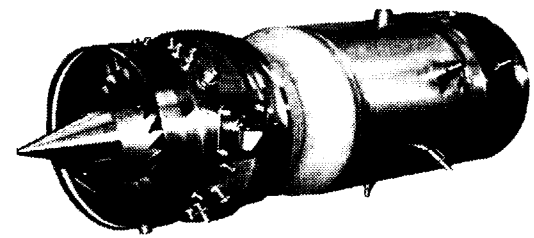
Turbine Based Combined/Combination Cycle

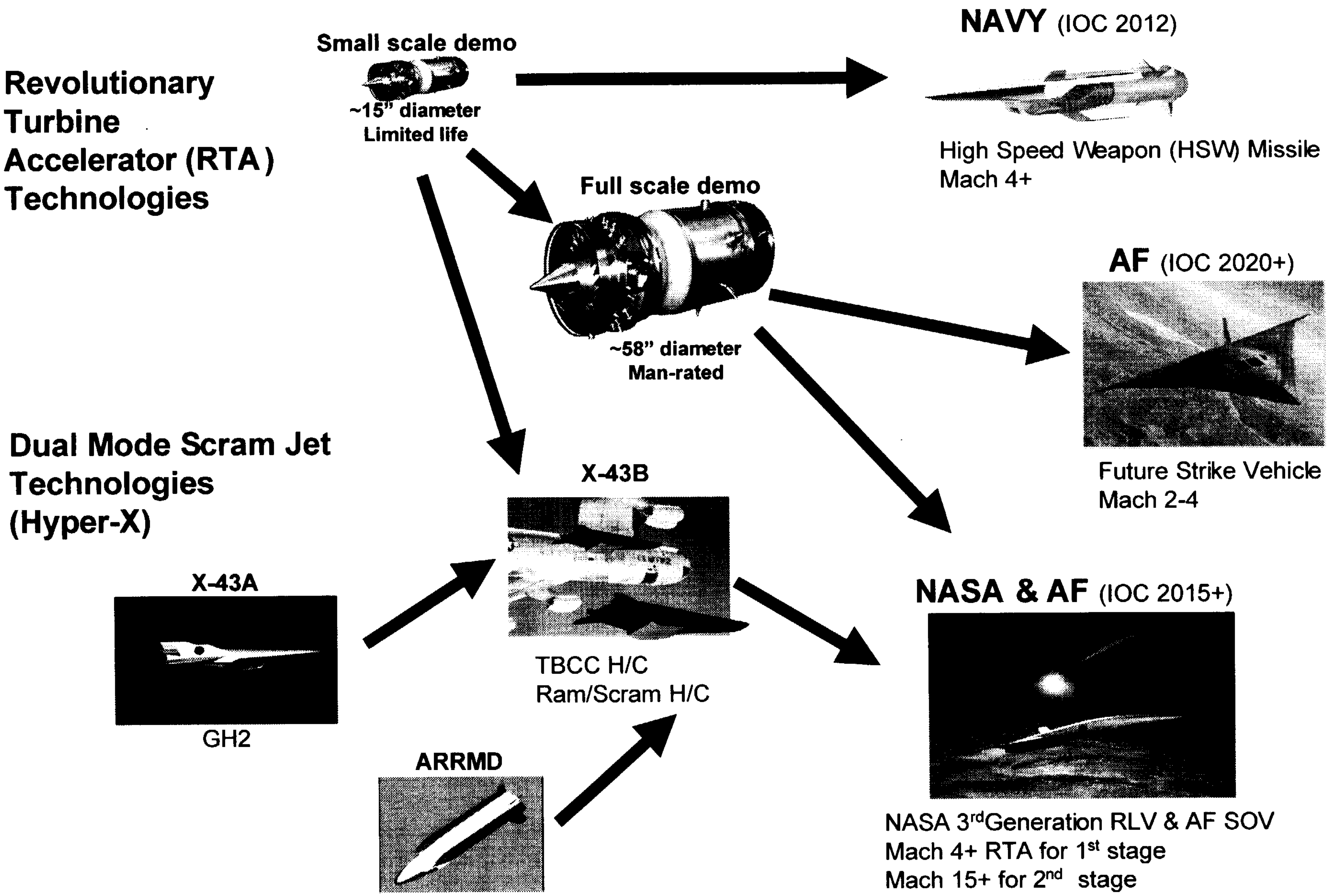
Revolutionary Turbine Accelerator (RTA)

Thrust/Weight ~20 (in-line)
Mach 4-5 Capable
Long Life



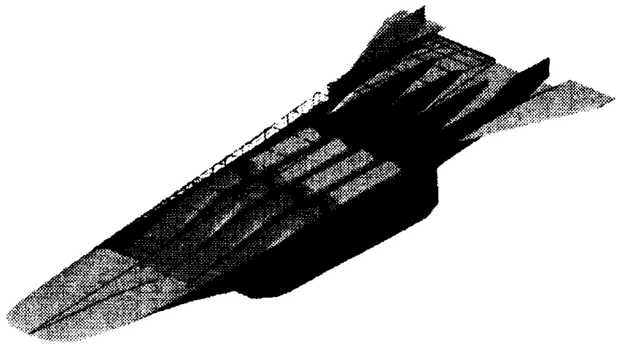
- **Current State-of-the-Art**
  - **J58 Mach 3+ capable engine**
- **Benefits of Technology**
  - **Mach 4-5 turbine accelerator**
  - **Simplifies ramjet/scramjet geometry (decreases weight)**
  - **Improves system capacity & operability**
  - **Improves safety, survivability, abort capability & launch flexibility**
  - **Increases reliability & durability**
- **Technical Challenges**
  - **High Mach compressor**
  - **Thermal management**
  - **Hot rotating components**
  - **Advanced materials**
  - **Propulsion/Airframe Integration**
- **Participants**
  - **GRC (lead), LaRC, MSFC**
  - **AF, NAVAIR**

Turbine Based Combined/Combination Cycle



Turbine Based Combined/Combination Cycle

SSTO (TBCC/RTA)



- SSTO
  - Turbine Accelerator Integrated with Dual Mode Scram Jet in Combined Flow Path
  - Over/under Configuration
  - Hyper-X type vehicle (Baseline)

Turbine Based Combined/Combination Cycle

TSTO (TBCC/RTA)

Vehicle System

- <u>First Stage:</u>
  Turbine Accelerator with
  Afterburner or Ram Jet

- <u>Second Stage:</u>
  AB RBCC and/or Rockets

Turbine Based Combined/Combination Cycle

TBCC/RTA Technical Challenges

Inlet Design:
- Location (ahead, inside SJ inlet)
- Mode Transition
- Boundary layer control
- Performance
- Highly offset, subsonic diffuser
- Quality of flow
- Unstart susceptibility
- Separate inlets vs. single aperture
- Variable geometry (in or out doors)
- Weight/complexity

Turbine Accelerator:
- Protection from high temperatures for all configurations
- In flight restart

Nozzle:
- Exit location
- Design and performance
- Size & weight
- Mode transition interaction

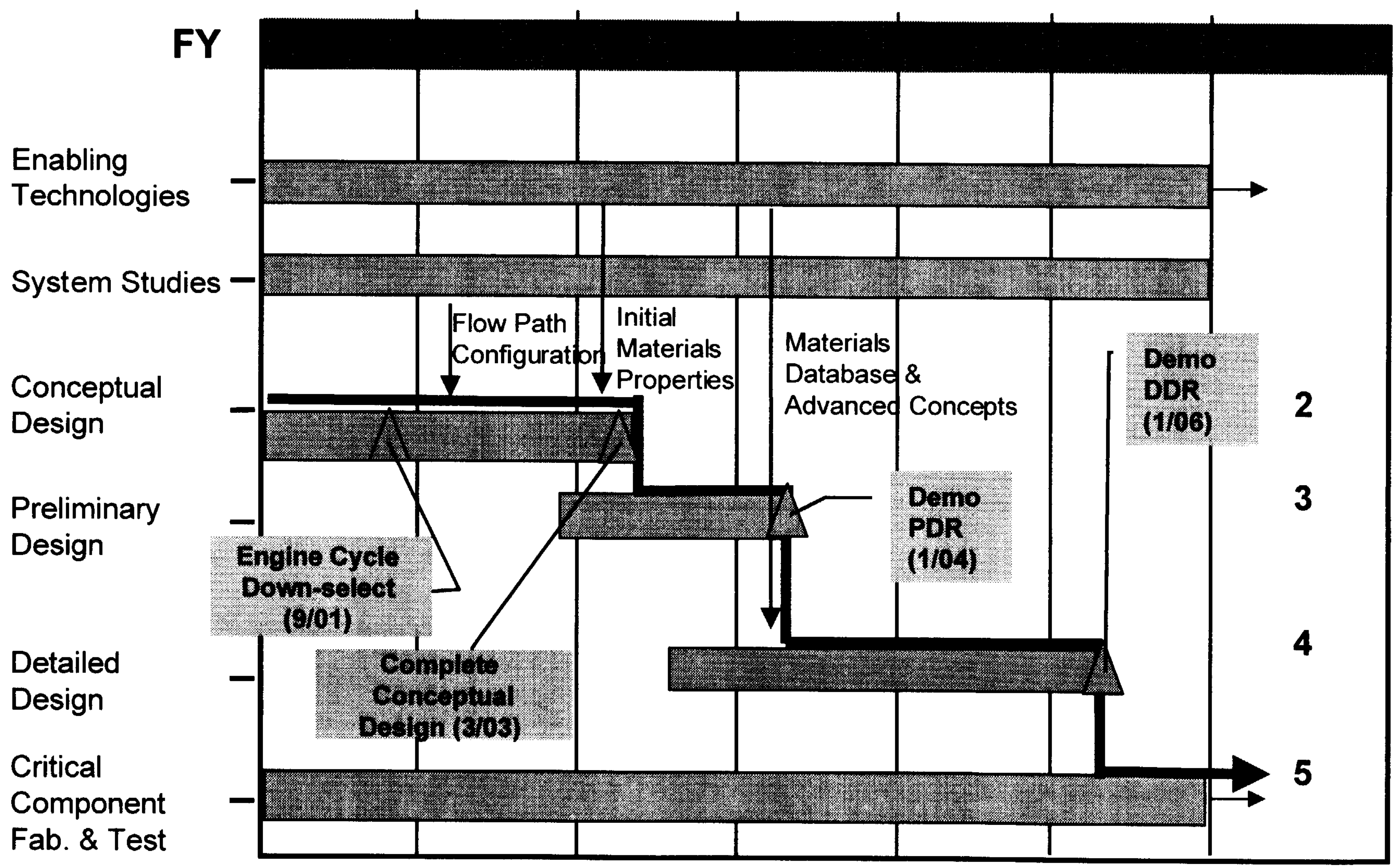
Additional Technical Challenges:
- Thermal management
- High temp seals
- Materials and Structures
- Integration
- Integrated flight controls
- Fuel system, cooling
- Vehicle design-CG Pitching moment

RAM SCRAM:
High speed system flowpath design and performance

Ejector Region:
- Mixing performance and its impact on overall system performance
- Mixing enhancement
- Mode transition
- Thermal choke performance and locations control

Turbine Based Combined/Combination Cycle

TBCC/RTA Project Plan



Turbine Based Combined/Combination Cycle

INTEGRATED AIRFRAME DEMONSTRATIONS

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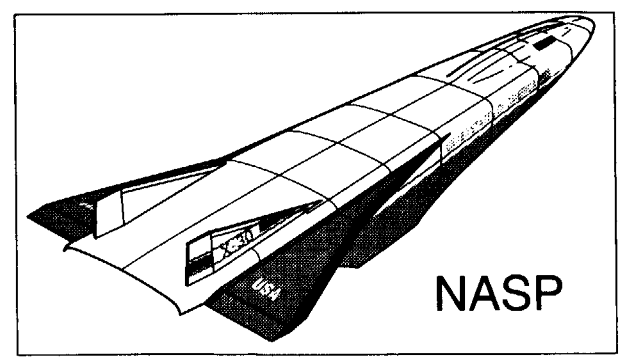
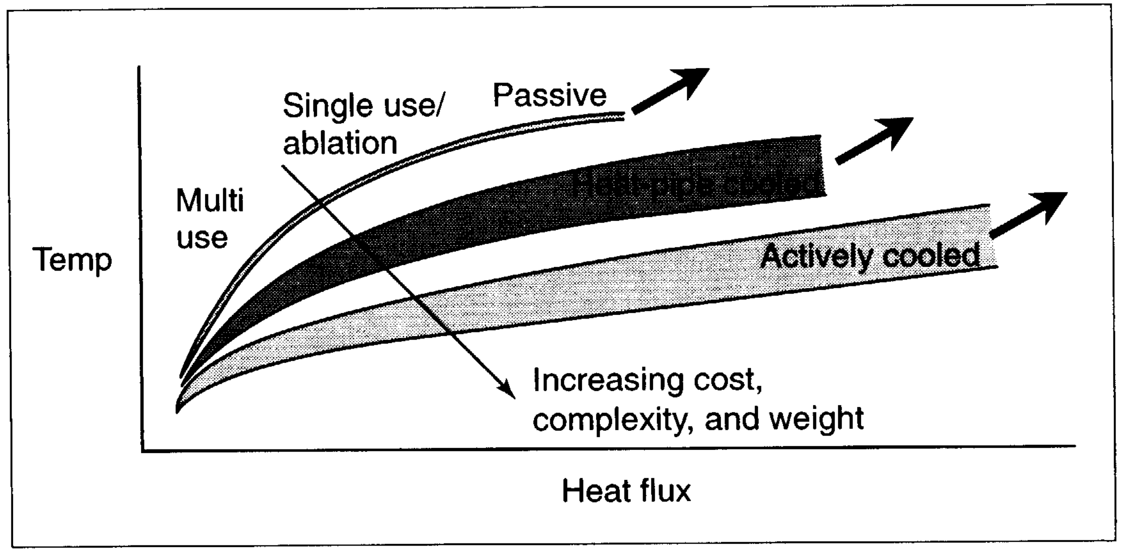
d.e.glass@larc.nasa.gov



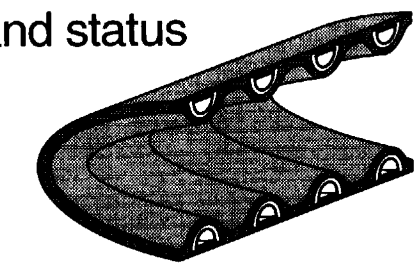
Space Transportation Technology Workshop

- Evolution of technology
  - Increase heat flux/ temperature capability
  - Decrease cost, complexity and weight
  - Increase size



- Control surfaces
  - Accomplishments and status
    - C/C elevon (NASP)
    - Ruddervator and flaperon (X-37)
  - Next step
    - Full size orbiter body flap

- Heat-pipe-cooled leading edges (HPCLE)
  - Accomplishments and status
    - Metallic (Shuttle)
    - C/C (NASP)

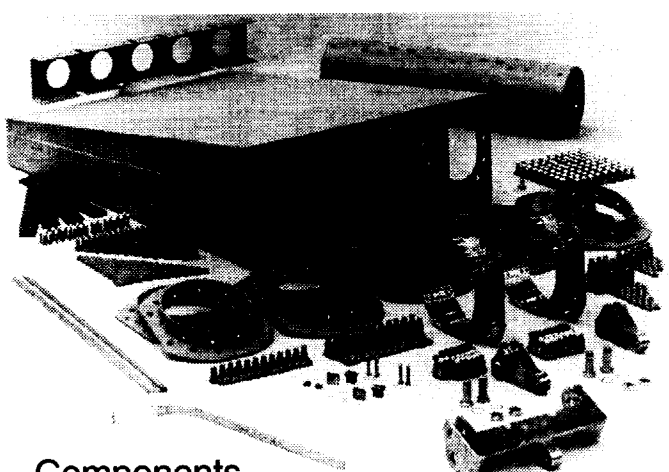


  - Next step
    - C/C HPCLE segment for radiant heating test and orbiter flight experiment

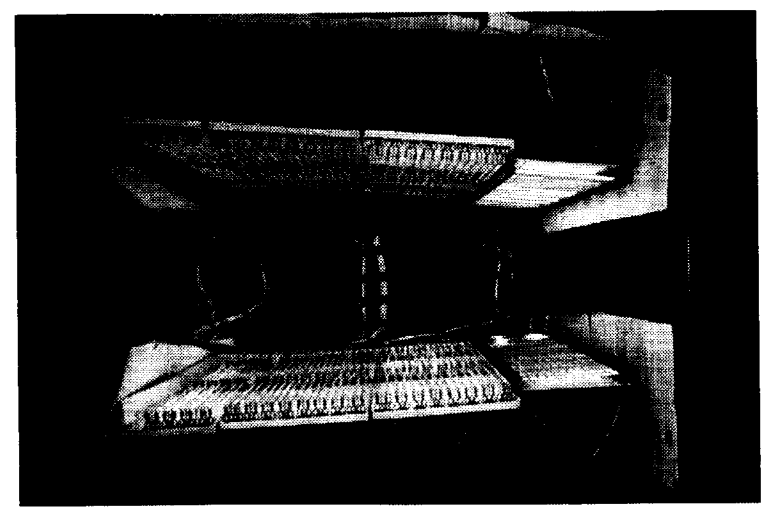
Space Transportation Technology Workshop

HOT STRUCTURE COMPONENTS FOR POTENTIAL FLIGHT DEMO

- Objective
  - Develop and verify the technology required for application of minimal weight control surfaces that meet NASP vehicle requirements
- Approach
  - Develop design and fabrication concepts
  - Verify concept design through sub-component fabrication and tests
  - Design and fabricate full-scale segment of C/C control surface
  - Verify design and fabrication technology by thermal/structural tests
- Payoff
  - Vehicle enabling
  - Reduced structural weight



Components

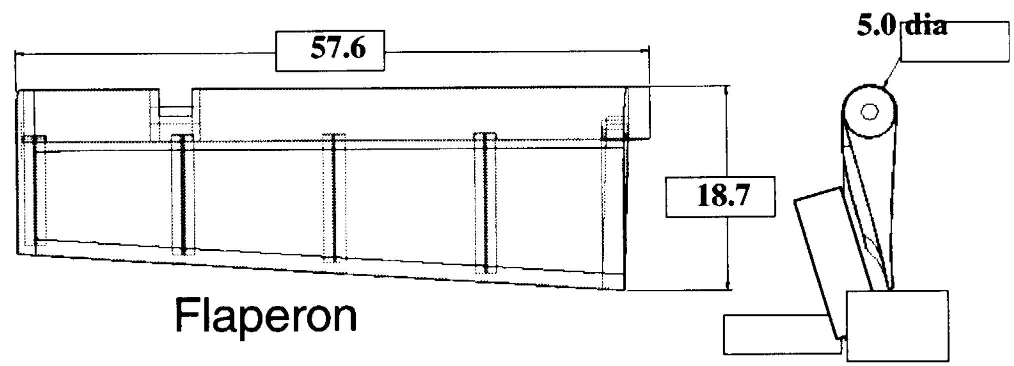


Space Transportation Technology Workshop

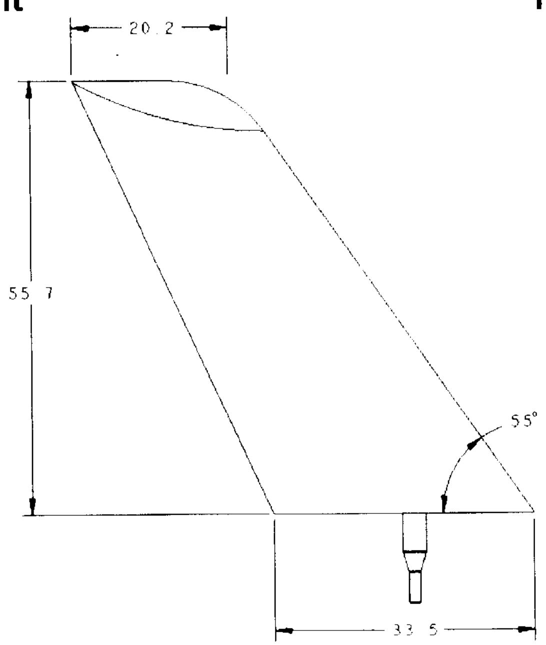
CONTROL SURFACES

C/C CONTROL SURFACE FOR NASP

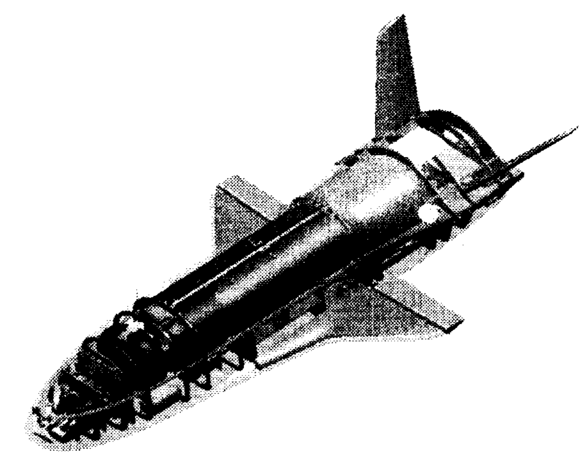
- Objectives
  - Develop and validate C/SiC control surfaces for the X-37
  - Deliver 2 flight approved flaperons and 2 moveable ruddervators for installation on the flight vehicle
- Team members
  - LaRC - lead
  - Boeing - requirements
  - BF Goodrich - C/SiC fabrication
  - MR&D - consultant
  - AFRL - test



Flaperon



Ruddervator



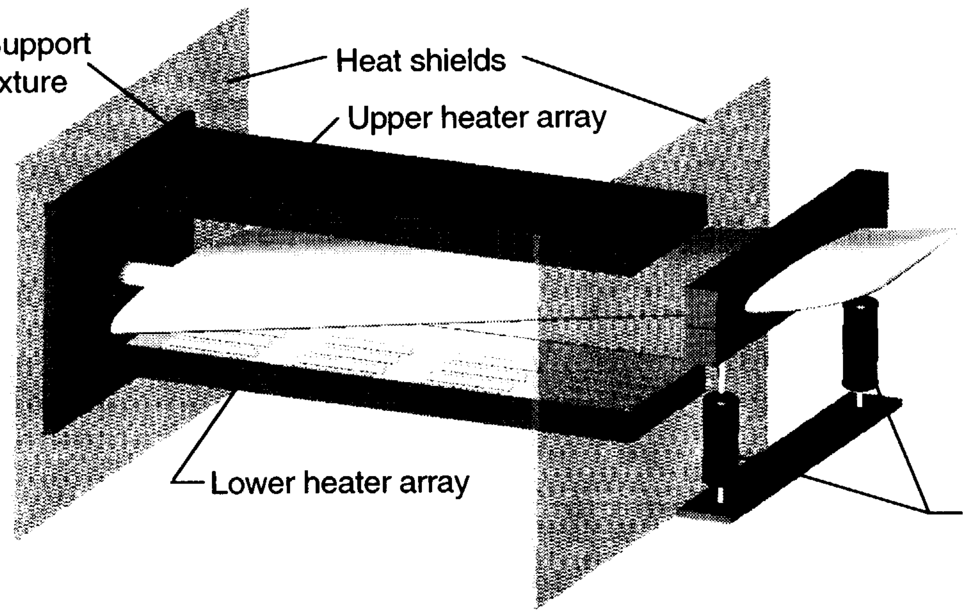
Space Transportation Technology Workshop

CONTROL SURFACES

X-37 FLIGHT COMPONENTS

.4

- Material property and sub-element (RT - 2800°F)
- Subcomponent (RT)
- Full scale thermal/structural test component
- Proof test of flight article (RT)



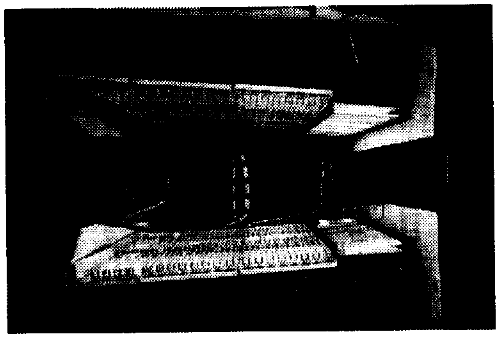
Schematic diagram of ruddervator thermal/structural test at AFRL

CONTROL SURFACES
X-37 FLAPERON AND RUDDERVATOR VALIDATION

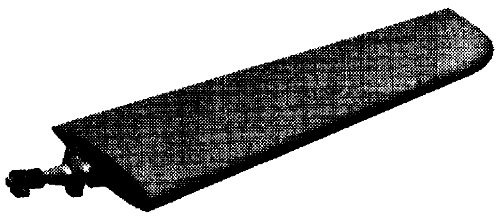
- Status
  - Design, analysis, and fabrication validated through thermal/structural tests and analysis of large full-scale segment of C/C control surface for NASP
  - Design, analysis, and fabrication will be validated through thermal/structural tests and analysis and through flight of small full-scale flaperons and ruddervators for the NASA/Boeing X-37 vehicle and small full-scale body flap for the X-38 vehicle
- Issues
  - Validation of major load bearing structural joints in C/C or CMC structures
  - Technology required for the fabrication of large multi-part components using C/C or CMC materials
  - Life cycle performance of large hot structures components

CONTROL SURFACES
STATUS & ISSUES

Hot Structures Control Surfaces



C/C control surface for NASP



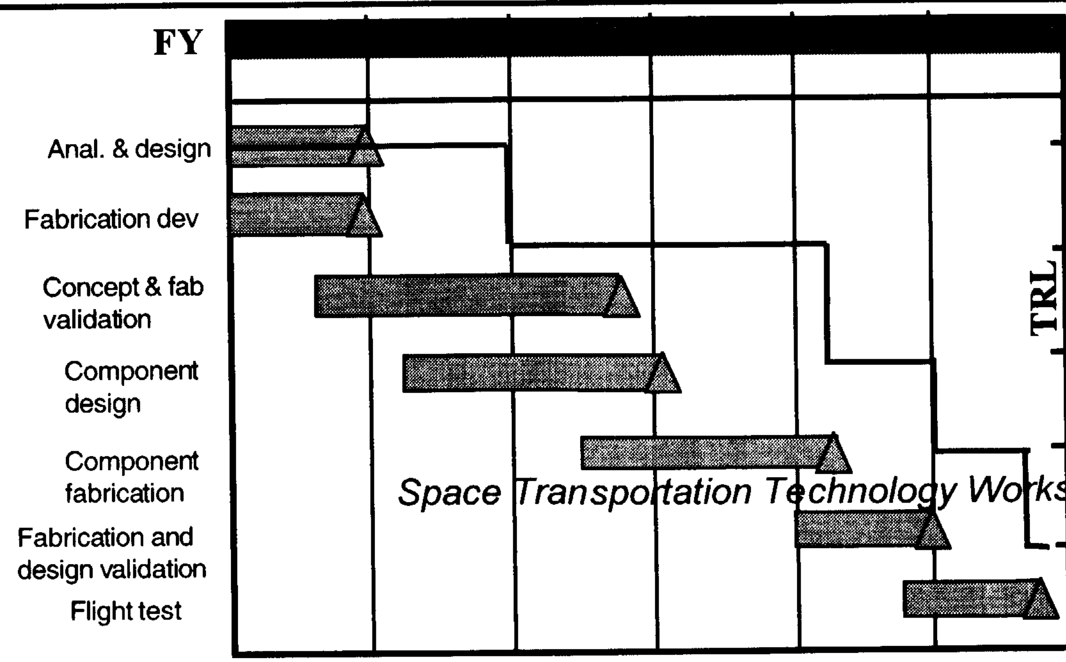
Ceramic matrix composite flap for X-37

[redacted]

- Phase I
  - Design concepts developed
  - Fabrication plan developed
  - Sub-component test articles designed
- Phase II
  - Sub-component test articles fabricated
  - Design/fabrication validated through sub-component analysis and tests
  - Full-scale component (shuttle or RLV size) design developed
- Phase III
  - Full-scale control surface fabricated
  - Design/fabrication validated through thermal/structural analysis and tests
  - Flight test

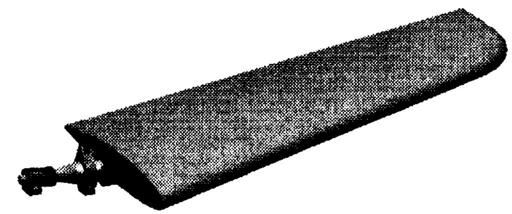
[redacted]

- **Current State of the Art**
  - Aluminum or low-temperature composite structure with ceramic tile TPS
- **Performance Metrics**
  - Reduced weight, more durable and less maintenance and operating costs than current Space Shuttle control surfaces
- **Potential risks**
  - Higher initial cost
- **Participants**
  - LaRC, DFRC, industry

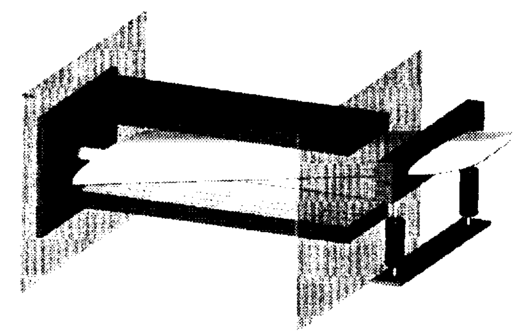


Space Transportation Technology Workshop

- Design and fabricate large full-scale C/C or CMC control surface component for Space Shuttle or RLV size vehicle

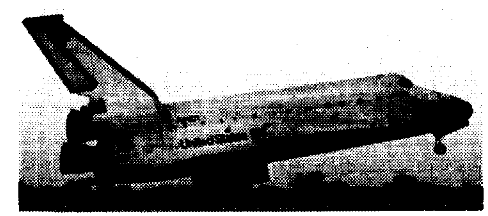


- Validate the design and fabrication procedure through static thermal/structural tests and analysis



- Evaluate life-cycle performance through simulated mul reentry thermal/structural load cycles

- Flight test on Space Shuttle or RLV size vehicle



Space Transportation Technology Workshop

CONTROL SURFACES

POTENTIAL TASKS FOR FLIGHT DEMO

- 12:45 - 1:00 Introduction 2nd Gen RLV Airframe — S. Welch
- 1:00 - 1:20 Airframe Design and Integration — S. Scotti
- 1:20 - 1:40 Aerothermodynamics — C. Miller
- 1:40 - 2:00 Structures and Materials — T. Johnson
- 2:00 - 2:20 Tanks — D. Smith
- 2:20 - 2:40 Thermal Protection Systems — M. Rezin
- 2:40 - 3:00 Integrated Airframe Demonstrations — D. Glass

- 3:00 - 3:05 BREAK

- 3:05 - 3:30 Introduction 3rd Gen RLV Airframe — D. Bowles
- 3:30 - 3:55 Integrated Design and Analysis — T. Gates
- 3:55 - 4:20 Integrated Thermal Str. & Materials — B. Jensen
- 4:20 - 4:45 Thermal Protection Systems — S. Johnson

3rd Gen Airframe/TPS:

3rd Generation Agenda

Hall Propulsion Technology Development
NASA Glenn Research Center

50 kW Thruster Technology

EXPRESS Ground/Space Correlation

Contact Info:

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"ST Day 2000: Reducing Risk for the Next Generations"

- Technology goals and objectives

  It is the goal of this activity to develop 50 kW class Hall thruster technology in support of cost and time critical mission applications such as orbit insertion.

- Background

  NASA MSFC is tasked to develop technologies that enable cost and travel time reduction of interorbital transportation. Therefore, a key challenge is development of moderate specific impulse (2000-3000s), high thrust-to-power electric propulsion. NASA GRC is responsible for development of a Hall propulsion system to meet these needs.

- Current Status

  First-phase, sub-scale Hall engine development completed. 10 kW engine designed, fabricated, and tested. Performance demonstrated >2400 s, >500 mN thrust over 1000 hrs of operation documented.

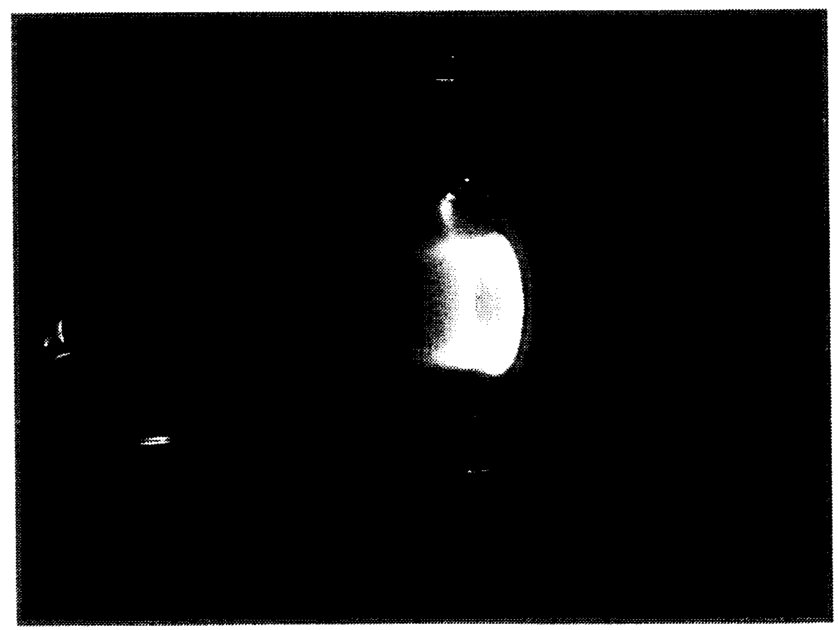
50 kW Thruster Technology

- **Major accomplishments (FY00):**

  The NASA T-220 10 kW Hall Effect Thruster demonstrated over 500 mN thrust at 2450 seconds specific impulse (Isp) and 59% total efficiency while demonstrating good erosion characteristics over 1000 hours of operation. This is the longest operation ever achieved on a high power Hall thruster (>5 kW). This test indicates the availability of 10 kW Hall thruster technology for future NASA, commercial, and military missions and confirms the technical approach for development of even higher power thrusters.

- **Near Term Plans (FY01):**

  Procure a 50 kW engine design and prepare diagnostics and test equipment.

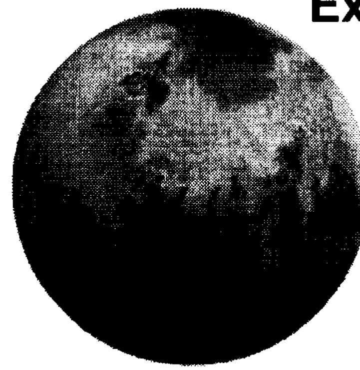


"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

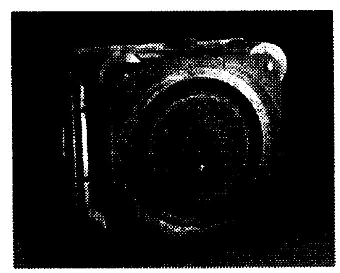
50 kW Thruster Technology

ISS Drag Makeup
Significantly reduces required refueling flights

Lunar/Mars Exploration
, Reduces Launch Vehicle Fleet



LEO to GEO space transportation *Four Times the Payload of Chemical Systems In Four Weeks using next generation Power levels*



- **Need Power Levels ~ 50 kW & Isps ~ 2000 sec**

Space Solar Power
Reduces number of launch vehicles required by a factor of 5 ! *Deliveries in few weeks to less than four months.*

"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

50 kW Thruster Applications

- Technology goals and objectives

  Compare measurements of critical plasma parameters from on-orbit with ground test data. Develop fundamental understanding of the differences enabling extrapolation to other thrusters/geometries for integration assessments.

- Background/Approach
  - Several different types of sensors integrated on two Russian Geo-Comsats (Express-A #2 & EXPRESS-A #3) utilizing 1.5 kW SPT-100 Hall thrusters.
  - Ground tests validating sensors and duplicating space measurements to be taken at NASA GRC
  - Additional GRC ground tests with alternate thrusters/geometries

EXPRESS Ground/Space Correlation

- **Sensors integrated on to Express-A, #2 and launched**
  - Data being collected
  - Data transfer and correlation with thruster operation being addressed
- **Sensors integrated on to Express-A, #3 and launched**
  - Data being collected
  - Data requirements also being addresses
- **GRC ground testing**
  - Planning stages - test details being discussed
  - S/C representative sensors being procured

Current Status

- Major accomplishments (FY00):

  Successful launch of sensor packages on EXPRESS-A #2, and EXPRESS-A #3

- Near Term Plans (FY01):

  Procure a duplicate set of EXPRESS-A #2, and EXPRESS-A #3 sensors. Plan ground test program.

EXPRESS Ground/Space Correlation

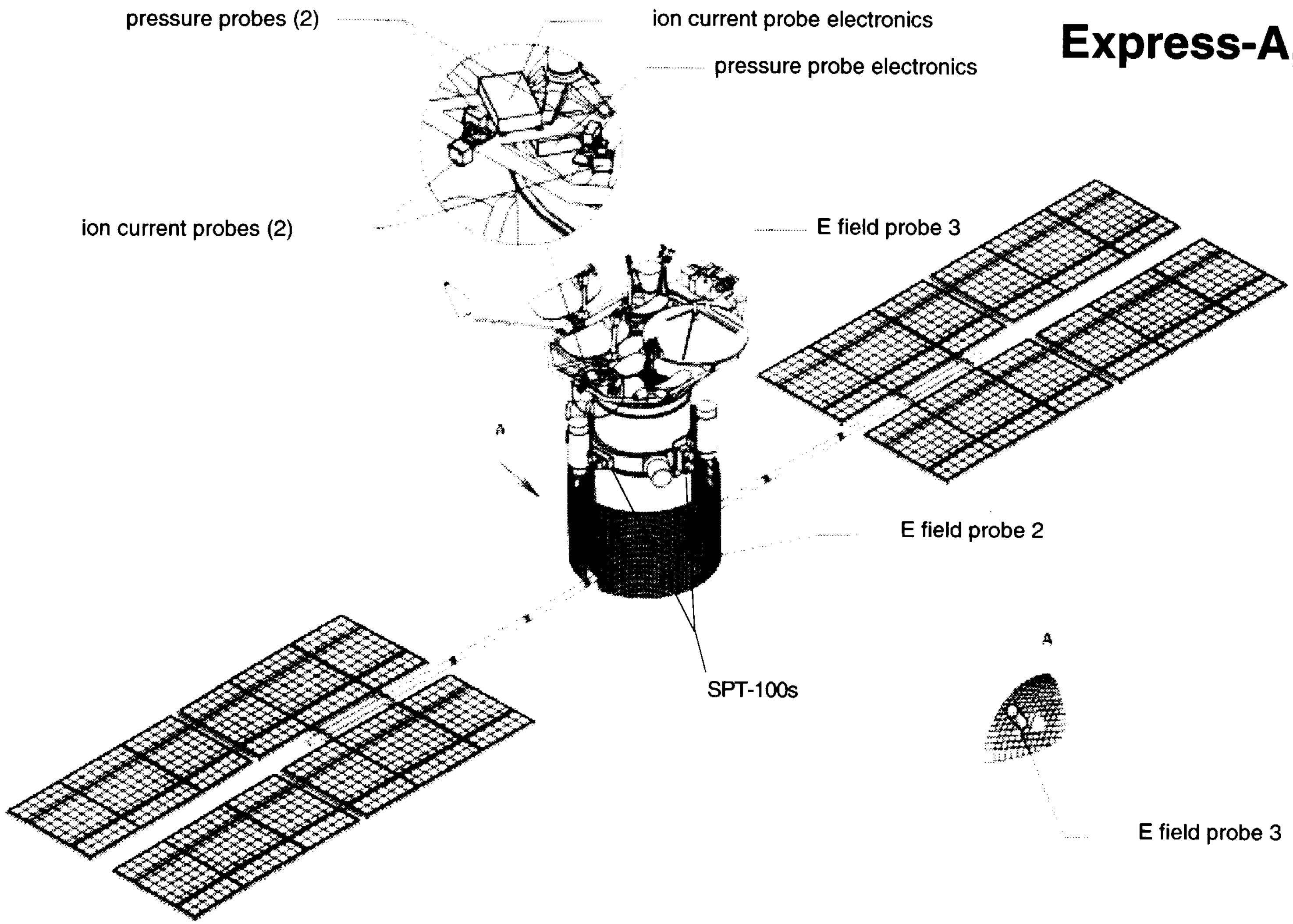
- Sensor Types
  - **Pressure: Measure local density to understand how plume expands Simple measurement, previously conducted**
    - Measurement in back flow region very difficult on ground
    - Maybe important for assessing corona phenomena for payload
  - **Electric Field Strength: Measure how the plasma modifies E-field at S/C surface**
    - Less simple measurement , previously conducted
    - Gives insight into how the spacecraft couples to the ambient space plasma
    - Maybe important for assessing corona phenomena for payload

EXPRESS Ground/Space Correlation

- **Sensor Types (continued)**
  - **Ion Current: Measure the flux density of the plume ions**
    - Simple measurement, not previously conducted
    - Easily compared with ground tests data and analytic predictions
    - Flux of ions needed for estimating thermal/momentum transfer to other parts of S/C
  - **Ion Current & Energy: Measure the flux density and energy of the plume ions**
    - Difficult measurement, not previously conducted
    - Provides desired information for determination of integration impacts
    - Flux and energy ions needed for determining thermal/momentum transfer and erosion of S/C

EXPRESS Ground/Space Correlation

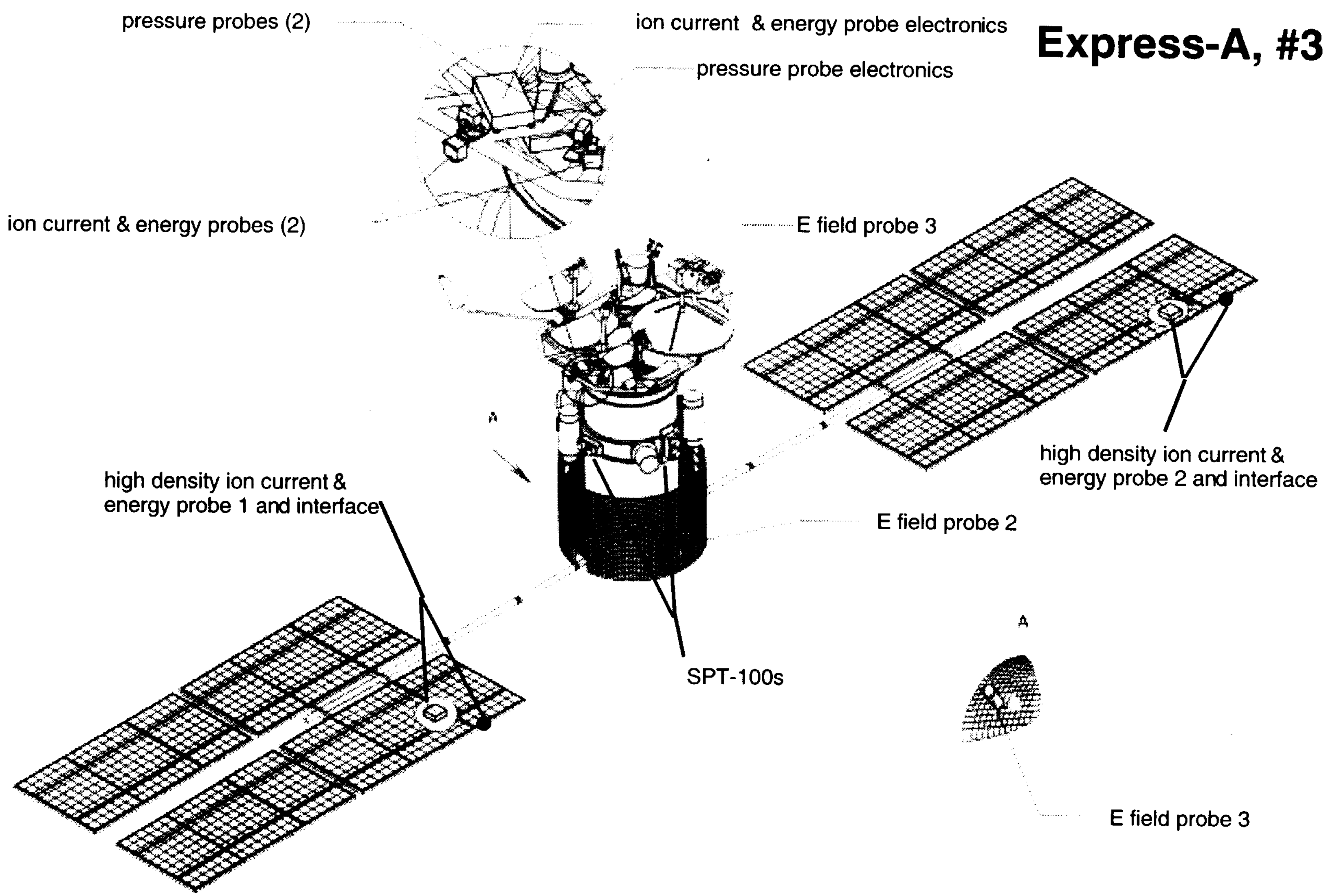
Express-A, #2



"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

Express-A, #3



"ST Day 2000: Reducing Risk for the Next Generations" - Hall Propulsion

EXPRESS Ground/Space Correlation

58/[illegible]/[illegible]/34

Overview of TPS tasks

Sylvia M. Johnson
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- Quick Processed, Low Cost Erosion Resistant TPS
- SmarTPS
- Advanced, High-Temperature Structural Seals
- UHTC Sharp Leading Edges
- High Temperature Felt TPS

3rd Gen Airframe/TPS:

Thermal Protection Systems

- **Quick Processed, Low Cost Erosion Resistant TPS**
  - **POC's:**
    - Dr. Daniel Leiser, David Stewart, Huy Tran, Dr. Susan White
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    - (650) 604-6076
    - dstewart@mail.arc.nasa.gov
    - (650) 604-6614
    - htran@mail.arc.nasa.gov
    - (650) 604-0219
    - swhite@mail.arc.nasa.gov
    - (650) 604-6617

Quick Processed, Low Cost, Erosion Resistant TPS

- **Objective**
  - Develop light weight & low cost durable TPS for easy application to RLV payload launchers
  - Develop quickly processed composite TPS processing & repair techniques
  - Develop higher temperature capability tile TPS
- **Benefits**
  - **Reduced installation & operations cost**
  - **Enhanced payload capability resulting from TPS weight reduction**
  - **Enhanced flight envelope & performance resulting from higher temperature capability TPS which can result in improved safety**

Quick Processed, Low Cost, Erosion Resistant TPS

Technical Accomplishment

More Capable Ceramic Tile TPS Demonstrated
POC: Dr. Daniel Leiser
September 2000

Relevant Milestone: Task 2 - Quick Processed Erosion Resistant TPS,
- Higher temperature capability (above 3,000°F) , and
- Faster processed ceramic tile TPS produced, 8/15/00

Shown: A graphic of an entry vehicle with a higher temperature capability tile TPS leading edge being tested in a hypersonic arc plasma stream that will be cheaper, safer and easier to repair.

Accomplishments
- Arc jet testing was completed on candidate ceramic tile TPS at 3,000°F for 2 and 4 minutes (Tile TPS currently limited to 2700°F);
- Arc jet testing was completed on candidate QUICTUFI tiles at 2800°F for 5 minutes.

Relation to Milestone
- This reduces the cost of ceramic tile TPS substantially by reducing the labor required and extends its usage capability to higher temperature locations (I.e., leading edges) where much more expensive (i.e., carbon/carbon), difficult to replace and flaw sensitive materials are characteristically applied .

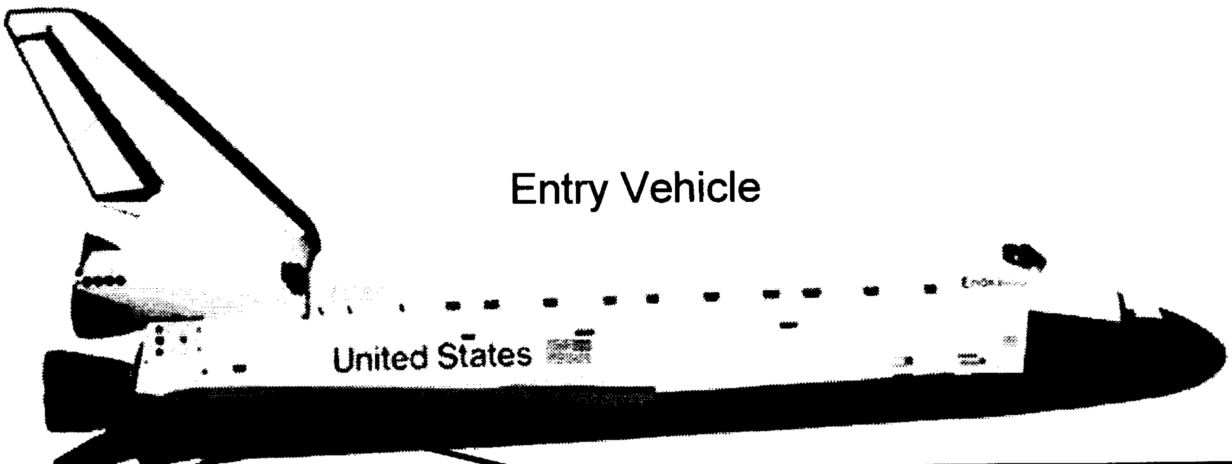
Future Plans: Continue extending the temperature capability of the materials reduce the labor required to produce these materials.

Quick Processed, Low Cost, Erosion Resistant TPS

Technical Accomplishment

Higher Temperature Capability Tile Leading Edge

Entry Vehicle



Ceramic Tile TPS in
Hypersonic Arc Plasma Stream

3rd Gen Airframe/TPS:

Thermal Protection Systems

Quick Processed, Low Cost, Erosion Resistant TPS

Technical Accomplishment

Aerogel–Tile Development

POC: Dr. Dan Leiser & Dr. Susan White

September 2000

Relevant Milestone: Autoclave equipment on-line to produce large scale Aerogel-Tiles. (September FY99)

Shown: Large Scale Autoclave Supercritical Processing Equipment that is used to produce either pure aerogels or aerogel-tile composites. Aerogels are organic, inorganic or metal oxide-based highly porous monoliths or nano-particulate materials.

- •Extremely light weight - critical for Space
- •Lowest solid conductivity: Superinsulator

Aerogel tiles exploit low thermal conductivity and low density of aerogels and AETB's high temperature capability and moderate density

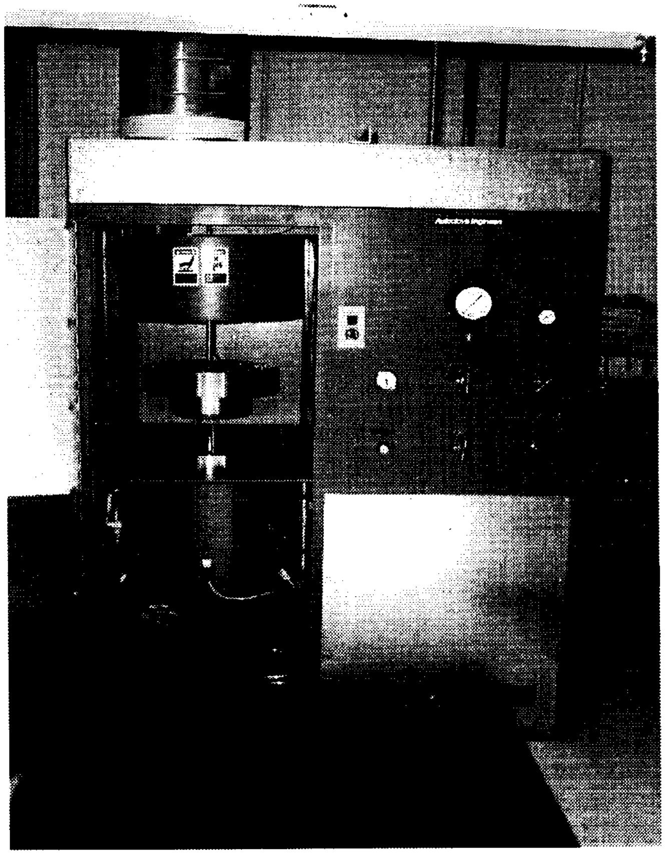
Accomplishment / Relation to Milestone and ETO: The Autoclave equipment is currently on-line and the operational procedures are being developed to produce large scale aerogel tiles, enabling progress towards the goal of reducing TPS weight.

Future Plans: Continue producing, characterizing and optimizing aerogel-tile composites tailored for specific spacecraft insulation applications.

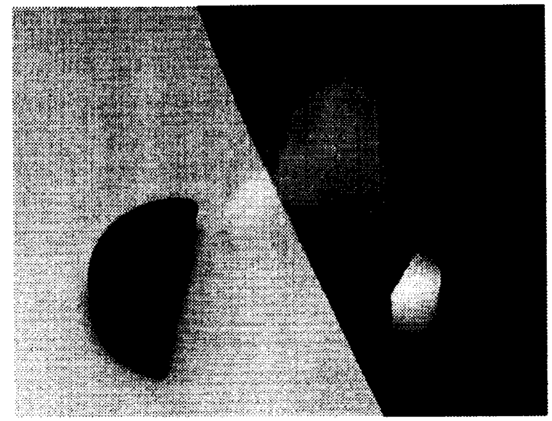
Quick Processed, Low Cost, Erosion Resistant TPS

Technical Accomplishment

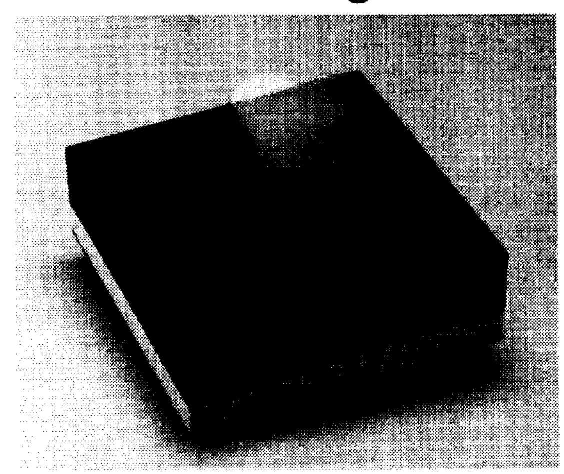
Aerogel Tile Development



Large-Scale Autoclave Equipment



Pure Aerogels



Aerogel-Tiles

Quick Processed, Low Cost, Erosion Resistant TPS
Technical Accomplishment

Erosion Resistant TPS
POC: Huy Tran
September 2000

Relevant Milestone: Task 2 - Quick Processed Erosion Resistant TPS,
- Resin impregnated fabric reinforced erosion resistant tile TPS surface successfully tested at 2200°F for 30 min.

Shown: A graphic of an erosion-resistant leading edge tile TPS with a fabric reinforced face.

Accomplishment
- Testing was completed on a fabric reinforced erosion resistant TPS at 2200°F for 30 minutes.

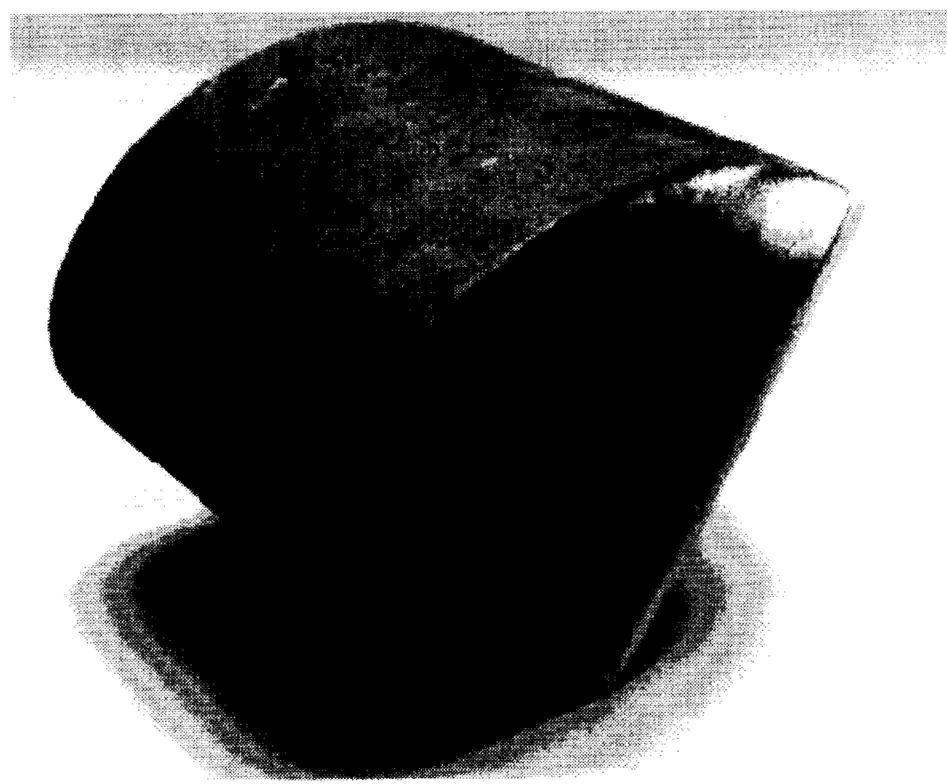
Relation to Milestone
- This material concept will reduce the cost of ceramic tile TPS substantially by extending its usage capability to more damage prone locations where characteristically much more expensive materials are applied .

Future Plans: Develop adhesion technique for multi-layered fabric reinforced face on tile TPS, further improving erosion resistance and perform arc jet testing on leading edge configuration test model

Quick Processed, Low Cost, Erosion Resistant TPS

Technical Accomplishment

Erosion Resistant Leading Edge Concept



3rd Gen Airframe/TPS:

Thermal Protection Systems

- SmarTPS
  - POC:
    - Frank Milos
    - Fmilos@mail.arc.nasa.gov
    - (650) 604-5636

SmarTPS

Passive Wireless Thermal-Overlimit Sensor

- **Background:** Inspection of intertile gaps, primarily for evidence of hot-gas inflow and subsurface charring, is a slow and labor intensive task that involves close-up, hand-on visual inspection. The highest priority for health monitoring of TPS is development of a sensor system that can automatically monitor the subsurface temperature and rapidly communicate the sensor data to outside the vehicle using wireless communications technology.

- **Technology goals and objectives:** The goal of this subtask is to develop a miniature sensor that combines a passive temperature measurement, an identification microchip, and a micro-antenna to enable wireless communications.

SmarTPS

Passive Wireless Thermal-Overlimit Sensor

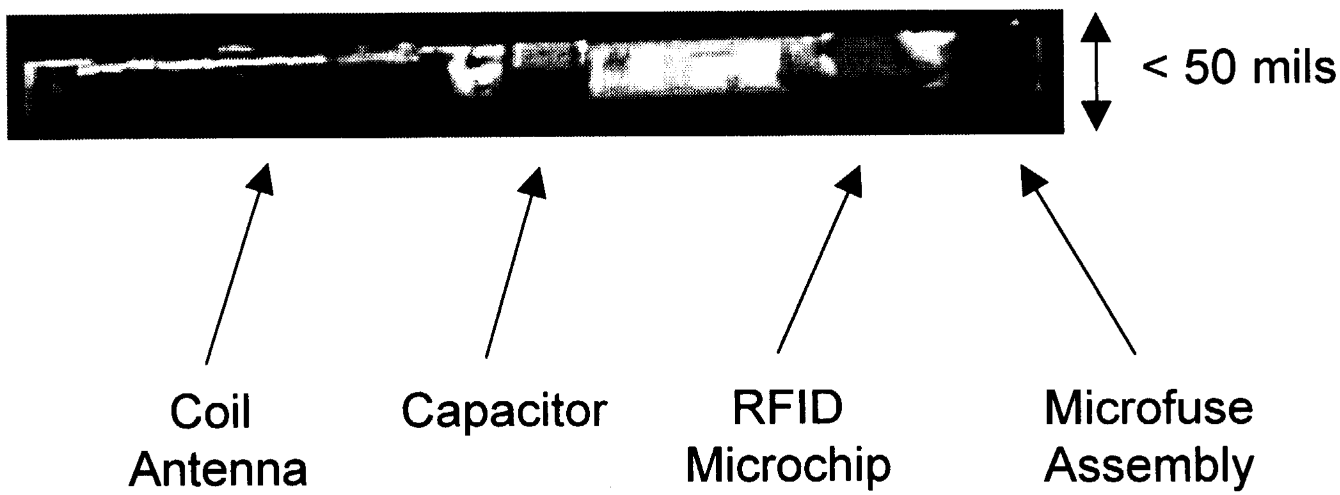
- **Current Status and major accomplishments:** A prototype passive sensor was designed and manufactured. The sensor fits into a 50-mil gap, can survive 15 minute exposure to about 650 °F (345 °C), and indicates a thermal-overlimit event using a fuse that melts at 558 °F (292 °C).

- **Near-term plans:** As required, additional sensors of the same (or slightly modified) design will be manufactured, and sensors will be tested in preparation for possible Shuttle Orbiter flight experiments.

- **Note:** currently TRL=4 to 5. After arc jet/qualification testing we will be at TRL= 5 to 6.

SmarTPS

Passive Wireless Thermal-Overlimit Sensor



- Sensor fits into 50-mil gap between TPS tiles
- Tag mass is 75 mg
- Microfuse opens at 558 °F to indicate a thermal-overlimit event (other fuse temperatures using different solder alloys are possible)
- Sensor should survive 15 minutes exposure to 650 °F

SmarTPS

Active Wireless Thermal-Profile Sensor

- **Background:** In some cases, rather than simply indicating a thermal-overlimit event, it is desirable to measure and record TPS temperatures. For example, in-flight TPS gap or surface temperatures may be useful for environment characterization and performance evaluation.

- **Technology goals and objectives:** The goal of this subtask is technology development to combine active sensors, micro-batteries, an identification microchip, and a micro-antenna for communications to enable in-flight data acquisition with on-ground data readout. In the long-term, real-time data acquisition is desirable for applications such as MMOD impact detection.

SmarTPS

Active Wireless Thermal-Profile Sensor

- **Current Status and major accomplishments:** A proof-of-concept prototype active sensor using COTS components was designed and manufactured. The electronics are bonded to the back of a TPS tile, and an attached Type-K thermocouple is placed anywhere within a TPS tile. The time and some criteria for data acquisition are downloaded to the microchip, subsequently temperature data are acquired and stored, and finally the time-tagged data are retrieved using wireless communications.

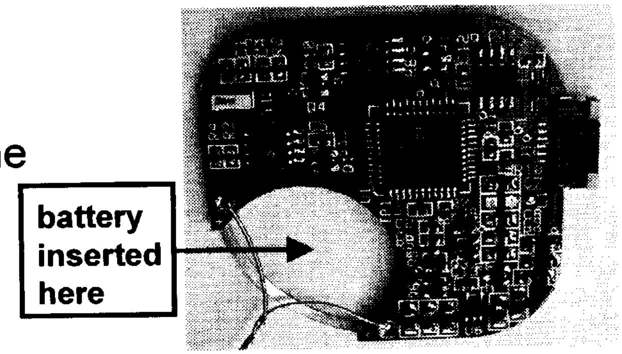
- **Near-term plans:** The prototype sensor will be tested and a demonstration model will be manufactured.

- **Note:** After some testing we will be at TRL= 3 to 4.

SmarTPS

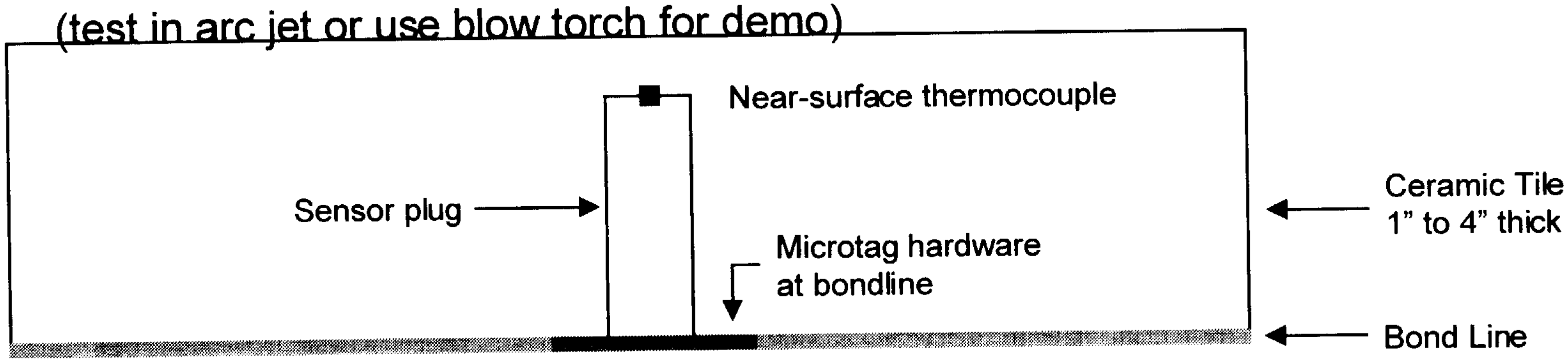
Active Wireless Thermal-Profile Sensor

- Tile sensor plug bonded to Microtag, this assembly then inserted into tight-fitting hole at back of tile.
- Periodically monitors temperatures at bond line and near the surface.
- Time-tagged data will be output to wand-style reader.
- Technique can be generalized for many uses
  - limited by microbattery life.
- For future designs, several thermocouples may be monitored simultaneously (however wires must be run to each TC location) with data output from one RFID device.



Prototype Active Microtag
(to scale)

Front Surface: transient temperature can exceed 2000°F
(test in arc jet or use blow torch for demo)



Back Surface: transient temperature below 300°F
(transient temperature to 650°F may be ok in future versions)

3rd Gen Airframe/TPS:

Thermal Protection Systems

SmarTPS

Surface Laser Measurement Tool

- **Background:** Surface TPS defects can be detected by a post-flight inspection. Currently for Shuttle a team of humans performs a hands-on inspection using rulers and other tools to measure the dimensions of holes, inter-tile steps and gaps, etc. In principle, this inspection could be performed more rapidly and reliably using smart automated scanning tools.

- **Technology goals and objectives:** The goal of this subtask is to develop portable laser-based tools for rapid surface inspection of TPS.

SmarTPS

Surface Laser Measurement Tool

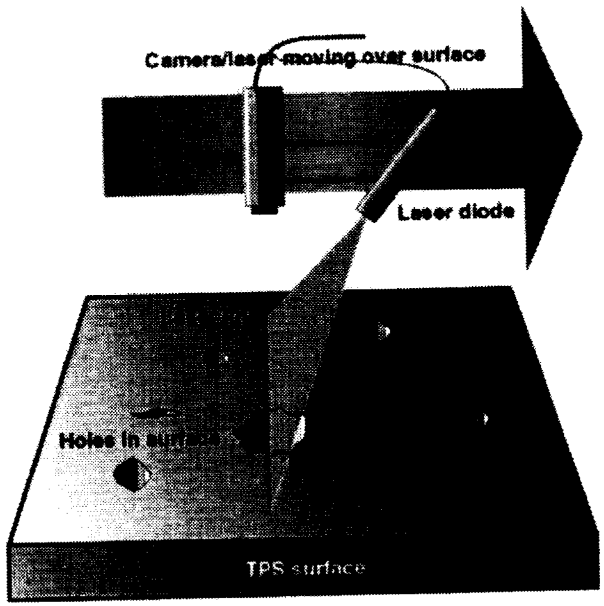
- **Current Status and major accomplishments**: Working with Joe Lavelle in Code SFT, a pre-prototype laser-scanning tool was manufactured and demonstrated. This hand-held tool scans a 3" x 3" surface area and obtains quantitative measurements of the surface depth suitable for obtaining full dimensions of surface flaws such as impact chips and holes.

- **Near-term plans:** An improved prototype device that uses two lasers has been designed. The prototype will be manufactured and tested in FY01.

- **Note:** TRL =3, will be 4 after new prototype is tested.

SmarTPS

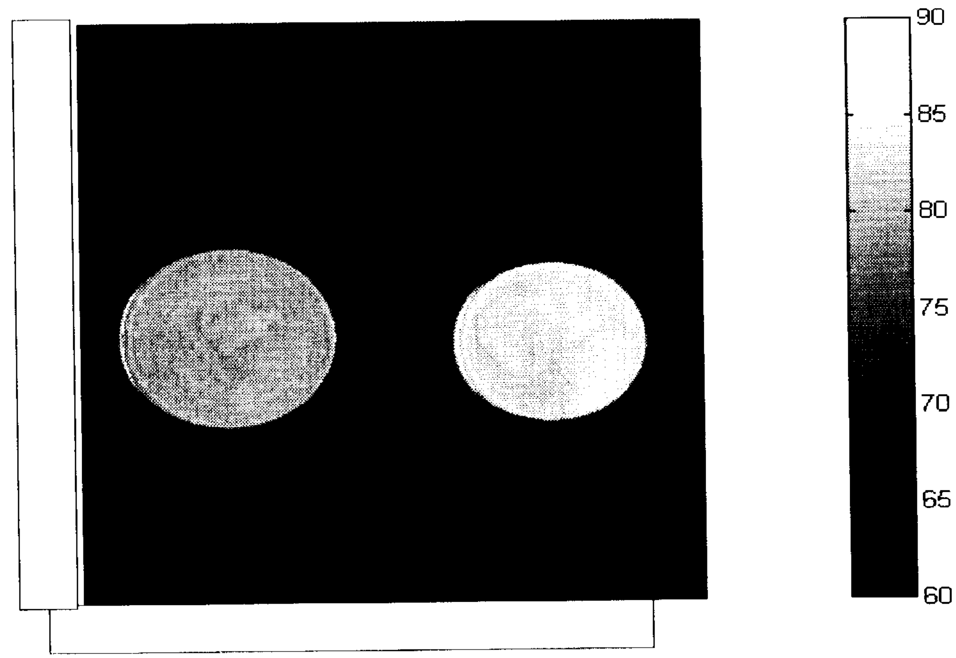
Surface Laser Measurement Tool



Theory of Operation

- The camera/laser sensor head moves across the surface.
- A straight laser line is projected down onto the surface at an angle from normal.
- Distortions in the reflected line indicate the depth of the surface.
- The prototype will use two lasers to eliminate masking effects.

Image of coins and holes from pre-prototype (shading indicates depth)



3rd Gen Airframe/TPS:

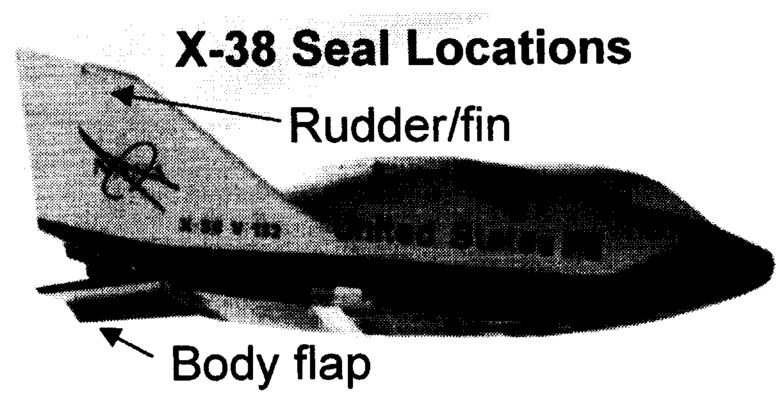
Thermal Protection Systems

- **Advanced, High Temperature Structural Seals**
  - **POC:**
    - **patrick.dunlap@grc.nasa.gov**

Advanced High Temperature Structural Seals

- **Technology goals and objectives**
  - Development and testing of advanced high temperature structural seal concepts for control surfaces of new generation of small reusable launch vehicles
- **Background**
  - Control surfaces of reusable launch vehicles require resilient seals to block high temperature flow between components that move relative to one another for multiple cycles
  - Current seal designs exhibit loss of resiliency after repeated load cycles at high temperatures
  - Advanced seals are required with higher levels of resiliency, flexibility, temperature endurance, and flow blocking capabilities
- **Significant program synergy with X-38 (CRV) control surface seal testing at JSC & GRC as well as X-37 program**
- **TPS-20 program partners:**
  - NASA GRC lead
  - NASA Ames & Boeing support

X-38 Seal Locations

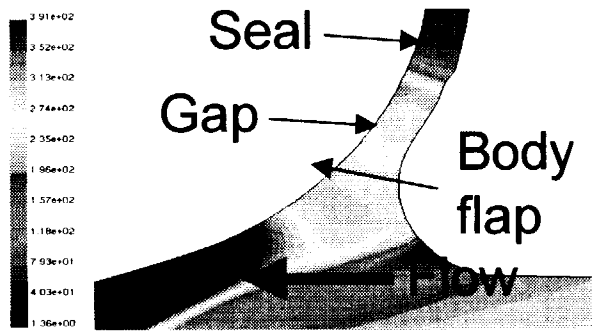


3rd Gen Airframe/TPS:

Thermal Protection Systems

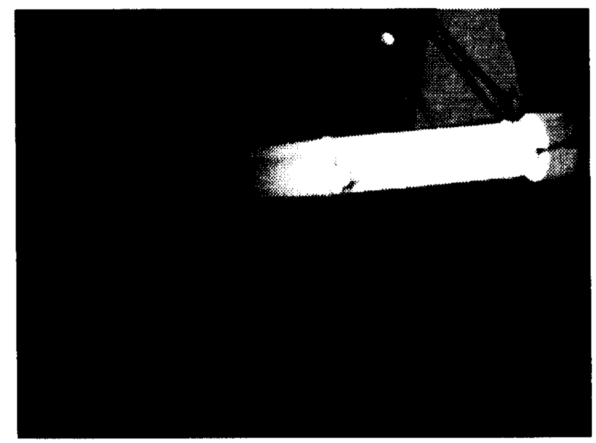
Advanced High Temperature Structural Seals

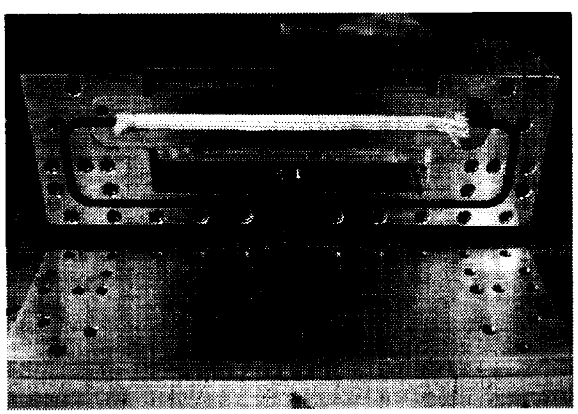
- **Major accomplishments**



⇐ **Preliminary aerothermal analyses revealed X-38 body flap seal temperatures of 2300°F**

GRC temperature exposure tests show reduction of resiliency & seal preload in baseline seal design (used on Shuttle) ⇒

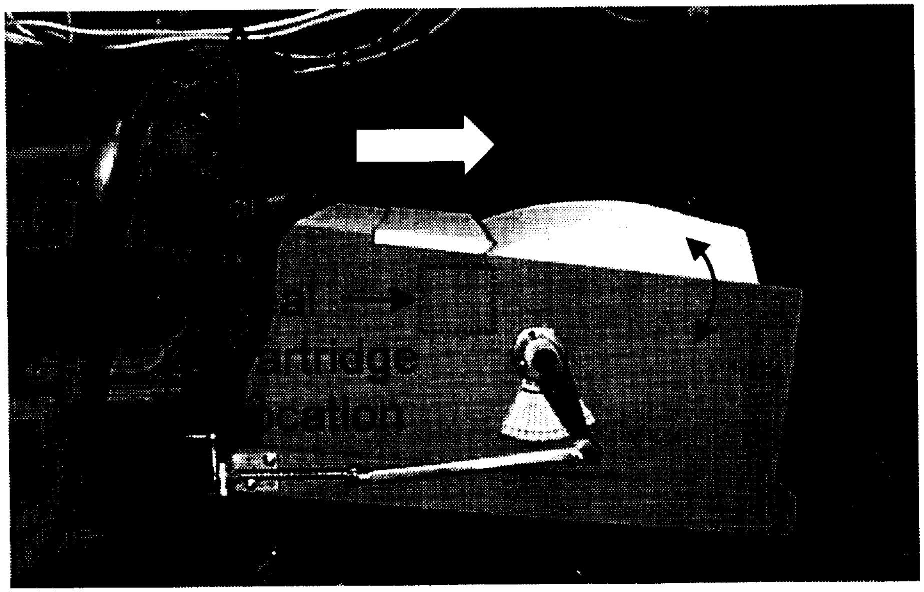


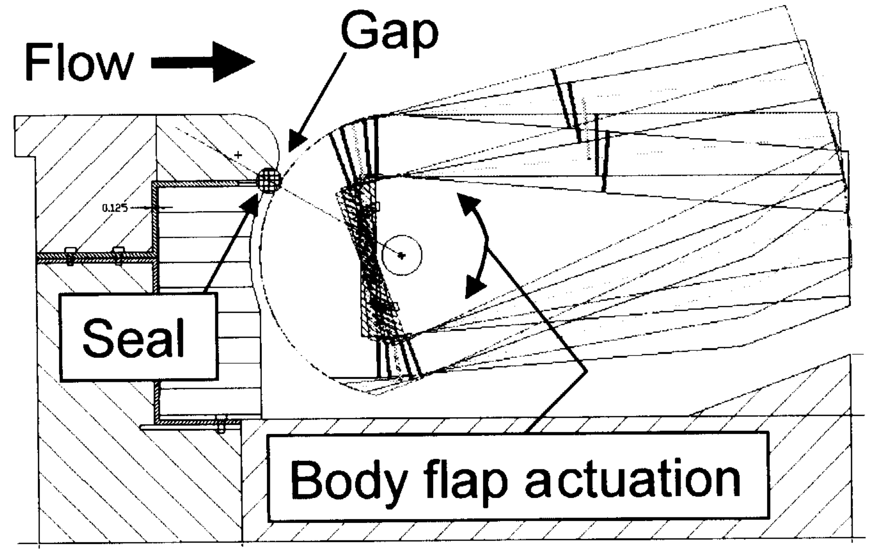


⇐ **GRC flow tests of baseline control surface seal before & after temperature exposure showed 25% increase in flow after exposure**

Advanced High Temperature Structural Seals

- **Major accomplishments (continued)**





- **Fabricated one-of-a-kind arc jet model to test simulated body flap seals under representative temperature and heating conditions in Ames panel test facility**
- **Baseline and advanced seals will be tested using replaceable seal cartridge**
- **Upstream and downstream temperature and pressure measurements will be used to validate aerothermal model**
- **Body flap actuation during test will be used to assess:**
  - **Effects of seal scrubbing**
  - **Increased aerthermal loads due to body flap deflection**

Advanced High Temperature Structural Seals

- Current status
  - Element seal designs (Gen 1) identified and will be tested at Ames arc jet test facility (1QFY01)
  - Arc jet test fixture being assembled and instrumented at Ames
- Near term plans & milestones
  - Complete fabrication of arc jet test fixture
  - Complete arc jet tests on baseline and advanced seal designs (Gen 1/Gen 2) at Ames
  - Validate aerothermal model based on results of arc jet testing
  - Assess gap width effects on seal heating rates & maximum temperatures
  - Assess effects of seal flow rates on maximum seal temperatures
- Contact info:

  - Dr. Bruce M. Steinetz, (216) 433-3302, Bruce.M.Steinetz@grc.nasa.gov
  - Patrick H. Dunlap, Jr., (216) 433-6374, Patrick.H.Dunlap@grc.nasa.gov

- **UHTC Sharp Leading Edges**
  - **POC's:**
    - ARC: jdbull@mail.arc.nasa.gov
    - Jeff Bull 650-604-5377
    - GRC: slevine@grc.nasa.gov
    - Stan Levine 216-433-3246
    - LaRC: d.e.glass@larc.nasa.gov
    - David Glass 757-864-5423

UHTC Sharp Leading Edges

- **Goal:** Advance TRL of UHTC sharp leading edges
- **Background:** UHTC sharp leading edges have been demonstrated in flight and ground tests to operate at temperatures as high as 5100 °F. The TRL of these materials and systems must be advanced in order for them to be adopted in viable sharp leading edged aerospace vehicles.
- **Major Accomplishments:**
  - ARC: Measured the thermal and mechanical properties of ZrB_2/SiC (ZS), $ZrB_2/C/SiC$ (ZCS), and HfB_2/SiC (HS) at 72, 742, 2192 and 2552 °F. Performed process refinement based on results of post-mortem micro-structural analysis of sharp leading edge components and flexure bars. Integrated NASA GRC CARES into UHTC design tools.

UHTC Sharp Leading Edges

- **Major Accomplishments (cont.):**
  - GRC: Hyper-X, Mach 10 selected for sharp leading edge case example. Identified low cost leading edge transition material (Honeywell C/SiC). Developed preliminary designs for leading edge using C/SiC transition to UHTC. Modified NASA CARES for use with ARC finite element analysis application (MARC).

- **Near Term Plans:**
  - ARC: Characterize UHTC materials. Process thermal mechanical data and update UHTC engineering database (TPSX). Identify ground test facility, geometry, and conditions for joint center evaluation of sharp leading edge systems per PLT (7/01).
  - GRC: Continue development of transition material. Hold PDR on sharp leading edge design (9/01).
  - ARC, GRC, LaRC: Investigate improved sharp leading edge materials, coated CMCs, improved UHTC compositions, etc.

- **Felts**
  - **POC's:**
    - Christine Johnson
    - NASA Ames Research Center
    - cjohnson@mail.arc.nasa.gov
    - (650) 604-6395

    - Marc Rezin
    - NASA Ames Research Center
    - mrezin@mail.arc.nasa.gov
    - (650) 604-6163

High Temperature Felt TPS

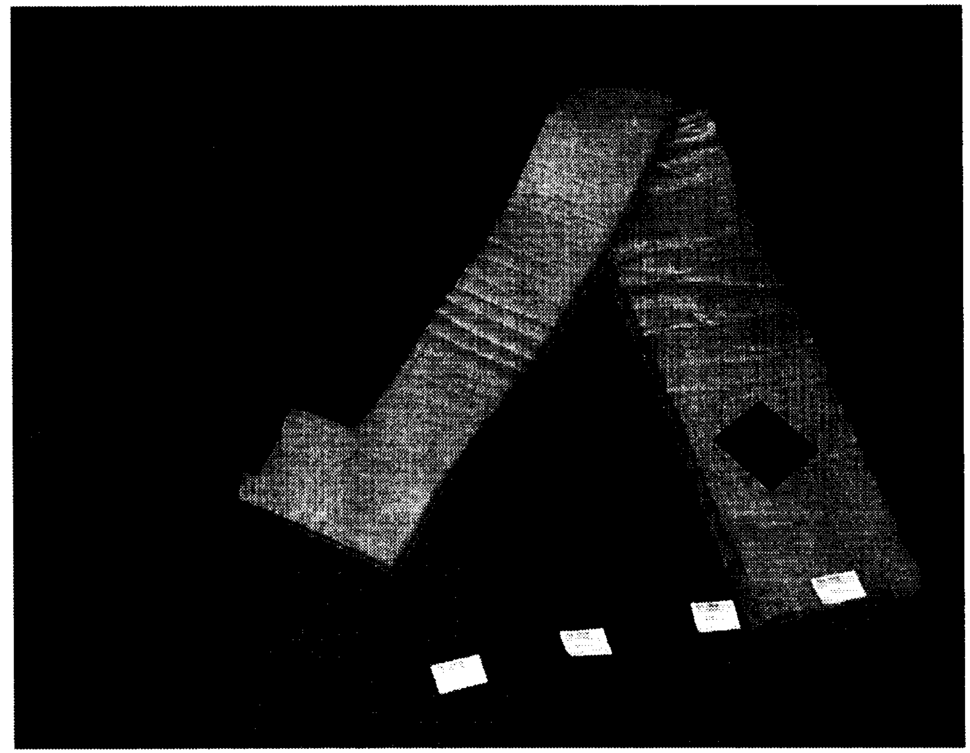
- **Technology Goals and Objectives**

  Development of a family of low cost, high temperature felts with multiple use temperature limits of up to 1500°F. By blending fibers of several types (carbon, refractory oxide, organic, and pre-ceramic), specific combinations of durability, temperature capability and cost can be produced.

- **Background**

  Current felt TPS (FRSI) has a multiple use temperature limit of 750°F, limiting its areas of use. Current TPS blankets (AFRSI) for multiple use up to 1500°F are more costly, less durable, and requires more labor for inspection and repair than the felt TPS under development in this task.

  High Temperature Felts contribute to lower initial and recurring costs for Reusable Launch Vehicles while enhancing their rapid turn-around capability.



High Temperature Felt TPS

- **Current Status, Major Accomplishments**

  Four different organo-ceramic hybrid felt types and three carbon-based felts have been fabricated.
  Coupon-level thermo-chemical stability assessment and mechanical property testing has produced promising results.

- **Near Term Plans**

  Component-level thermo-chemical stability assessment in the Ames AHF arc jet facility, and durability screening in a vibro-acoustic environment, are currently scheduled for the week of 11/13/00.

FY01 and Beyond Program Plan

POC: Dave Bowles
3rd Gen Airframe Program Manager
(757) 864-3095
d.e.bowles@larc.nasa.gov

3rd Gen Airframe/TPS:

3rd Generation Airframe Technologies

- **Project Scope:**
  - Develop and demonstrate 3rd generation airframe technologies that provide significant reductions in cost of space transportation systems while dramatically improving the safety and higher operability of those systems.

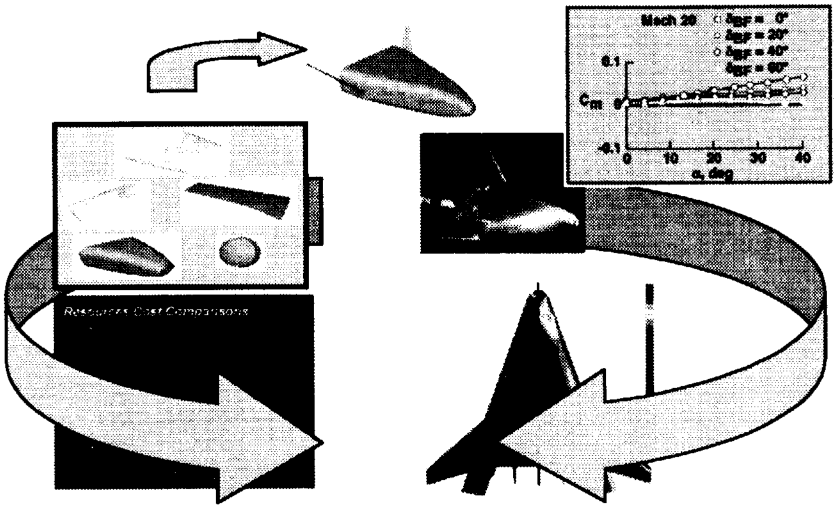
- **Supports Goal 9**
  - Earth-to-Orbit (Goal 9): Conduct research and technology development and demonstrations which will enable U.S. industry to increase safety by four orders of magnitude (loss of vehicle/crew probability less than 1 in 1,000,000 missions) and reduce costs by two orders of magnitude ($100's per pound) within 25 years.

3rd Gen Airframe/TPS:

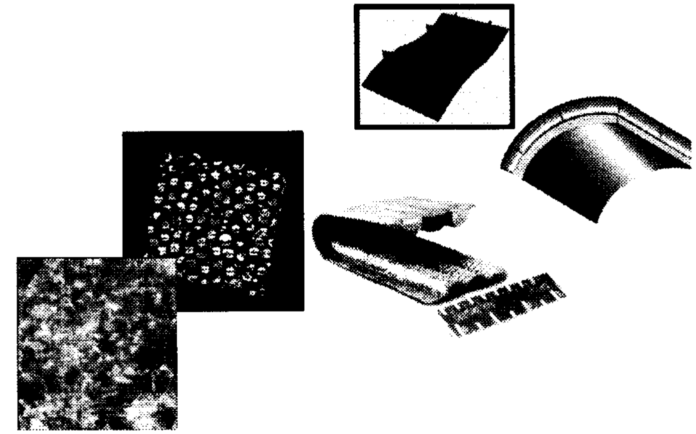
Project Description

3rd Gen Airframe/TPS:

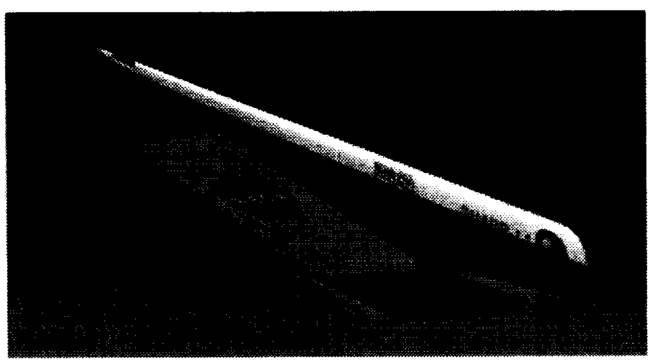
Airframe Technology Elements



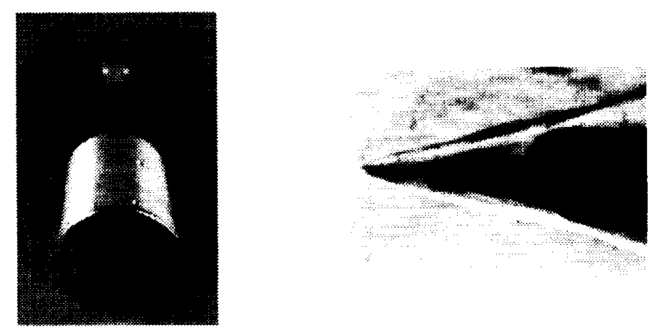
Integrated Airframe Design
(LaRC Lead)



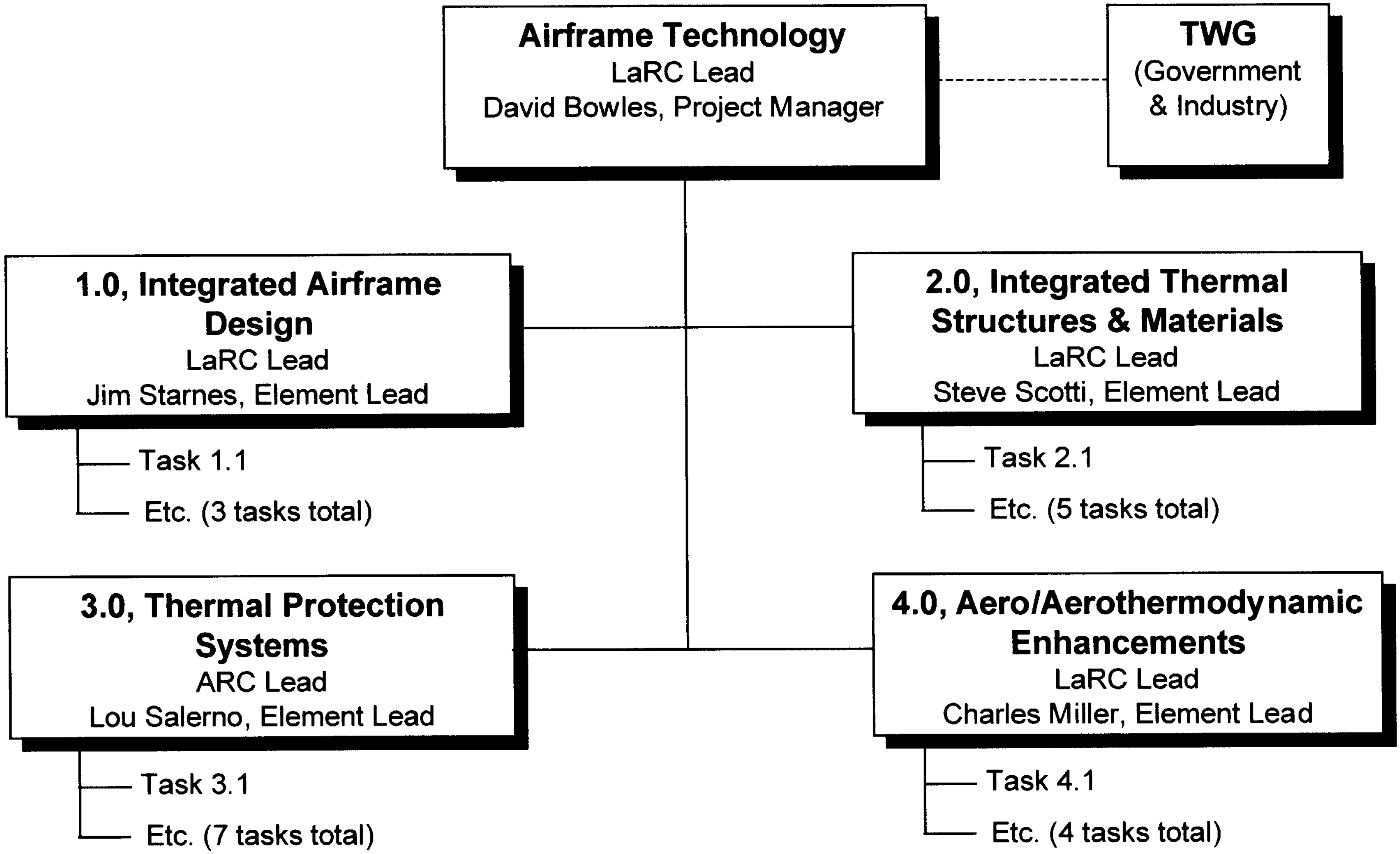
Int. Thermal Structures & Materials
(LaRC Lead)



Thermal Protection Systems
(ARC Lead)



Aero/Aerothermo Enhancement
(LaRC Lead, No FY00 Funding)



3rd Gen Airframe/TPS:

Airframe Organization and WBS

- Integrated Design & Analysis
  - Dr. James H. Starnes
  - (757) 864-3168
  - j.h.starnes@larc.nasa.gov
- Integrated Thermal Structures & Materials
  - Dr. Stephen J. Scotti
  - (757) 864-5431
  - s.j.scotti@larc.nasa.gov
- Thermal Protection Systems
  - Dr. Louis J. Salerno
  - (650) 604-318
  - lsalerno@mail.arc.nasa.gov
- Aero/Aerothermodynamic Enhancements
  - Dr. Charles G. Miller
  - (757) 864-5221
  - c.g.miller@larc.nasa.gov

3rd Gen Airframe/TPS:

Element Lead Contact Information

1. Dave Bowles (Acting Chair), Project Manager, LaRC
2. Jim Starnes, Integrated Airframe Design Element Lead, LaRC
3. Steve Scotti, Integrated Thermal Structures and Materials Element Lead, LaRC
4. Lou Salerno, Thermal Protection Systems Element Lead, ARC
5. Charles Miller, Aero/Aerothermal Enhancement Element Lead, LaRC
6. Frances Hurwitz, GRC
7. Pete Rodriguez, MSFC
8. Jason Hatakeyama, Boeing
9. Derek Townsend, Lockheed Michoud
10. Ravi Deo, Northrup-Grumman
11. Mike Stropki, DoD (alternate Dan Cleyrat)
12. Tom Dragone- OSC
13. Roger Kimmel, DoD

Ex-Officio:

1. Marshall Merriam ARC
2. Partha Dasgupta, GRC
3. Gaspare Maggio, SAIC

TWG Scope

- **Government and Industry participants**
- **Primary responsibilities**
  - Review technical progress and results (annual?)
  - Recommend technical priorities
  - Foster coordination with industry and other government agencies

3rd Gen Airframe/TPS:

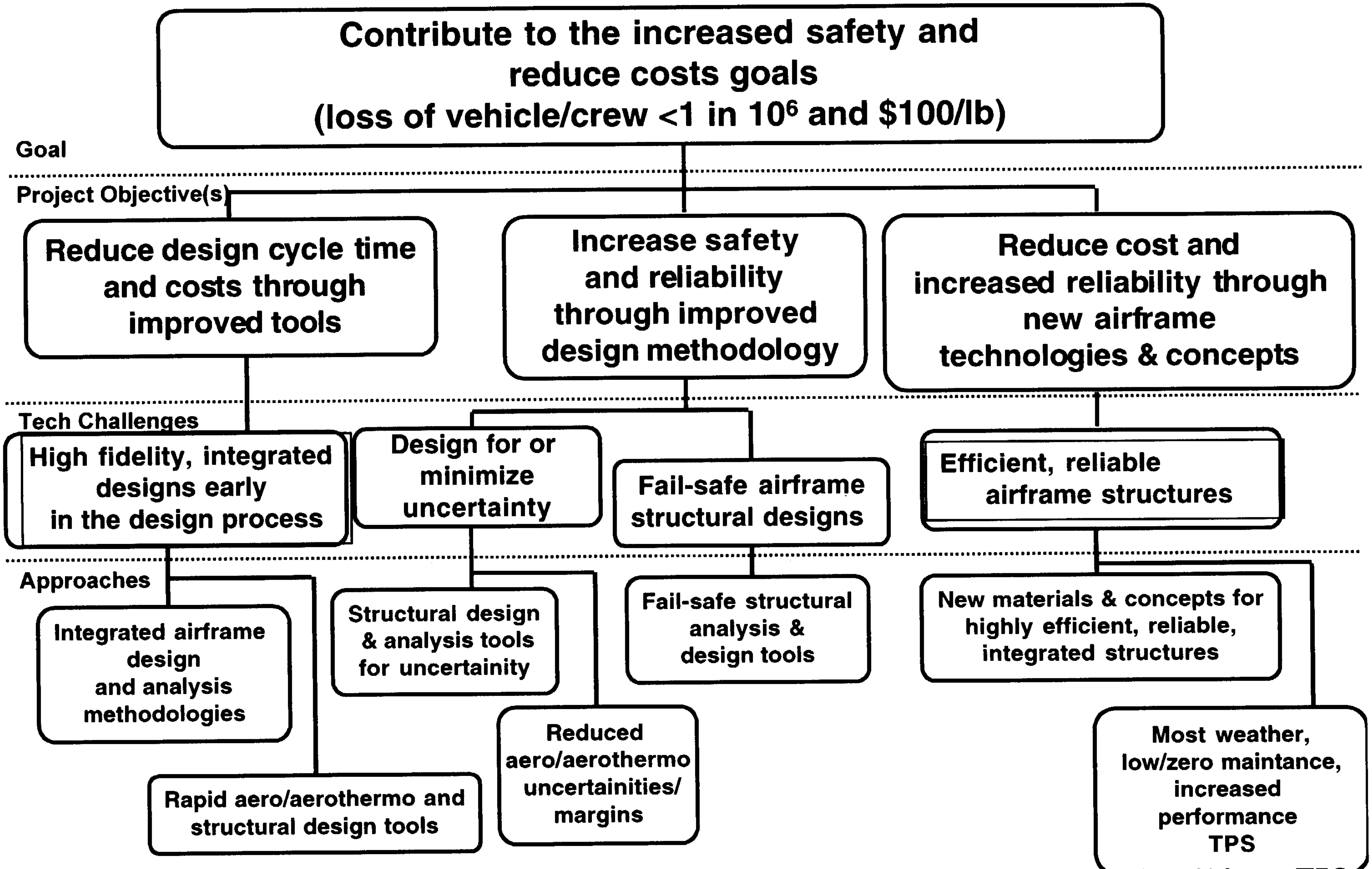
Technical Working Group (TWG)

3rd Gen Airframe/TPS:

Top Level Budget Summary

3rd Gen Airframe/TPS:

Task Structure and Leads



3rd Gen Airframe/TPS:

Goals, Objectives, Challenges, Approaches

- ♦ **Goal:**
  - Reduced Cost ($100/lb)
  - Increased Safety (LOC/LOV 1 in 10^6)
- ♦ **Challenge:**
  - How to meet both simultaneously?
- ♦ **Strategy:**
  - Requires paradigm change

Conventional Paradigm: *New Paradigm:*

Cost ↓ *Safety* ↓   *Cost* ↓ *Safety* ↑

- Paradigm change achieved by

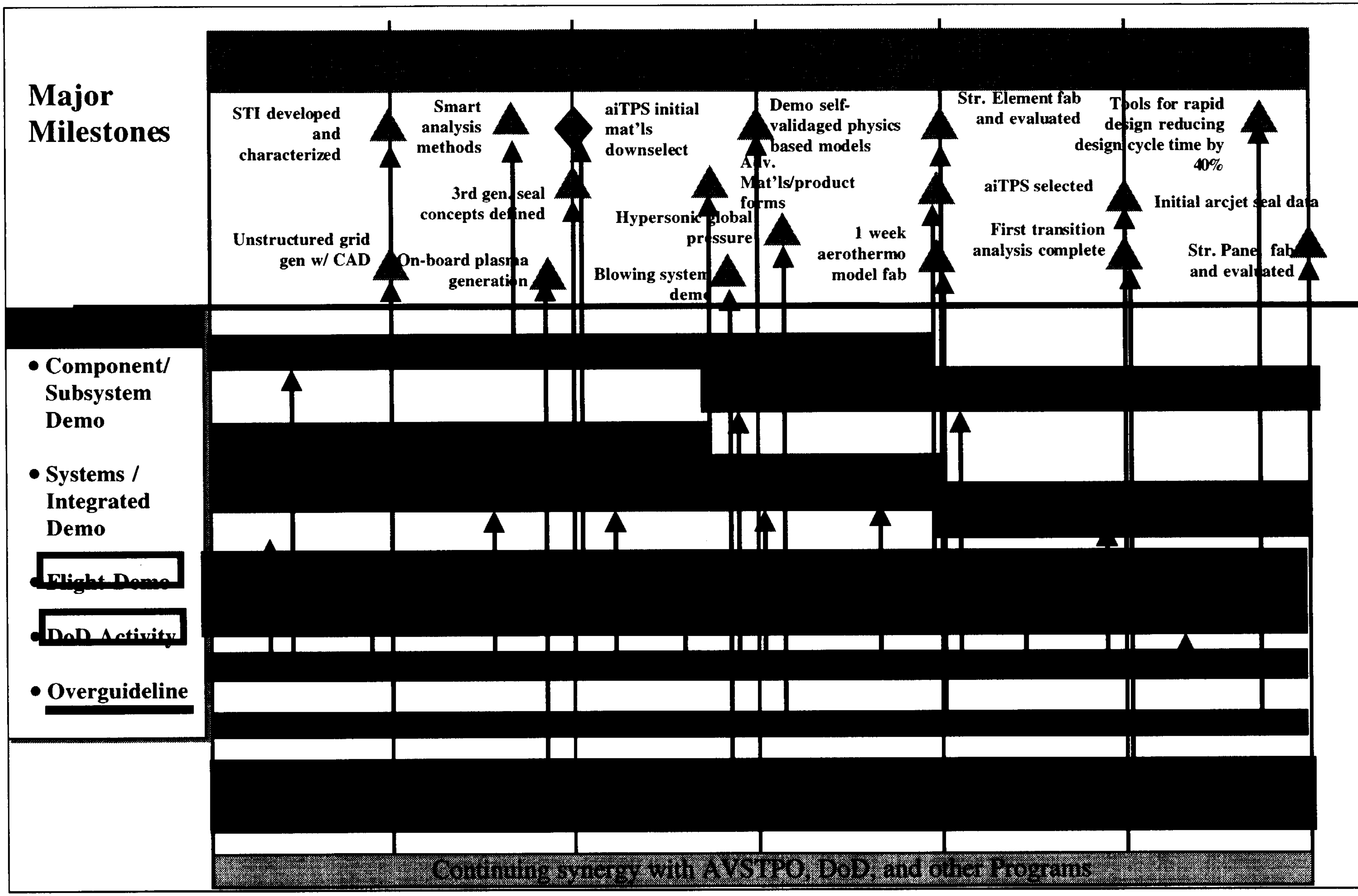
Inherent Reliability through Robust Designs

Advanced Airframe Technologies Allow Robust Designs at Reduced Weights

- ♦ *High fidelity, reliability based analysis and design methodologies*
- ♦ *Advanced materials and structural concepts*

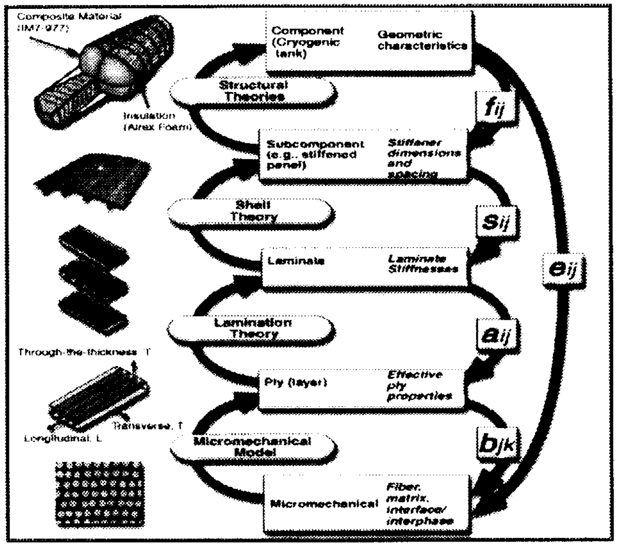
3rd Gen Airframe/TPS:

Strategy for Meeting the Goals



3rd Gen Airframe/TPS:

Project Roadmap



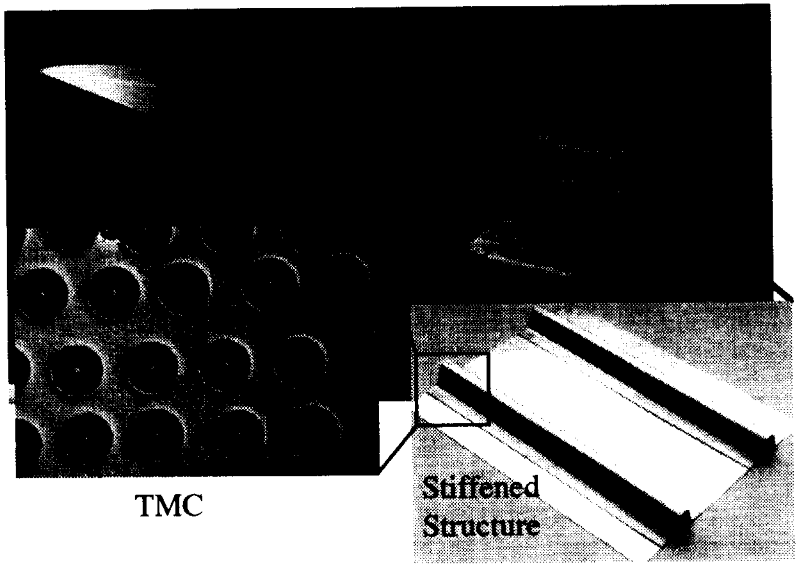
- ◆ Goals
  - Contribute to 100x cost reduction and 10, 000x safety improvement goals
- ◆ Objectives
  - Develop integrated airframe design and analysis technologies to reduce design cycle time by 40% and design cost
  - Develop verified fail-safe structures design and analysis technologies that increase the reliability by an order of magnitude and increase performance

- Integrated advanced design and analysis methods that reduce design cycle time
- Airframe structural design and analysis methods that relate risk, cost and performance
- Verified fail-safe structural design and analysis methods that increase reliability

- ◆ Major FY01 / 02 Products
  - Parametric studies to identify key parameters (9/01)
  - Develop "smart" analysis methods that can automatically account for uncertainties (9/02)
- ◆ Major FY03 - 06 Products
  - Develop high-fidelity physics-based analysis methods for predicting coupled thermal-structural response (9/03)
  - Structural design and sizing for residual strength (9/04)
  - Rapid, hierarchical analysis (9/06)

3rd Gen Airframe/TPS:

Integrated Airframe Design



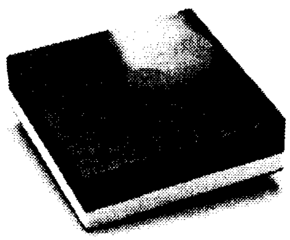
- Goals
  - Contribute to 100x cost reduction and 10, 000x safety improvement goals
- Objectives
  - Efficient and reliable hot wing structures with low maintenance and fabrication costs
  - Efficient and reliable conformal cryotank structures with low maintenance and fabrication costs

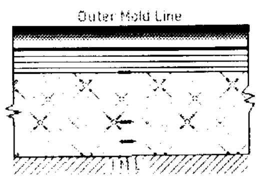
- Ultra-high properties over extended temperature ranges for both hot wing and conformal cryotank structures
- Large-scale fab of structures into high-efficiency/reliable/functional component hardware for both hot wing and conformal cryotank structures
- Thermal & thermal-structural concepts including control/accommodation of temperatures and thermal stresses

- Major FY01 / 02 Products
  - Select constituents and processes (9/01)
  - Advanced adhesives for non-autoclave processing (9/02)
  - MMC and Al-Mg-Be materials characterization (9/02)
- Major FY03 - 06 Products
  - Integrated airframe concepts defined and assessed (12/02)
  - TMC fiber/matrix interaction studies (9/03)
  - Advanced cryogenic insulation (9/03)
  - MMC and Al-Mg-Be cryogen compatibility (9/03)
  - Structural elements made of adv materials fab and evaluated (9/04)
  - Structural panels made of adv mat'ls (9/06)

3rd Gen Airframe/TPS:

Integrated Thermal Structures and Materials





STI Exploits Embedded Phases of Nanostructural or Energy Transport Control Materials into Tiles, Blankets, and other TPS to isolate and control cryopumping, radiation, convection, and conduction

- Goals
  - Increased TPS safety, reliability, operability, and decreased cost
- Objectives
  - Necessary ground development and characterization
  - Development and demonstration of highly reusable TPS with extended life cycle capabilities, including most weather flight capability and fail-safe performance
  - Assessment, simulation, and prediction of TPS degradation and failure

- Higher temperature lower density systems
- Improved operating margins
- Fault tolerant systems
- Most weather capability
- Low/zero maintenance

- Major FY01 / 02 Products
  - Superthermal Insulation materials development and characterization (9/01)
  - Initial aiTPS materials downselection (9/02)
  - 3rd gen seal concepts defined (9/02)
- Major FY03 - 06 Products
  - Completed initial arcjet testing of seal concepts (9/05)
  - MITAS graded layer systems for mechanical/thermal test (9/06)

3rd Gen Airframe/TPS:

Thermal Protection Systems

- Goals
  - Contribute to 100x cost reduction and 10, 000x safety improvement goals
- Objectives
  - Reduce time for aero/aerothermo design of aerospace vehicles (factor of 20 by 2010)
  - Reduce aero/aerothermo uncertainties/margins and enhanced performance by 10x

- **Decrease ground-based facility testing time by a factor of 20**
- **Develop aerothermo multidisciplinary techniques**
- **Decrease CFD prediction times by a factor of 30**
- **Determination and control of boundary layer transition**
- **Flow control or modification of flow environment**

- **Major FY01 / 02 Products**
  - **Unstructured grid generation with CAD (10/01)**
  - **Low shrinkage metal model casting (12/01)**
- **Major FY03 - 06 Products**
  - **High resolution image acquisition (12/02)**
  - **Automated 3-D image mapping software (12/03)**
  - **1 week aerothermo model fab (9/04)**
  - **First transition analysis complete(12/05)**
  - **Tools for rapid design reducing design cycle time by 40% (6/06)**

3rd Gen Airframe/TPS:

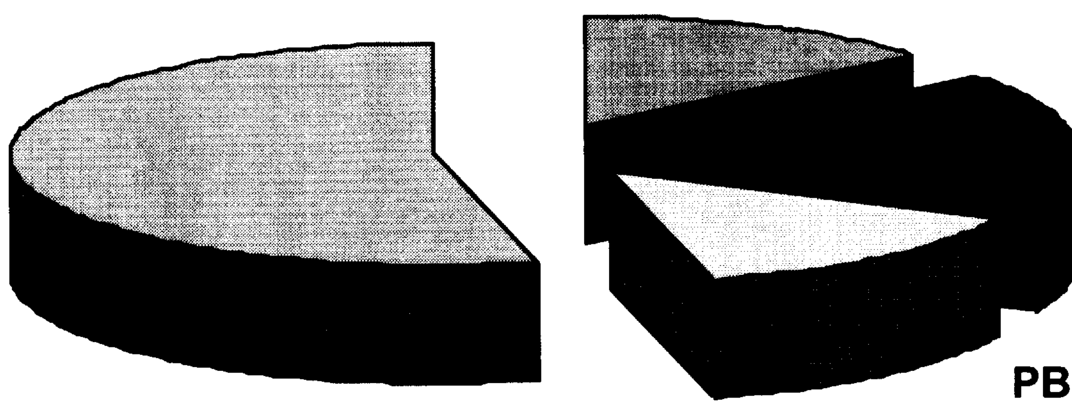
Enhanced Aero/Aerothermo

3rd Gen Airframe/TPS:

Acquisition Strategy

- Varies across elements and tasks
  - University grants (existing and new)
  - Existing task assignment contracts
  - Specific RFPs ?
  - In-House (facilities, materials, equipment, PBC's, etc.)

FY01 Funding Distribution (Net $7.76M)



3rd Gen Airframe/TPS:

Risk Management

- **Overall Project Level Risks**

  Objective: Develop and demonstrate 3rd generation airframe technologies that provide significant reductions in cost of space transportation systems while dramatically improving the safety and higher operability of those systems

  - Risk:
    - Uncertainty in funding and budget reduction constraints
  - Risk Mitigation Strategy:
    - Use Descope plan within budget constraints
  - Risk:
    - Lack of good systems analysis to identify technology cost/benefit trades
  - Risk Mitigation Strategy:
    - Develop systems analysis to conduct cost/benefit trades
    - Utilize TWG to help set technology priorities
  - Risk:
    - High risk technologies, all of which might not proceed as planned
  - Risk Mitigation Strategy:
    - Use multiple technical approaches where feasible

- Solid Technical Plan in Place
- Strong Intercenter Team (ARC, GRC, LaRC, MSFC)
- Looking Forward to Industry/Academia Input and Participation

3rd Gen Airframe/TPS:

FY01 Summary Comments

- **Focus on those activities that will be continued/built upon in FY01**
- **Topics include**
  - **Integrated Design and Analysis**
    - Damage Tolerance & Repair
    - Safe Structures Design Technology
  - **Integrated Thermal Structures & Materials**
    - Resins for transfer molding or infusion processing
    - Nonautoclave processable adhesives
    - Automated Tape Placement Device with e-beam cure
  - **Thermal Protection Systems**
    - Quick Processed, Low Cost Erosion Resistant TPS
    - SmarTPS
    - Advanced High Temperature Structural Seals
    - UHTC Sharp Leading Edges
    - High Temperature Felt TPS

3rd Gen Airframe/TPS:

FY00 Research Highlights

Integrated Design and Analysis Overview

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- **PMC Damage Tolerance & Repair**
  - **POC's:**
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    - d.r.ambur@larc.nasa.gov

    - Dr. Tom S. Gates
    - (757) 864-3400
    - t.s.gates@larc.nasa.gov
- **Safe Structures Design Technologies**
  - **POC:**
    - Dr. Damodar R. Ambur, NASA LaRC
    - (757) 864-3449
    - d.r.ambur@larc.nasa.gov

3rd Gen Airframe/TPS:

Integrated Design and Analysis

PMC Damage Tolerance and Repair
Goals & Objectives

- Develop methodology for assessing the effects of manufacturing defects
- Develop damage tolerance criteria and damage tolerance database for RLV cryogenic tank structures
  - impact
  - pressure leakage
  - cryogenic permeation
  - validated damage prediction tools
- Develop repair technology

PMC Damage Tolerance and Repair
Current Program Status

- Initiated in FY1999 as Bantam Damage Tolerance Program
- Continued as PMC Damage Tolerance Program during FY2000 with reduced funding level
- Needs continuation to address technology issues that will limit composites application to cryogenic tank structures

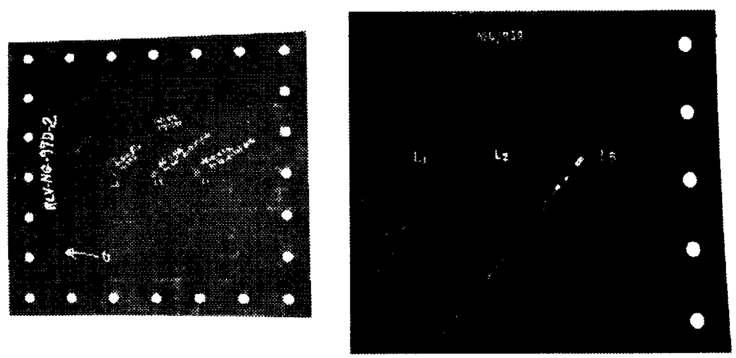
PMC Damage Tolerance and Repair
Current Technical Status

- FY1999:
  - Established damage tolerance requirements (impact, pressure leakage, cryogenic permeation)
  - Fabricated and impact tested flat and curved thin-skin panels made of different material forms
  - Conducted impact damage tolerance tests for damage resistance and barely visible damage (BVID); developed a 0.05 in. dent depth BVID criterion
  - Developed analytical methods to predict the impact response and damage resistance for curved, thin laminated composites
- FY2000:
  - Assessed existing repair methods for stiffened-skin and sandwich constructions
  - Developed analysis methods for optimally sizing bolted and bonded anisotropic patch repairs
  - Completed compression-after-impact strength tests on three material forms
  - Developed analytical models and methods to assess the critical size of delaminations for combined loading conditions
  - Assessed mixed-mode fracture toughness for IM7/977-2 and AS4/PEEK material systems at cryogenic temperatures
  - Conducting pressure leakage threshold tests

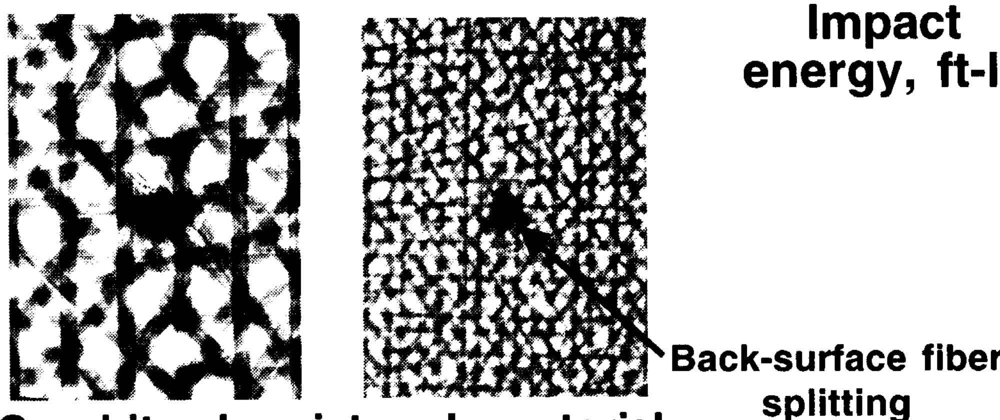
PMC Damage Tolerance and Repair

ENERGY THRESHOLDS FOR BARELY VISIBLE IMPACT DAMAGE OF CURVED THIN LAMINATES MADE OF DIFFERENT MATERIAL FORMS

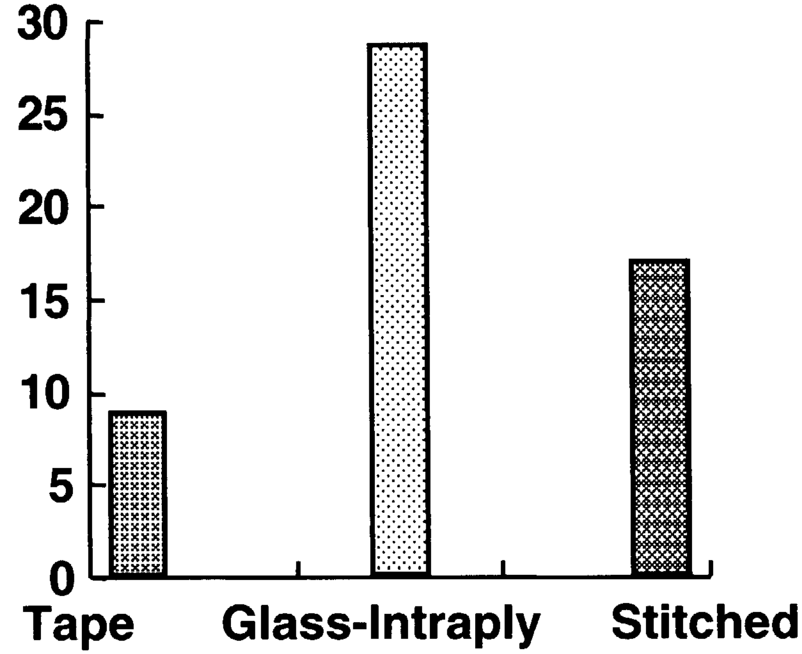
Criterion: 0.05-in. dent depth



Pre-impregnated tape material



Graphite-glass intra-ply material



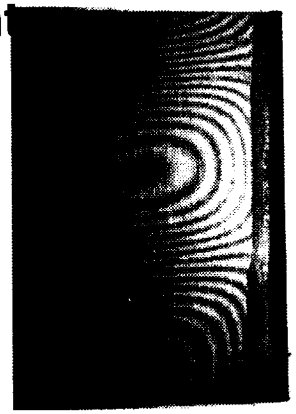
3rd Gen Airframe/TPS:

Integrated Design and Analysis

PMC Damage Tolerance and Repair

TYPICAL COMPRESSION RESPONSE AND FAILURE OF 16-PLY-THICK CURVED PLATES LOADED IN COMPRESSION

Displacement con



Undamage d

Failed specimen

Impact damaged

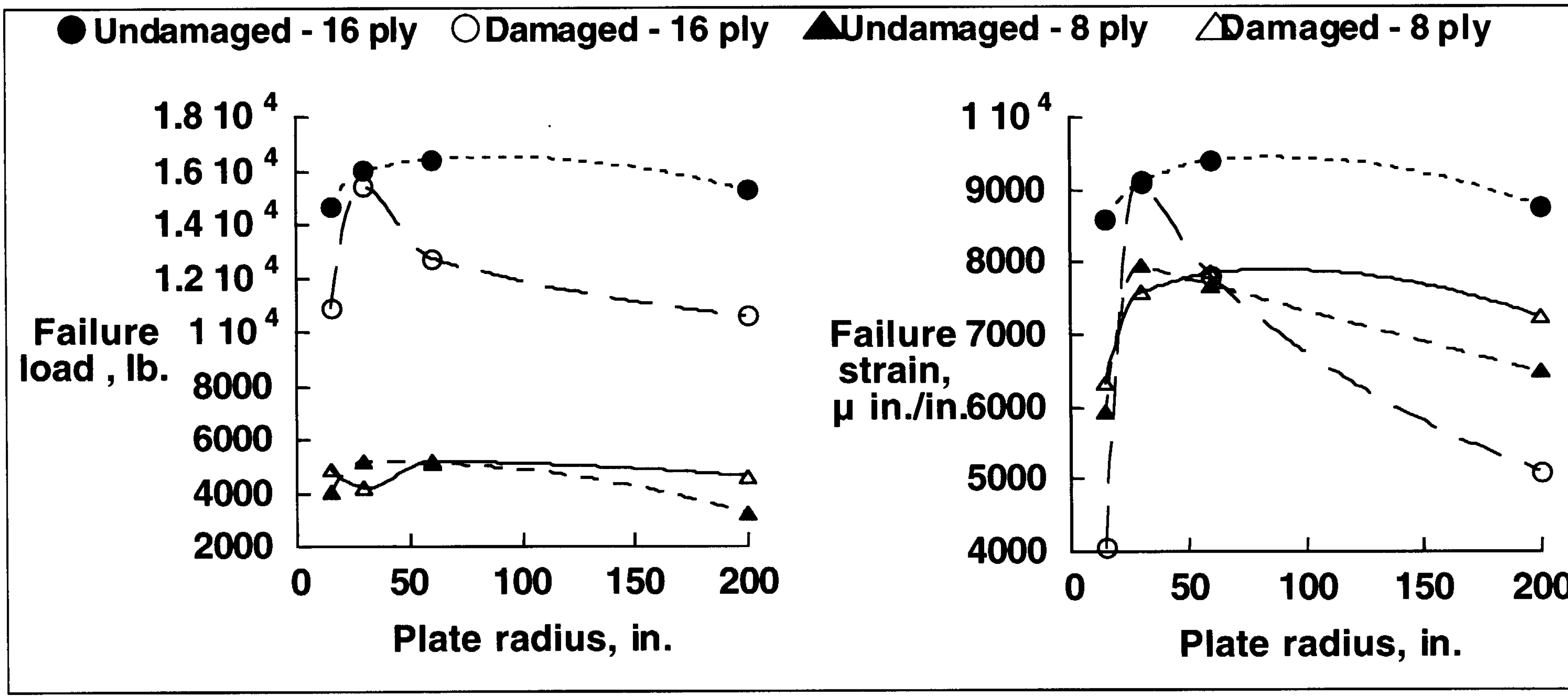
Impact damage location

Failure location

PMC Damage Tolerance and Repair

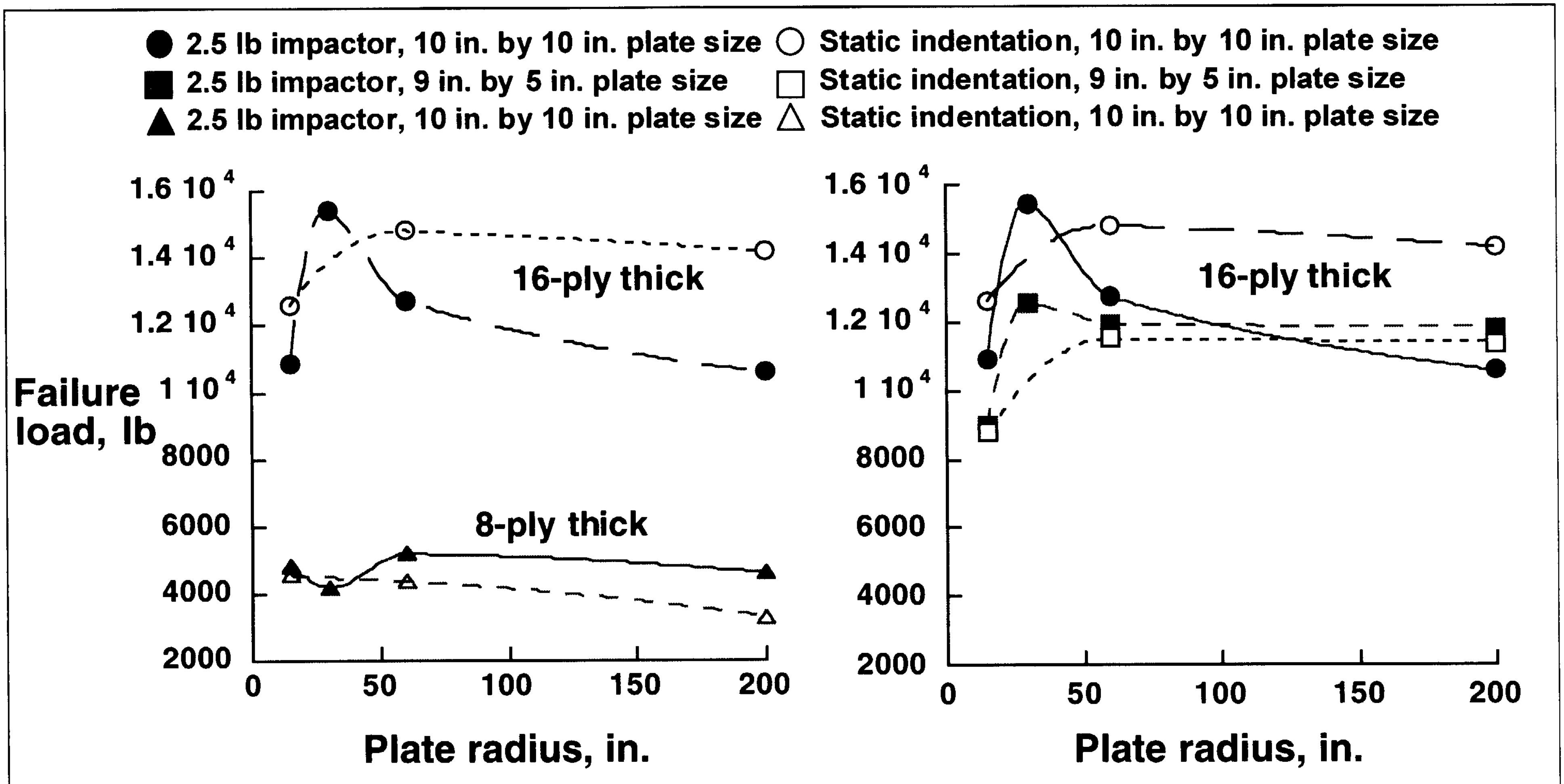
COMPARISON OF COMPRESSION-AFTER-IMPACT STRENGTH RESULTS FOR CURVED THIN PLATES

AS4-3502 Prepreg Tape Material



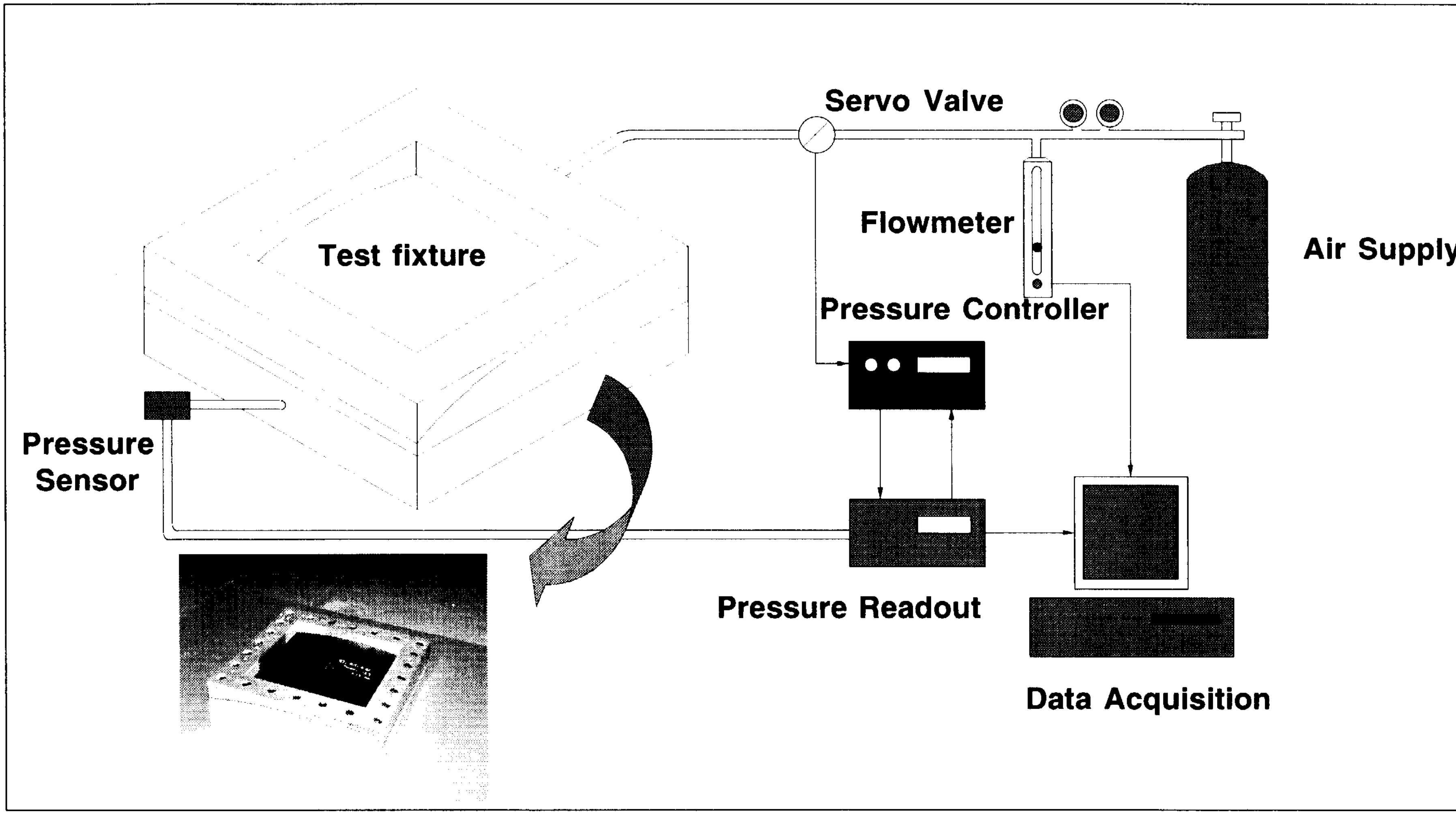
PMC Damage Tolerance and Repair

COMPARISON OF RESIDUAL STRENGTH RESULTS FOR PLATES SUBJECTED TO DROPPED-WEIGHT IMPACT AND STATIC INDENTATION DAMAGE



PMC Damage Tolerance and Repair

SCHEMATIC DIAGRAM OF TEST SET-UP FOR PRESSURE LEAKAGE TESTS



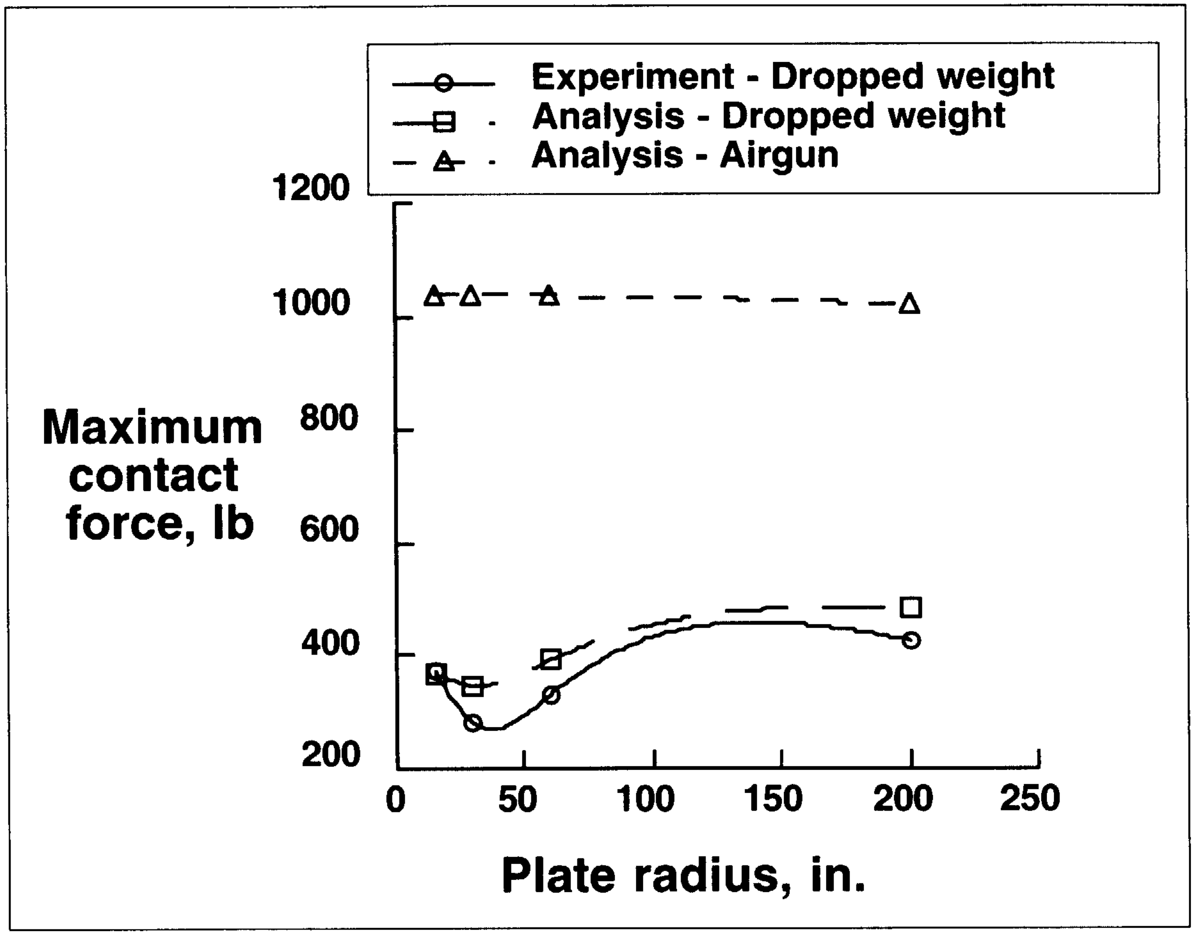
PMC Damage Tolerance and Repair

SUMMARY OF ANALYTICAL EFFORTS

- Impact response of thin curved laminates
- Finite element analysis to assess critical manufacturing defect size for combined mechanical and thermal loaded structures
- Methods for optimizing bonded and bolted repairs

PMC Damage Tolerance and Repair

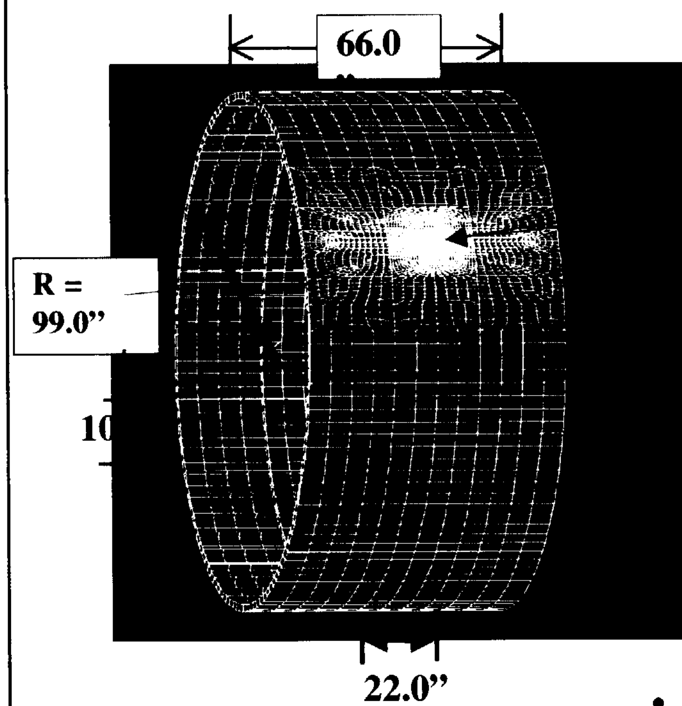
DEVELOPED NONLINEAR ANALYSIS METHOD FOR ACCURATELY DETERMINING IMPACT RESPONSE AND DAMAGE INITIATION



PMC Damage Tolerance and Repair

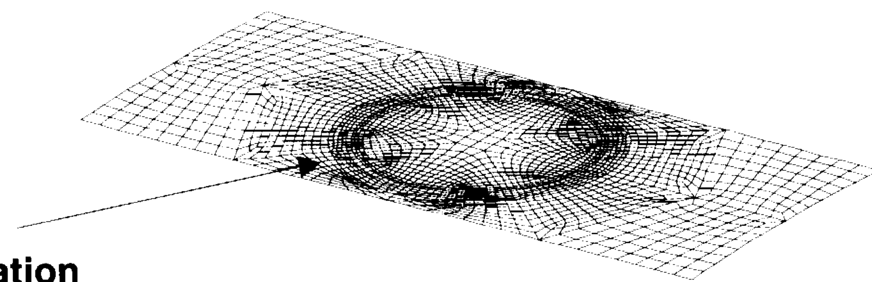
DELAMINATION GROWTH STUDIES
Modeling and Analysis Approach

Global model



- **Number of elements: 10,664**
- **Dof: 64,314**

Local model



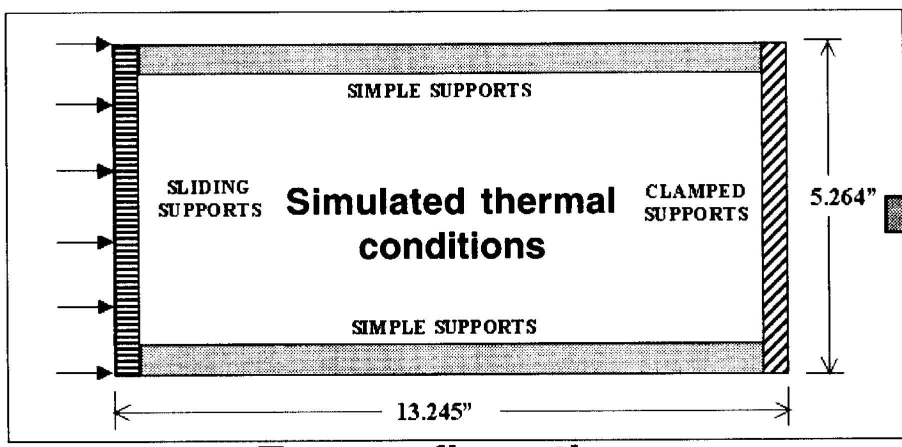
- **Number of elements: 7,784**
- **Dof: 46,548**

Virtual crack closure technique to determine strain energy release rates.
Parametric studies with combined mechanical, thermal and internal pressure loading conditions.

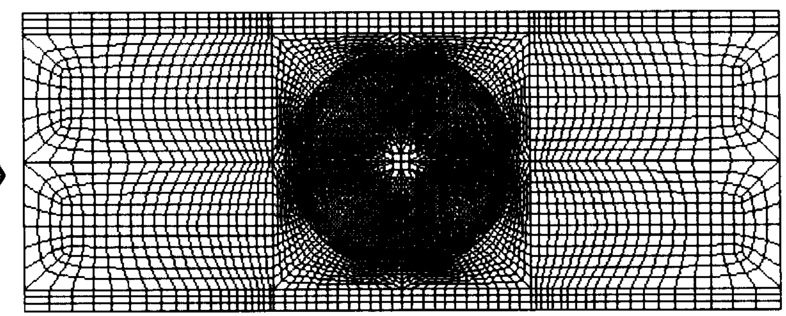
- **Critical delamination size and location.**
- **Stiffened skin and sandwich constructions.**

PMC Damage Tolerance and Repair

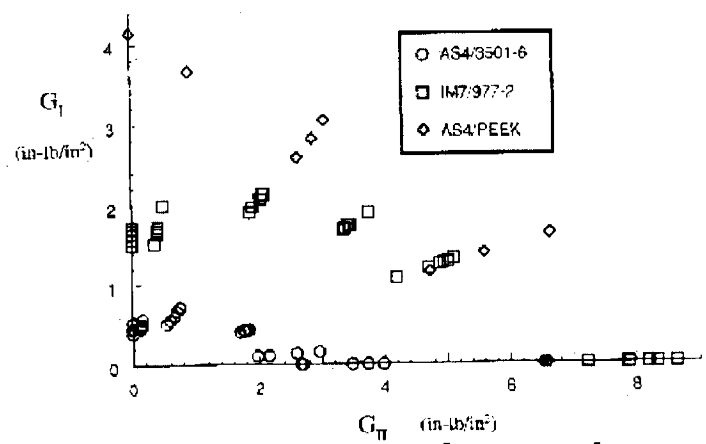
APPROACH FOR DELAMINATION GROWTH VERIFICATION TESTING



Test configuration



Finite element model



Fracture toughness data

Experimental verification of the critical size and location of delaminations

3rd Gen Airframe/TPS:

Integrated Design and Analysis

PMC Damage Tolerance and Repair

NEAR-TERM PLANS

- **Conduct pressure leakage tests on laminates made from different material forms**
- **Complete compression-after-impact strength tests on laminates made from different material forms**
- **Complete delaminated panel compression tests at cryogenic temperatures to verify criticality of the effects of defects**

- PMC Damage Tolerance & Repair
  - POC - Dr. Damodar R. Ambur/Dr. Tom S. Gates, NASA LaRC
- Safe Structures Design Technologies
  - POC - Dr. Damodar R. Ambur, NASA LaRC

3rd Gen Airframe/TPS:

Integrated Design and Analysis

Safe Structures Design Technologies

Goals and Objectives

- Develop validated second generation nonlinear progressive failure analysis method for composite structures subjected to combined mechanical loads
- Develop non-deterministic analysis and design methods that bound manufacturing uncertainties
- Conduct sensitivity analyses for manufacturing uncertainties
- Develop and demonstrate 3rd. generation progressive failure analysis method that includes combined mechanical and thermal load effects and delaminations
- Develop design and analysis relationships between structural weight and reliability for composite structures subjected to combined mechanical and thermal loads
- Develop hybrid deterministic and non-deterministic analysis and design methods that account for uncertainties at the material, structures, and mission levels
- Conduct hierarchical sensitivity analyses and identify design trends for multiple length scales subjected to combined loads

Safe Structures Design Technologies

- Current Program Status
  - Initiated in FY2000
  - Efforts continue under the 3rd Generation RLV Program
- Current Technical Status
  - Developed analytical methods and algorithms for using the current damage progression methods to predict the response of nonlinearly deformed structures
  - Conducted progressive damage verification tests on a compression-loaded composite cylinder
  - Conducting progressive damage verification tests on a composite panel subjected to nonlinear deformation with in-plane shear loading
  - Initiated tools development for predicting delamination initiation and growth

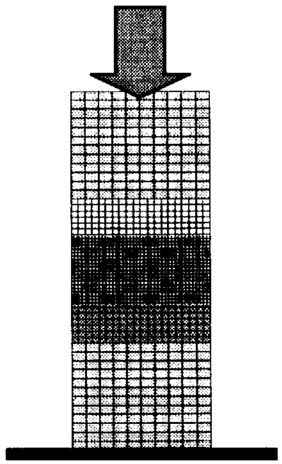
Safe Structures Design Technologies

MECHANICS TECHNOLOGY FOR PROGRESSIVE FAILURE ANALYSIS

- Embed progressive failure criteria and material degradation models with robust nonlinear structural mechanics solver STAGS
- Provide progressive damage capability coupled with large displacement, large rotation deformation states for laminated composite structures
- Provide traditional and state variable damage models
  - Maximum strain with ply discounting
  - Crack density based criteria for failure and degradation
  - User interfaces include ABAQUS/UMAT
- Incorporate artificial damping feature to mitigate non-convergence problems in re-establishing equilibrium
- Establish consistency between first and second variations for the energy functional
- Enhance visual depiction of progressive damage simulation
- *Increased design robustness through evaluation of extreme loading conditions and understanding possible composite structures failure scenarios*

Safe Structures Design Technologies

COMPRESSION-LOADED POSTBUCKLING COMPOSITE PANEL

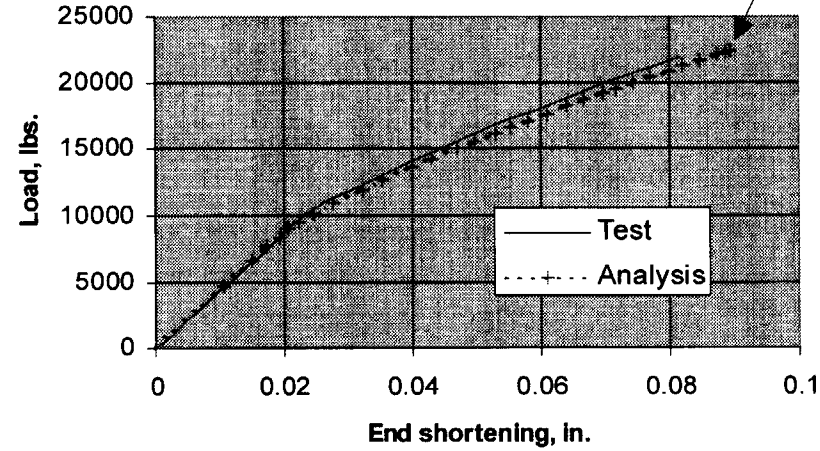


24-ply Graphite-epoxy orthotropic laminate

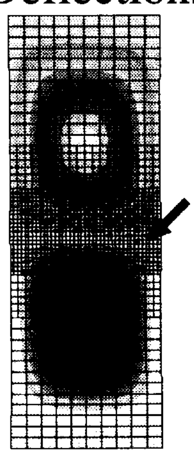
Starnes & Rouse, AIAA Paper 81-0543

Failure load =21,910 lbs
End shortening at failure = 0.0818 in.

Massive failures occur after this last solution

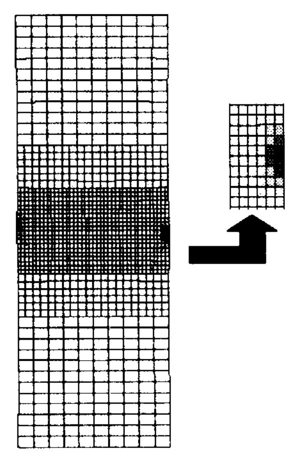


Out-of-plane Deflections



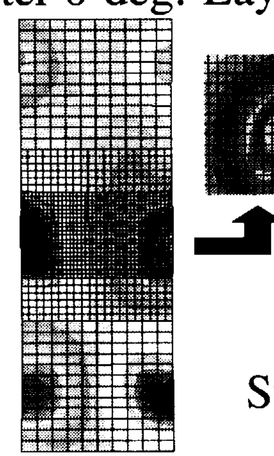
Node Line in Buckle Pattern

Percent Failed Plies



Close-up of Failed Region

Inplane Shear Stress in Outer 0-deg. Layer



Close-up Showing Stress Relief

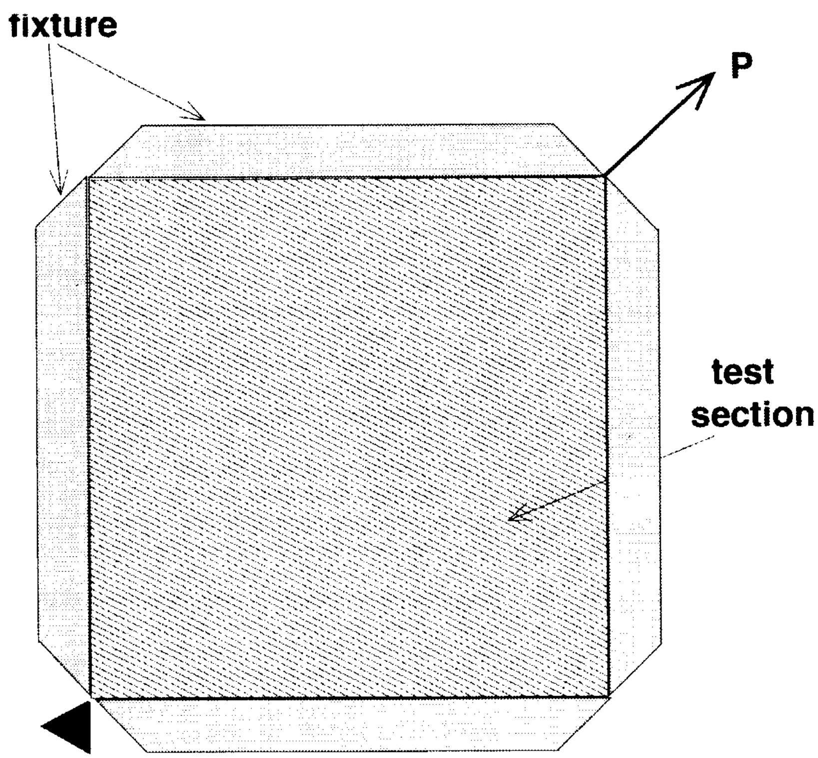
3rd Gen Airframe/TPS:

Integrated Design and Analysis

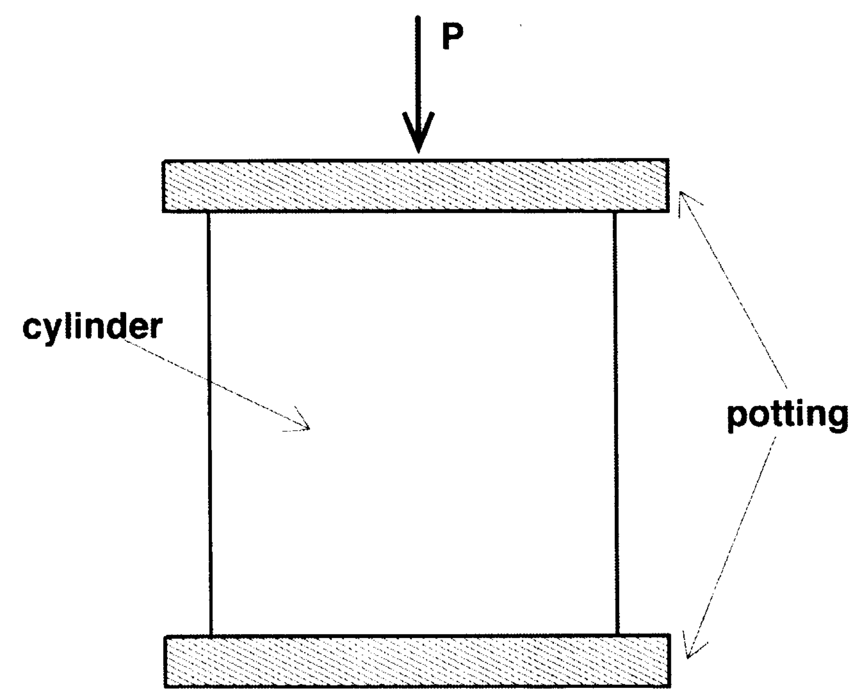
Safe Structures Design Technologies

CORRELATION OF PROGRESSIVE FAILURE ANALYSIS RESULTS
FOR PANELS AND SHELLS

Stiffened and Unstiffened Panels
Loaded in a Picture Frame



Cylinders in Axial Compression



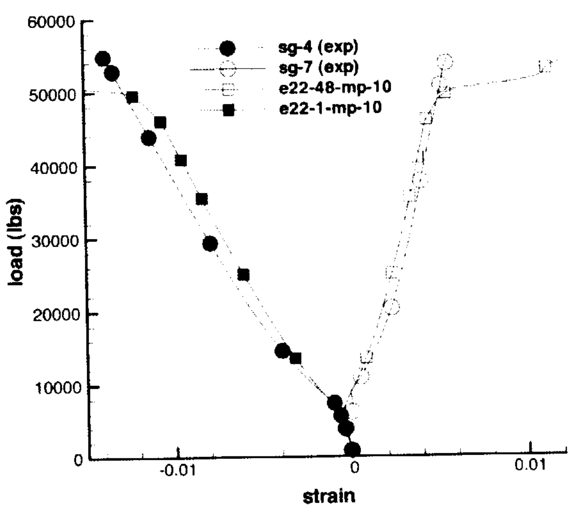
Safe Structures Design Technologies

UNSTIFFENED PANEL LOADED IN PICTURE FRAME SHEAR

- Panel size: 12-in. by 12-in.; Thickness: 0.0896-in.
- Stacking sequence is $[\pm 45/0/90]_{2s}$
- $E_{11} = 18.5$ Msi, $E_{22} = 1.67$ Msi, $G_{12} = 0.87$ Msi, $G_{13} = 0.87$ Msi, $G_{23} = 0.258$ Msi, $\mu_{12} = 0.3$
- $X_T = 0.233$ Msi, $X_C = 0.21$ Msi, $Y_T = 0.0147$ Msi, $Y_C = 0.0287$ Msi, $SC = 0.02975$ Msi

Failure Load:
54,807 lbs - Test
54,447 lbs - Analysis

Strain Normal to Fiber Direction on Top and Bottom Surfaces at Center of Test-Section



Map of Matrix Failure Region

3rd Gen Airframe/TPS:

Integrated Design and Analysis

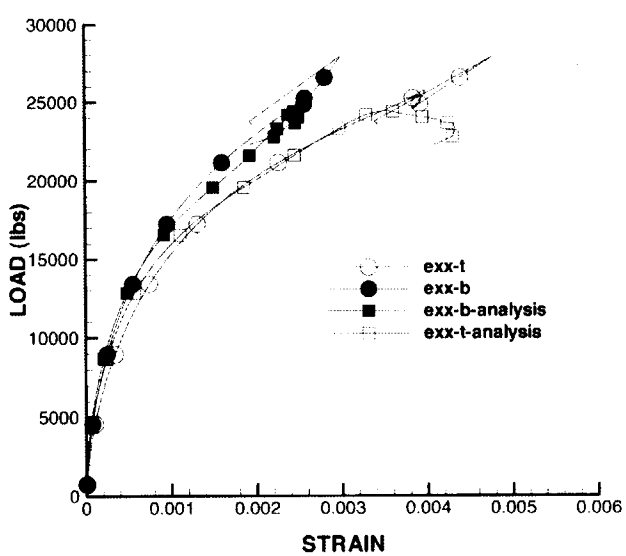
Safe Structures Design Technologies

BEAD-STIFFENED PANEL LOADED IN PICTURE FRAME SHEAR

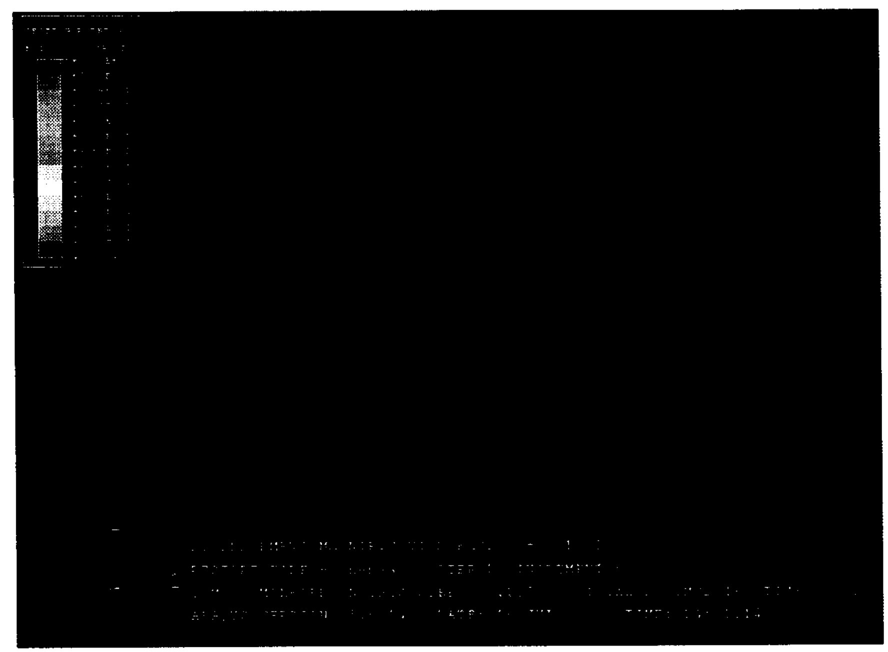
- Panel size: 12-in. by 12-in.; Thickness: 0.08-in.
- Stacking sequence is $[\pm 45/\pm 45/0/\pm 45/90]_s$
- E_{11} = 18.0 Msi, E_{22} = 1.50 Msi, G_{12} = 0.82 Msi, G_{13} = 0.82 Msi, G_{23} = 0.82 Msi, μ_{12} = 0.3
- X_T = 0.30 Msi, X_C = 0.20 Msi, Y_T = 0.013 Msi, Y_C = 0.031 Msi, SC = 0.027 Msi

Failure Load:
27,936.9 lbs -Test
26,995.9 lbs -Analysis

Axial Strain on the Top and Bottom Surfaces at Center of Panel



Map of Matrix Failure Region



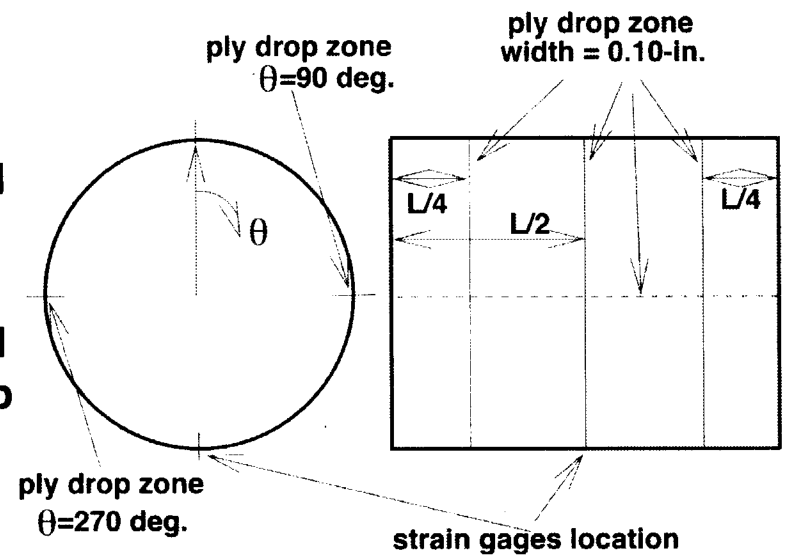
3rd Gen Airframe/TPS:

Integrated Design and Analysis

Safe Structures Design Technologies

EFFECTS OF MANUFACTURING UNCERTAINTIES ON COMPOSITE CYLINDER AXIALCOMPRESSION RESPONSE

- Cylinder is 16.0-in. long; 16.0-in. diameter
- Laminate is $[\pm 45/0/90]_{2s}$ and 0.08-in. thick
- E_{11} = 19.0 Msi, E_{22} = 1.450 Msi, G_{12} = 0.814 Msi, G_{13} = 0.814 Msi, G_{23} = 0.55 Msi, μ_{12} = 0.3
- X_T = 0.156 Msi, X_C = 0.156 Msi, Y_T = 0.00725 Msi, Y_C = 0.0145 Msi, SC = 0.010826 Msi
- Two models were considered:
    - Model 1:
        - Measured geometric imperfection modeled
        - 7,560 elements; 4-noded
    - Model 2:
        - Measured geometric imperfection modeled
        - Laminate imperfection modeled as ply drop
        - 10,692 elements; 4-noded



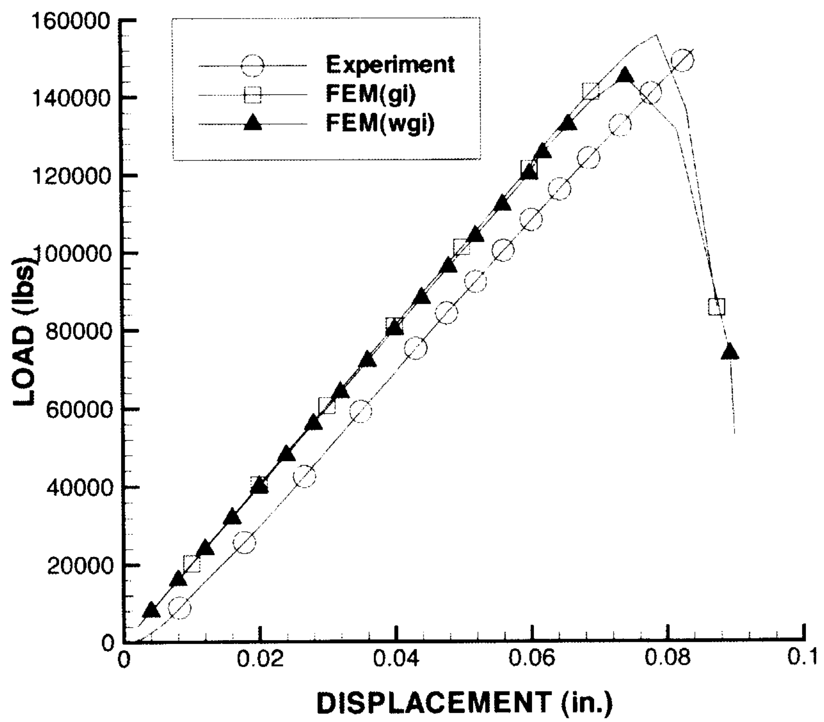
3rd Gen Airframe/TPS:

Integrated Design and Analysis

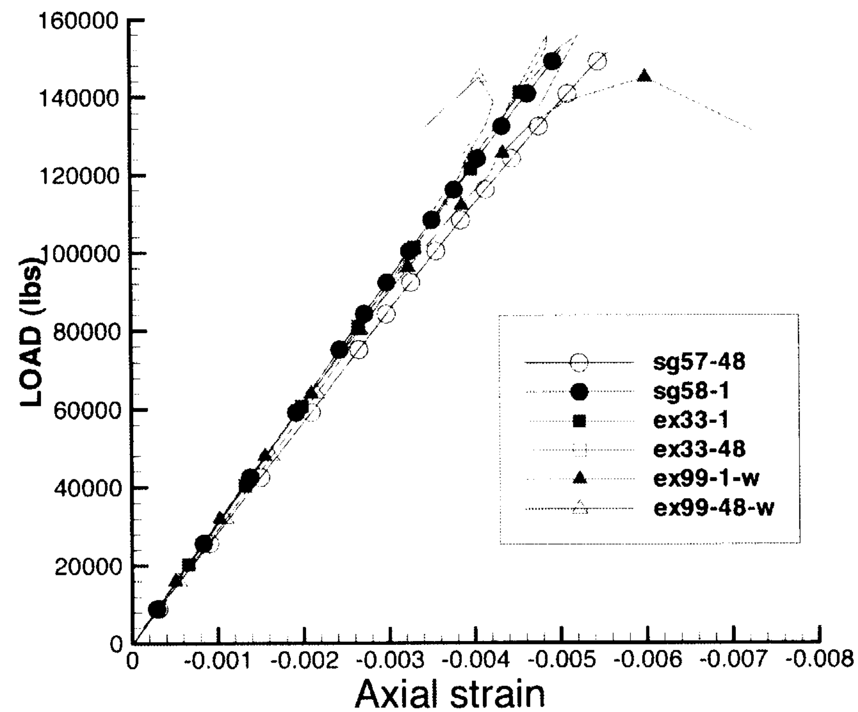
Safe Structures Design Technologies

EFFECT OF MANUFACTURING UNCERTAINTIES ON
COMPOSITE CYLINDER AXIAL COMPRESSION RESPONSE (Contd.)

Load Vs. End-shortening Results



Load Vs. Axial Strain Results



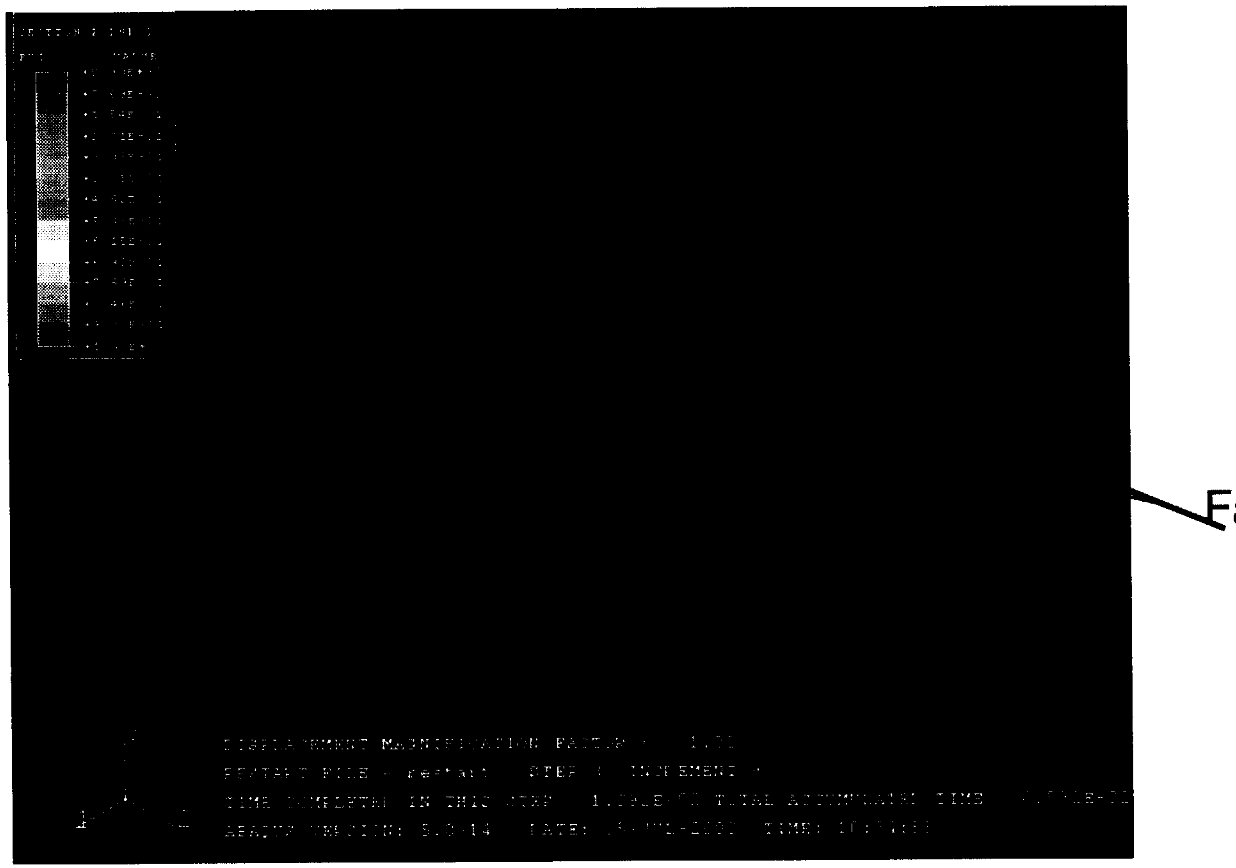
3rd Gen Airframe/TPS:

Integrated Design and Analysis

Safe Structures Design Technologies

EFFECT OF MANUFACTURING UNCERTAINTIES ON COMPOSITE CYLINDER AXIAL COMPRESSION RESPONSE (Contd.)

Map of Failure Region for Model 1

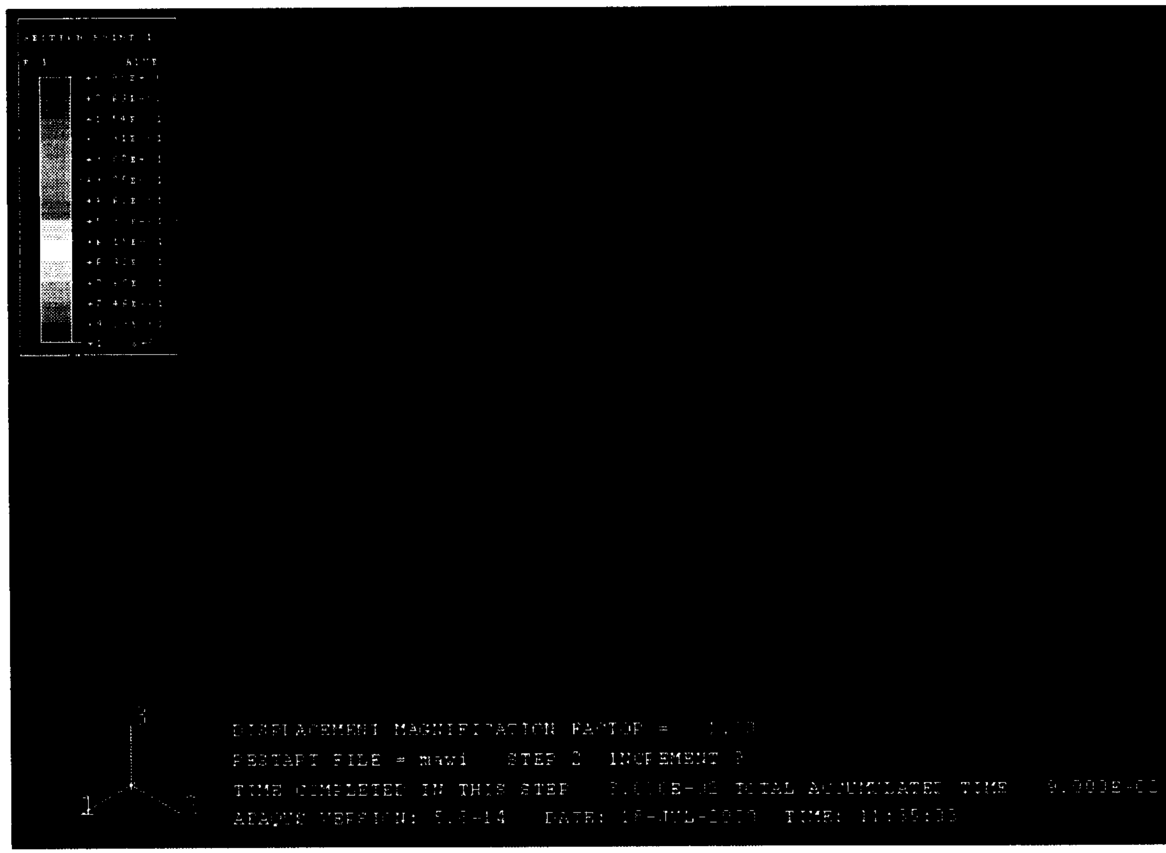


Safe Structures Design Technologies

EFFECT OF MANUFACTURING UNCERTAINTIES ON COMPOSITE CYLINDER AXIAL COMPRESSION RESPONSE (Concluded)

Map of Failure Region for Model 2

Failure modes and damage region results obtained using Model 2 compare well with experimental results



3rd Gen Airframe/TPS:

Integrated Design and Analysis

Safe Structures Design Technologies

NEAR-TERM PLANS

- Conduct inplane shear tests on stiffened and unstiffened panels
- Correlate analytical and experimental results
- Continue efforts to validate the decohesion element for simulating the delamination failure mode
- Incorporate decohesion element into STAGS finite element analysis code

Integrated Thermal Structures & Materials Overview

Dr. Brian Jensen
NASA Langley Research Center
(757) 864-4271
b.j.jensen@larc.nasa.gov

3rd Gen Airframe/TPS:

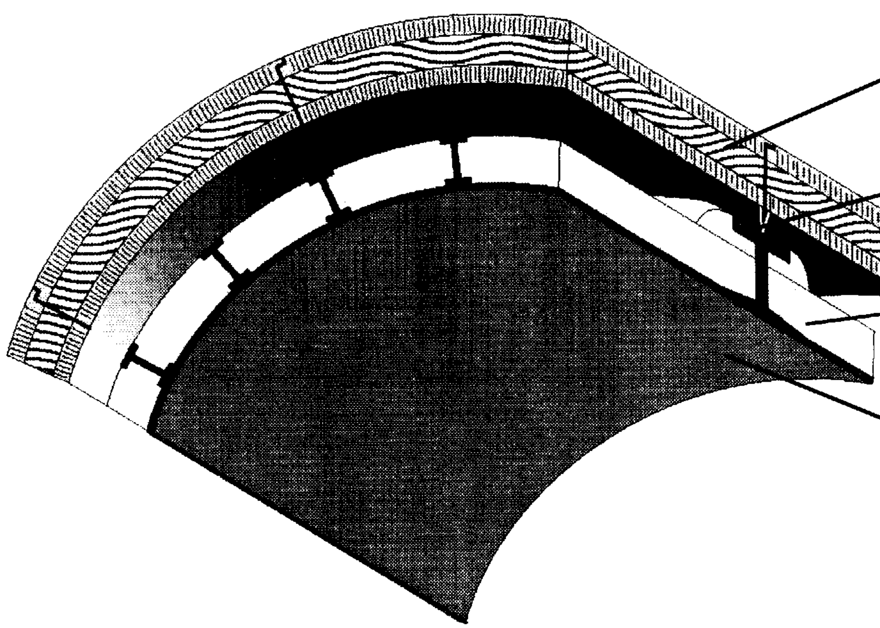
Int. Thermal Structures and Materials

- **Resins for transfer molding or infusion processing**
  - **POC:**
    - Paul M. Hergenrother
    - (757) 864-4270
    - p.m.hergenrother@larc.nasa.gov
- **Nonautoclave processable adhesives**
  - **POC:**
    - Dr. Brian J. Jensen
    - (757) 864-4271
    - b.j.jensen@larc.nasa.gov
- **Automated Tape Placement Device with e-beam cure**
  - **POC:**
    - Harry L. Belvin
    - (757) 864-9436
    - h.l.belvin@larc.nasa.gov

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

High Temperature RLV Tank Concept



TPS:
SA/HC (LaRC Metallic tile)

Support Structure:
Gr-Poly lattice

Cryogenic insulation:
LaRC TEEK™ foam panels
E-Beam cured adhesive

Tank wall:
Externally stiffened Gr-Poly
Liquid Crystal Polymer (LCP) coating

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

- Resins for transfer molding or infusion processing
  - POC - Paul M. Hergenrother, NASA LaRC
- Nonautoclave processable adhesives
  - POC - Brian J. Jensen, NASA LaRC
- Automated Tape Placement Device with e-beam cure
  - POC - Harry L. Belvin, NASA LaRC

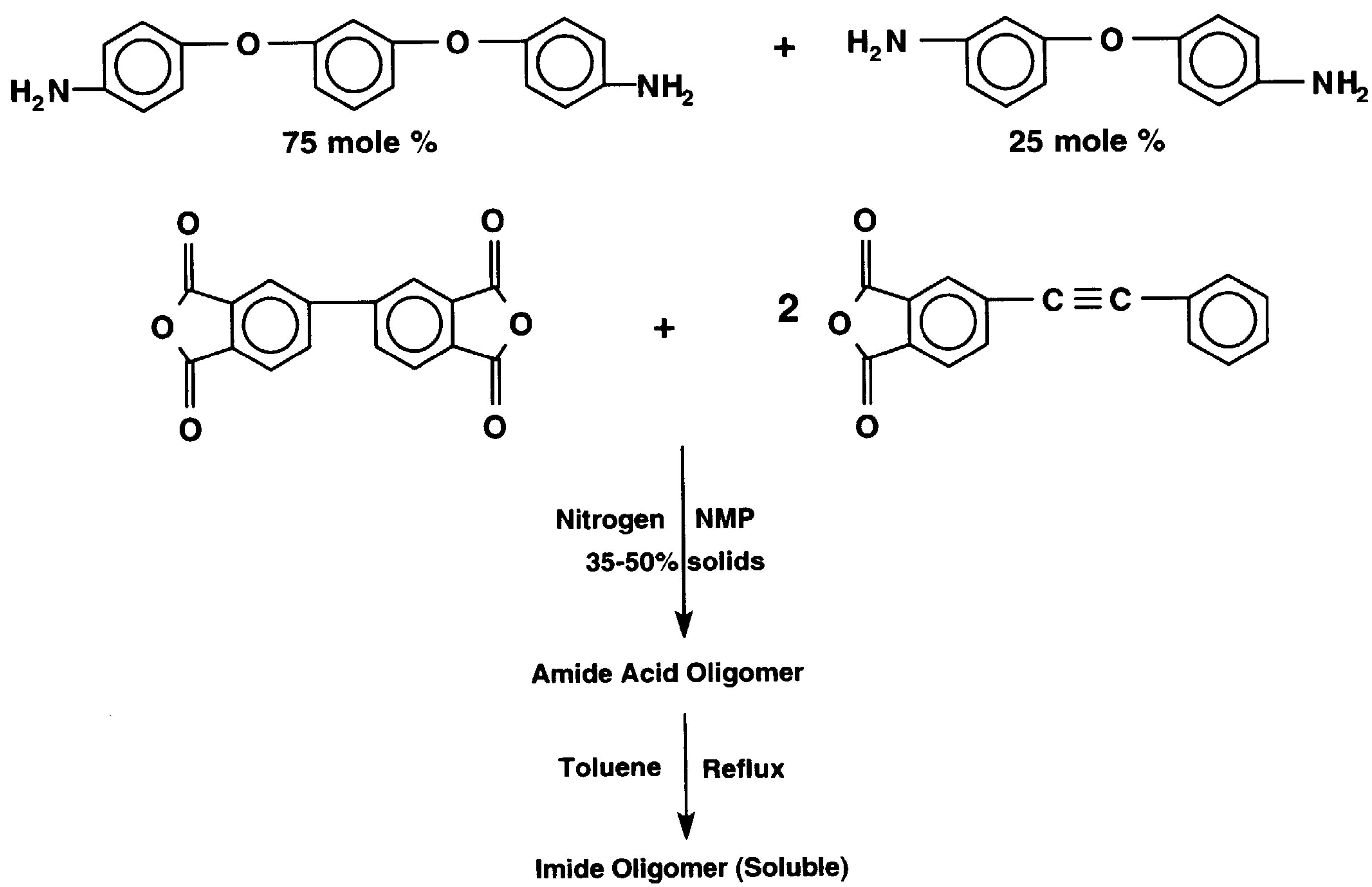
3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

Accomplishments, RTM/RI Resins

- LaRC prepared 5 resins with Tgs as high as 625°F, <1% volatiles, moderate toughness and low melt viscosity and sent to Boeing or Lockheed Martin
- GRC prepared 4 resins with Tgs as high as 700°F, <10% volatiles and low melt viscosity and sent to Boeing
- Boeing successfully fabricated 2' x 2' x 36 ply composites by resin infusion (RI) of stitched preforms from all NASA supplied resins
- Lockheed Martin successfully fabricated 13" x 14" x 16 ply composites by resin transfer molding (RTM) from all NASA supplied resins

Chemistry of PETI-298



Calculated Mn 750 g/mole = PETI-298

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

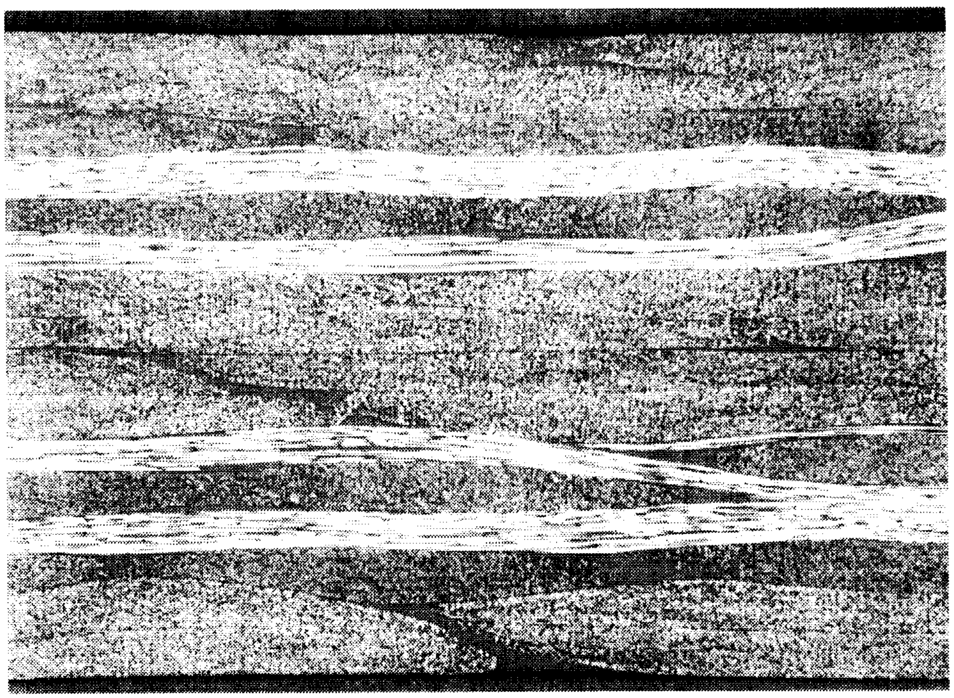
Comparison of PETI Oligomers Prepared From 1,3,3 and 1,3,4 - APB

APB Diamine	Calculated Mn, g/mole	Glass Transition Temp., °C Initial	Cured*	Melt Viscosity @ 280°C, poise
1,3,3	750	132	258	1-6
1,3,3	1250	151	244	5-15
1,3,4	750	139	298	6-13
1,3,4	1250	165	285	10,000**

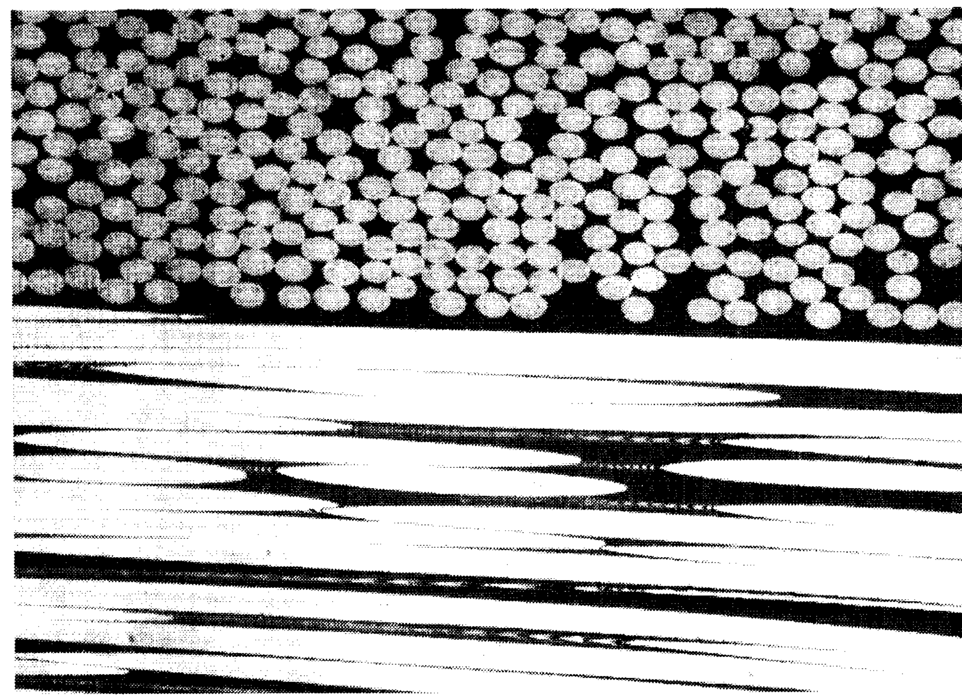
* Cured 1 hour at 371°C

**Viscosity dropped to ~30 poise at 325°C

Photomicrographs of PETI-298 Laminates Fabricated Via RTM

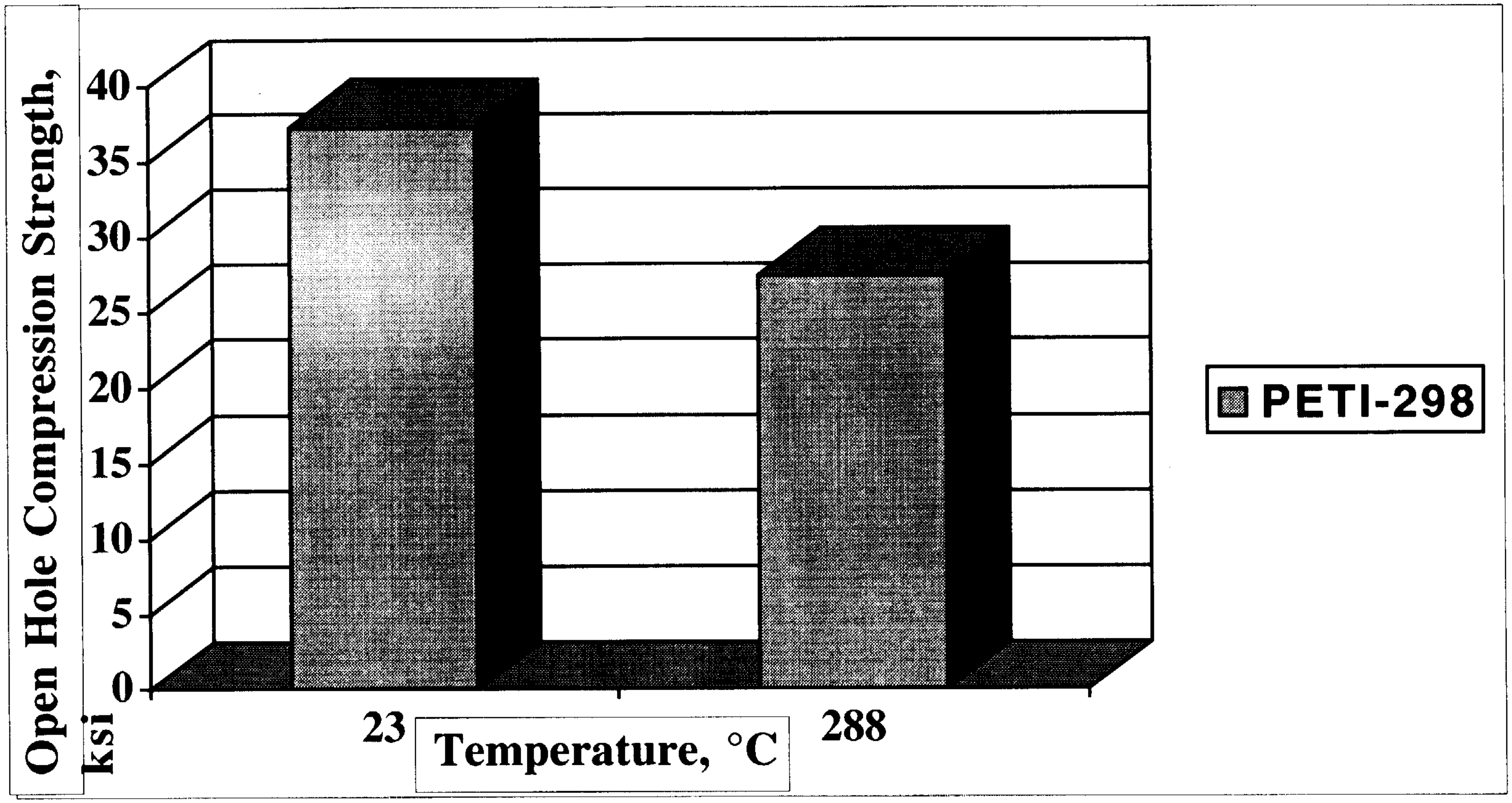


25 x Magnification



400 x Magnification

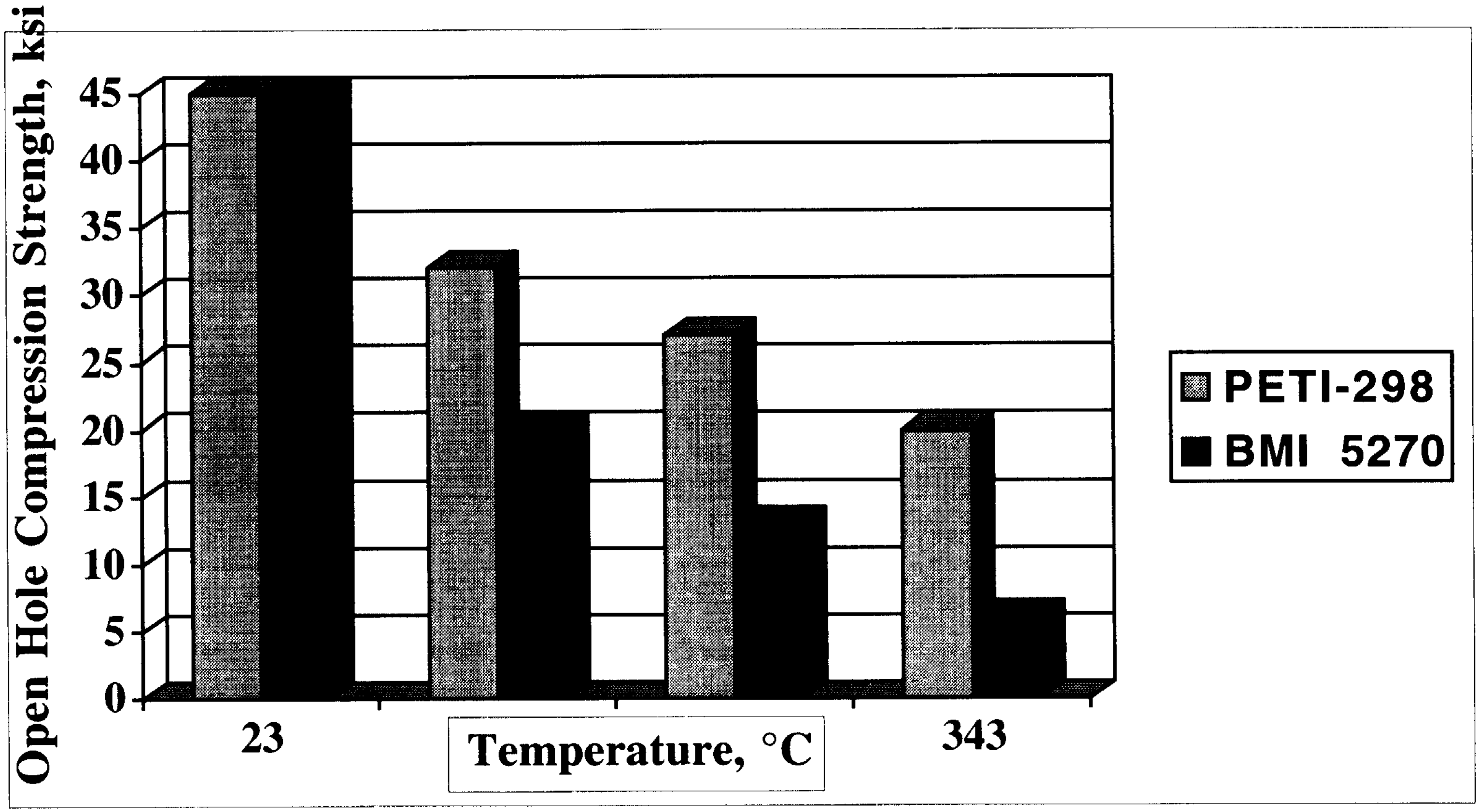
Mechanical Properties of AS-4/PETI-298 Fabric Composites Fabricated Via Resin Transfer Molding (8 ply)



PETI-298 cured 1 hr @ 370°C, Tg = 302°C (8 ply AS-4 fabric)

Un-notched Compression Strength at 23°C = 60 ksi

Mechanical Properties of IM-7 PETI-298 Stitched Composites Fabricated Via Resin Infusion (36 ply)



PETI-298 cured 1 hr @ 370°C, postcured at 370°C, Tg = 338°C (Panel 36 ply x 22"x 22", stitched)

BMI 5270 cured 4 hr @ 190°C, postcured at 232 and 260°C , Tg = 299°C

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

- Resins for transfer molding or infusion processing
  - POC - Paul M. Hergenrother, NASA LaRC
- Nonautoclave processable adhesives
  - POC - Brian J. Jensen, NASA LaRC
- Automated Tape Placement Device with e-beam cure
  - POC - Harry L. Belvin, NASA LaRC

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

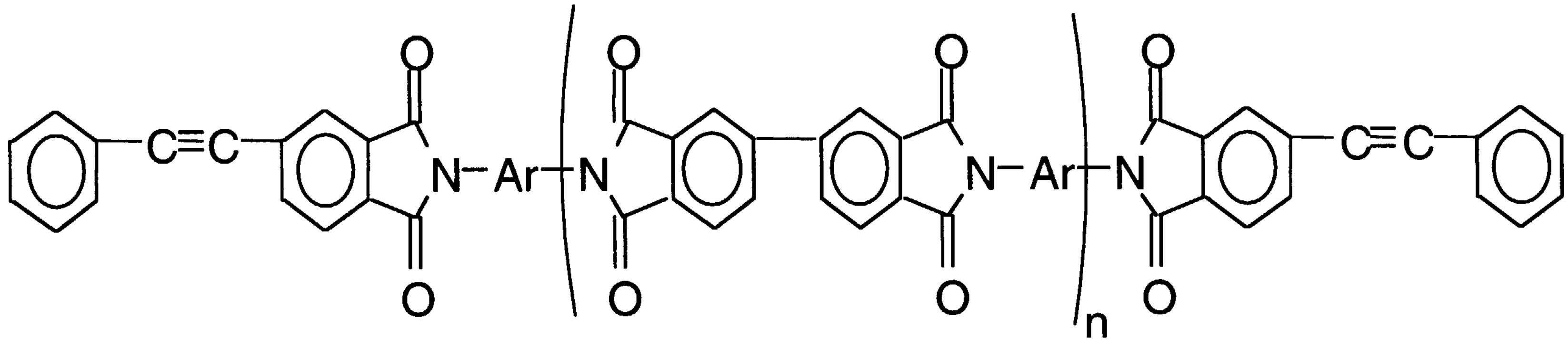
Accomplishments, LaRC PETI-8

- Developed and supplied to Cytec Fiberite several non-autoclave processable adhesives.

- LaRC PETI-8 is a phenylethynyl terminated polyimide adhesive which has low melt viscosity and excellent melt stability at temperatures below 300°C, allowing the production of excellent adhesive bonds under vacuum bag pressure, without the need for external pressure normally supplied by an autoclave. Heating at 316°C for 8 hours provides excellent titanium to titanium tensile shear strengths from 75°F to at least 350°F and excellent flatwise tensile strengths at 75°F.

- Plan to continue work on adhesives which do not require an autoclave for processing. Concentrate on vacuum bag / oven processing, hot melt adhesives and the use of e-beam radiation to cure advanced adhesives. Optimize the properties of LaRC PETI-8 by studying various formulations of the adhesive tape and various cure conditions.

LaRC PETI-8



Titanium to Titanium Tensile Shear Strengths

Required	Achieved
5000 psi at 75° F	**7400 psi**
3500 psi at 350° F	**6200 psi**

Flatwise Tensile Strength (Composite Skins over Titanium core)

Required	Achieved
1000 psi at 75° F	**1370 psi**

Bonding Conditions:

Vacuum Bag Only Pressure, 316°C, 8 hour hold, 5V CAA surface treatment

Cytec Fiberite Results for PETI-8 Bonding

Evaluated 550°F, 575°F and 600°F cycles from 4-12 hours under vacuum bag only pressure for several different formulations. Shown are results for 600°F, 4 hour cycle.

PETI-8 Tensile Shear Strength	75°F	350°F
Titanium substrate, CAA Anodized	7000 psi (min.)	5000 psi (min.)
PETI-5 composite substrate (interlaminar failure at both test temperatures)	5500 psi	4500 psi

PETI-8 Flatwise Tensile Strength	75°F
2024 Al face sheets, FPL etched, 3/16" Ti core	1800 psi

Cytec currently preparing two 2' x 2' PETI-5 composite panels to be bonded together as a wide area specimen.

- **Resins for transfer molding or infusion processing**
  - **POC - Paul M. Hergenrother, NASA LaRC**
- **Nonautoclave processable adhesives**
  - **POC - Brian J. Jensen, NASA LaRC**
- **Automated Tape Placement Device with e-beam cure**
  - **POC - Harry L. Belvin, NASA LaRC**

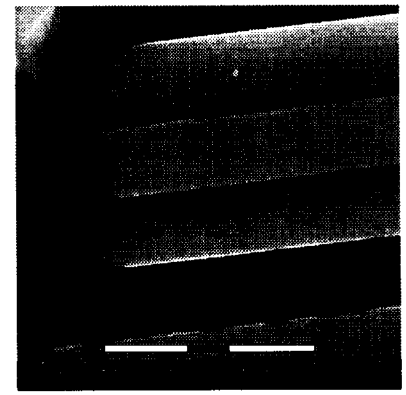
3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

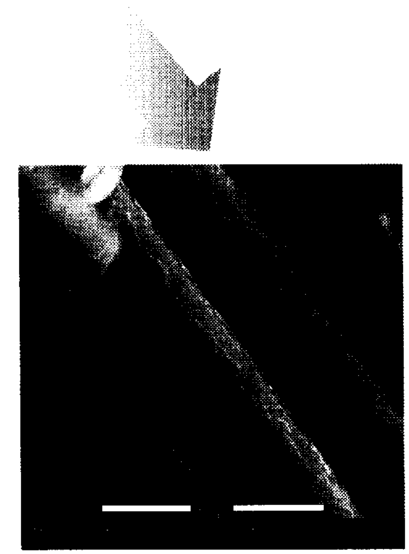
Accomplishments, ATP with E-Beam Cure

- GRC has Cooperative Agreement with Kent State University to study e-beam irradiation of polyimide thin films. (Shows little effect on mechanical properties or Tg)
- GRC has Cooperative Agreement with University of Delaware to study new e-beam curable resins. (Extent of cure dependent on molecular mobility)
- GRC in-house e-beam curable resin development. (Diels-Alder trapping of quinodimethane intermediates formed under radiation)
- LaRC and Boeing developing a tape laying machine with e-beam cure-on-the-fly processing. Undergoing acceptance testing at Boeing and will be shipped to LaRC when facilities are ready.

- **Products/ Benefits/Payoff:**
  - Validate the cause of low performance in E-beam cured graphite/epoxy composites and investigate methods for improving their performance through the use of novel sizings or resin additions.
  - The goals are to:
    - Positively identify the deficiencies causing reduced properties in E-beam cured composites
    - Identify and demonstrate the best method for performance improvement
  - Improved performance of E- beam composites will enable out-of-autoclave fabrication of large cryo tanks. Higher performance of these materials directly reduces RLV vehicle weight.



E-Beam Cured Cat-B



Thermally Cured 8552

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

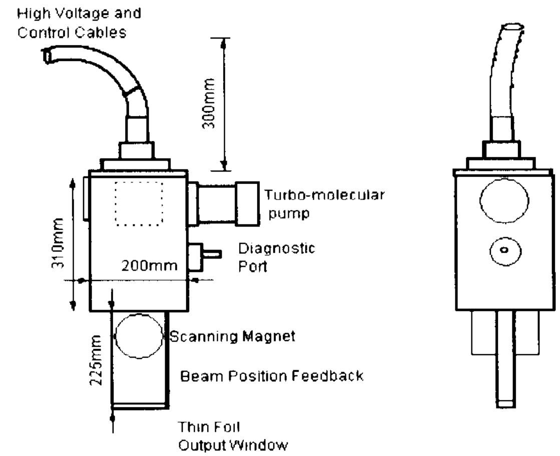
E-beam Gun Head from Electron Solutions, Inc.
E-beam Gun Head from Electron Solutions, Inc.
Boeing Tape Laying Gantry

• Description

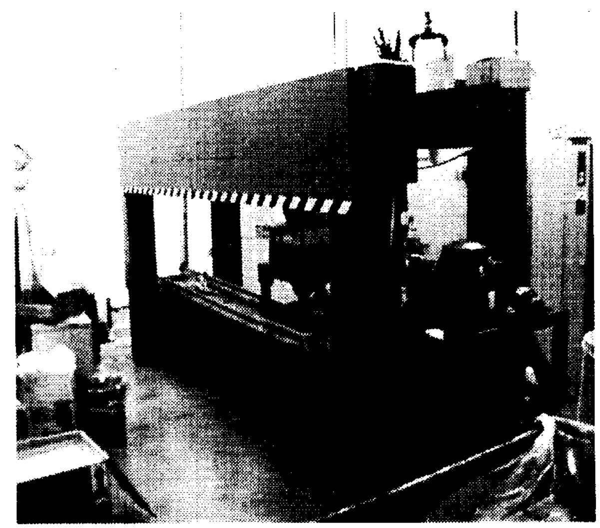
This task will design, fabricate and deliver a tape laying device capable of laying E-beam "cure-on-the-fly" (COTF) prepreg for material evaluations.

• **Products/ Benefits/Payoff:**

COTF E- beam curing will enable out-of-autoclave fabrication of RLV cryo tanks which will substantially reduce overall vehicle weight.



E-beam Gun Head from Electron Solutions, Inc.



Boeing Tape Laying Gantry

3rd Gen Airframe/TPS:

Int. Thermal Structures and Materials

2nd Generation RLV Airframe Structures and Materials

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Presented at the RLV Technology Workshop
NASA Marshall Space Flight Center
October 10-11, 2000

- Goals and Objectives
- Structures and Materials Roadmap
- Recent Accomplishments
- Description of NASA-led Tasks
- Summary

2nd Gen Airframe/TPS - Structures and Materials:

Presentation Outline

- Develop and demonstrate verified airframe and cryotank structural design and analysis technologies
  - Damage tolerance, safety, reliability and residual strength technologies
  - Robust nonlinear shell and cryotank analysis technologies
  - High-fidelity analysis and design technologies for local structural detail features and joints
  - High-fidelity analysis technologies for sandwich structures

- Demonstrate low cost, robust materials and processing
  - Polymeric Matrix Composite (PMC) and metallic materials and processing
  - Refractory composite and metallic hot structures materials and processing

2nd Gen Airframe/TPS - Structures and Materials:

Goals and Objectives

- Develop and demonstrate robust airframe structures and validated integrated airframe structural concepts
  - Low cost fabrication and joining
  - Operations efficient designs and inspection techniques, NDE
  - Scale-up and integrated thermal structural test
  - Airframe structures IVHM

- Demonstrate low cost, robust repair techniques

- Develop verified integrated airframe structural concepts
  - Integrated (Primary & cryotank struct./Insulation/TPS) structural concepts

2nd Gen Airframe/TPS - Structures and Materials:

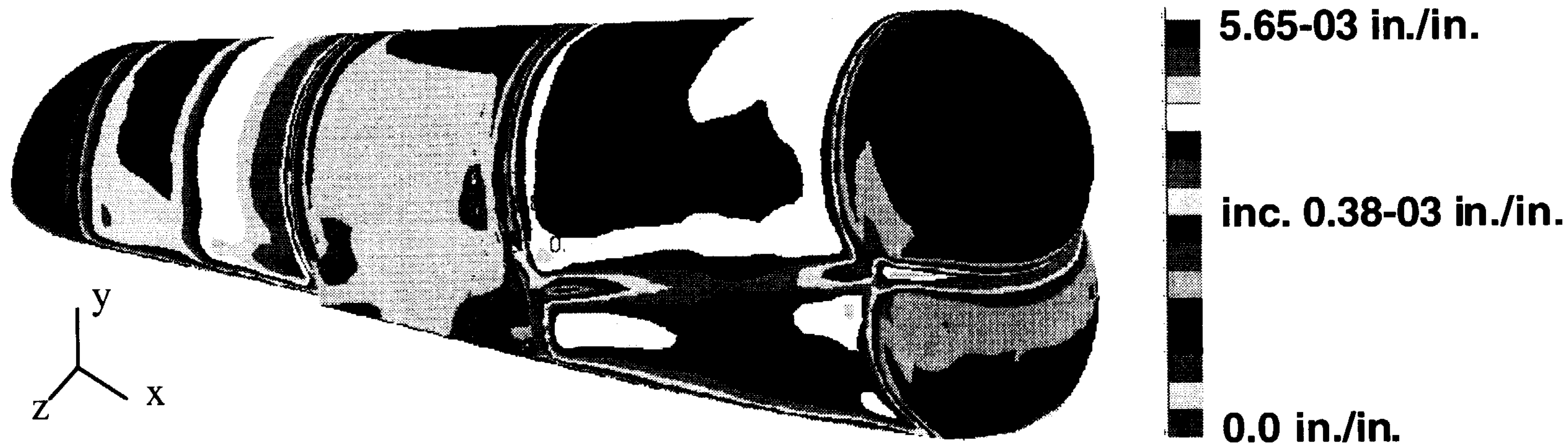
Goals and Objectives - Cont.

- Plans developed for all structures and materials technology tasks work is being initiated
- High-fidelity nonlinear shell analysis capability under development for response, damage tolerance and residual strength analyses
- Lifecycle and durability testing of materials and structures are currently being conducted
- Tests of curved stiffened composite panel planned for cryo-pressure box test facility
- Cryo-pressure box successfully completed Operational Readiness Review (ORR)
- Developing test capability for Helium permeation under combined temperature and mechanical loads

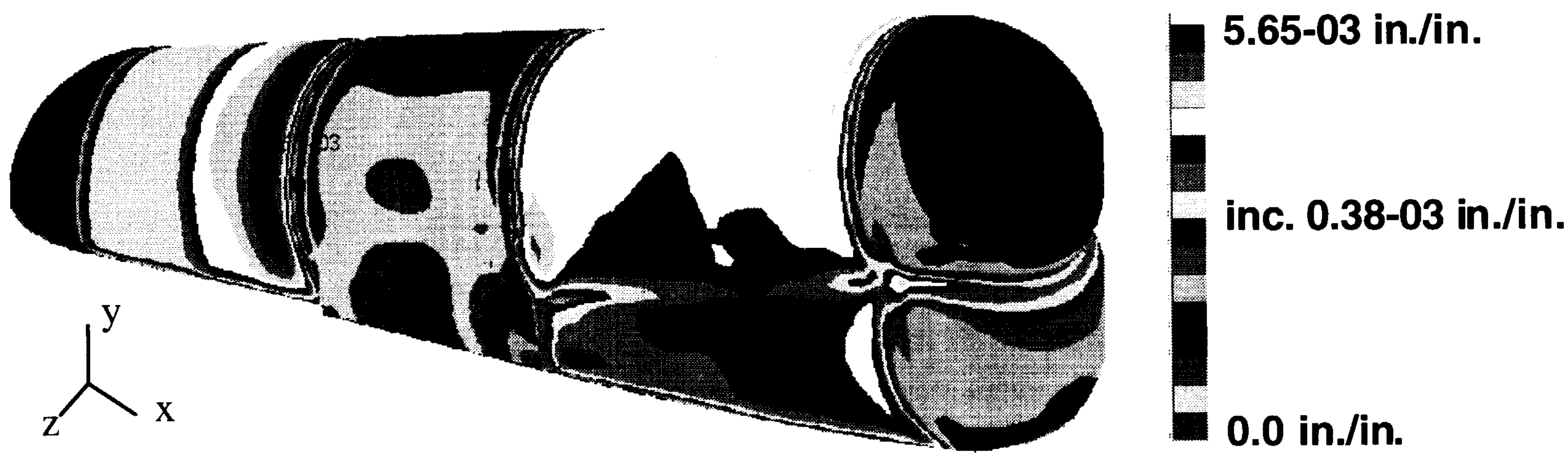
2nd Gen Airframe/TPS - Structures and Materials:

Recent Accomplishments

Maximum Principal Strain Plots



Linear Analysis

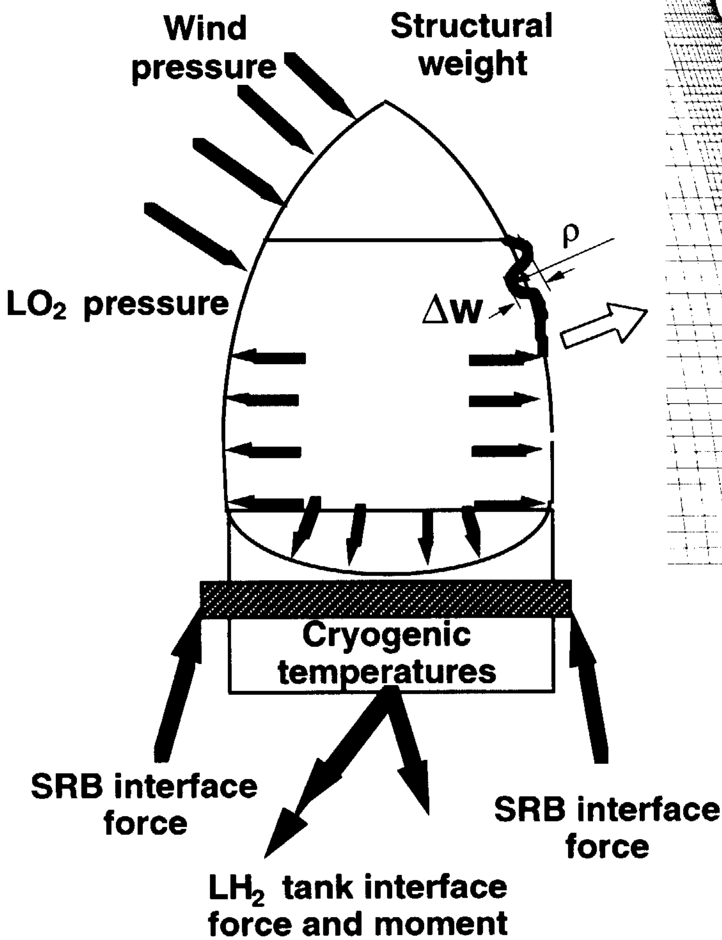


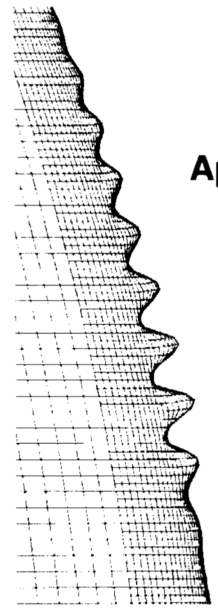
Nonlinear Analysis

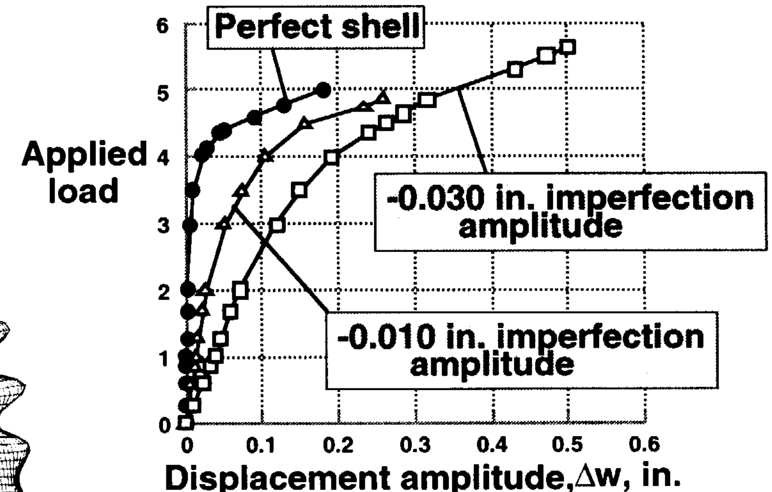
2nd Gen Airframe/TPS - Structures and Materials:

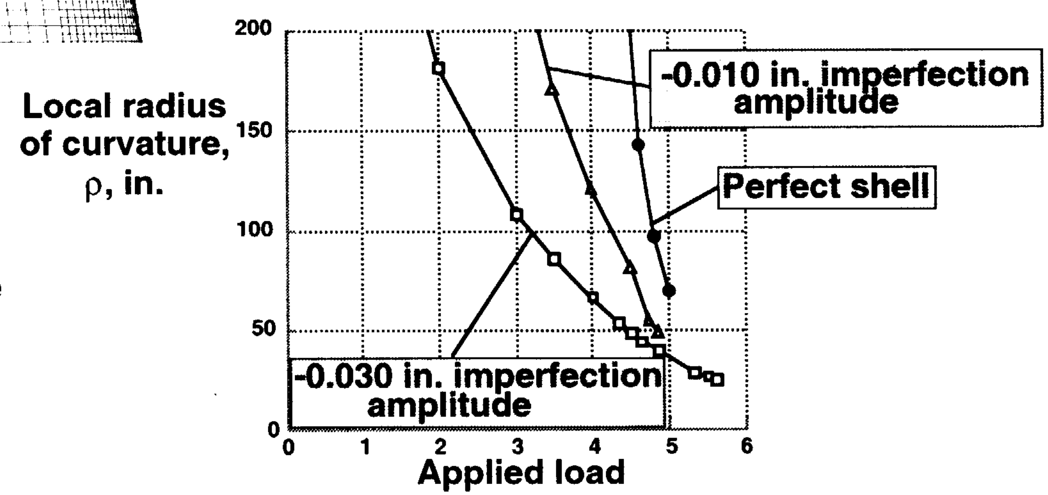
Multi-Lobed Tank Nonlinear Analysis

Space Shuttle Superlightweight External Tank Identifies LO_2 Tank Local Stability Mode



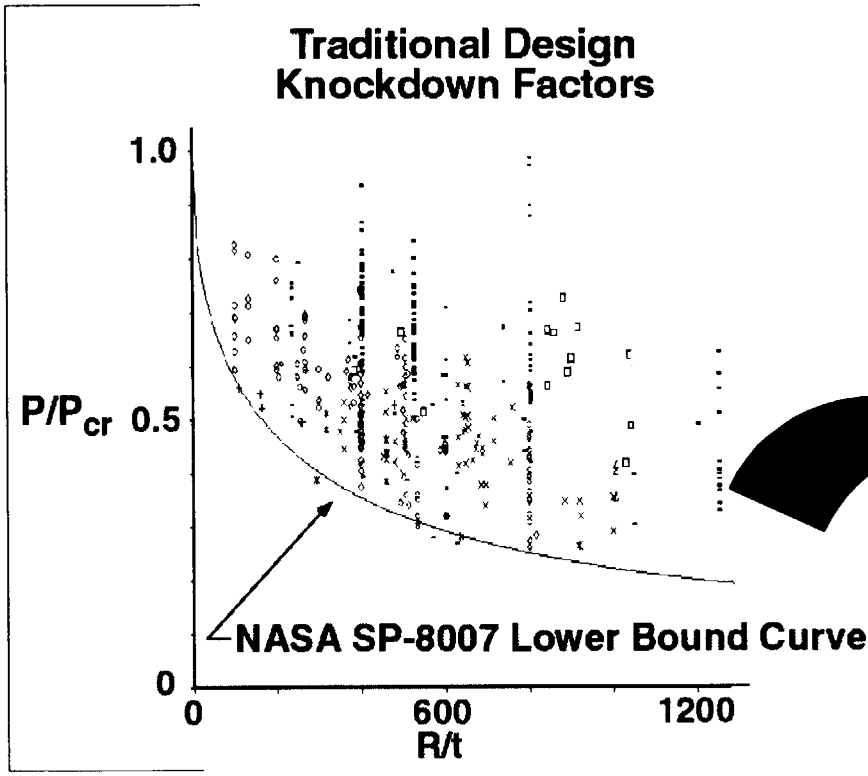




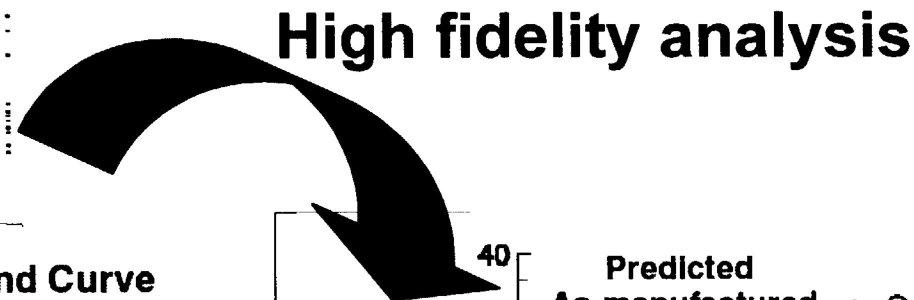


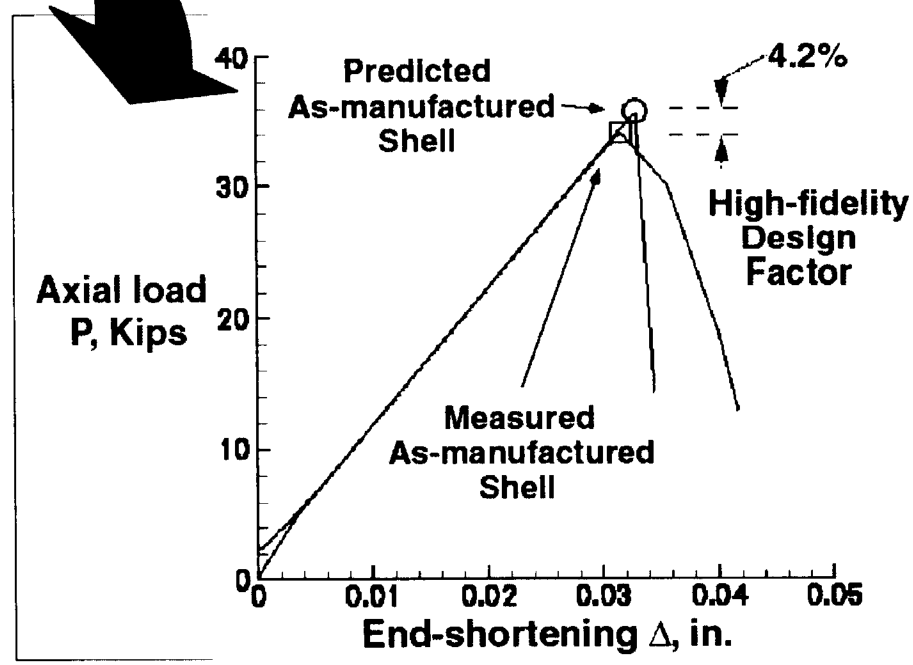
2nd Gen Airframe/TPS - Structures and Materials:

High Fidelity Nonlinear Analysis



Objective: Develop verified high fidelity analysis tools to reduce dependence on tests

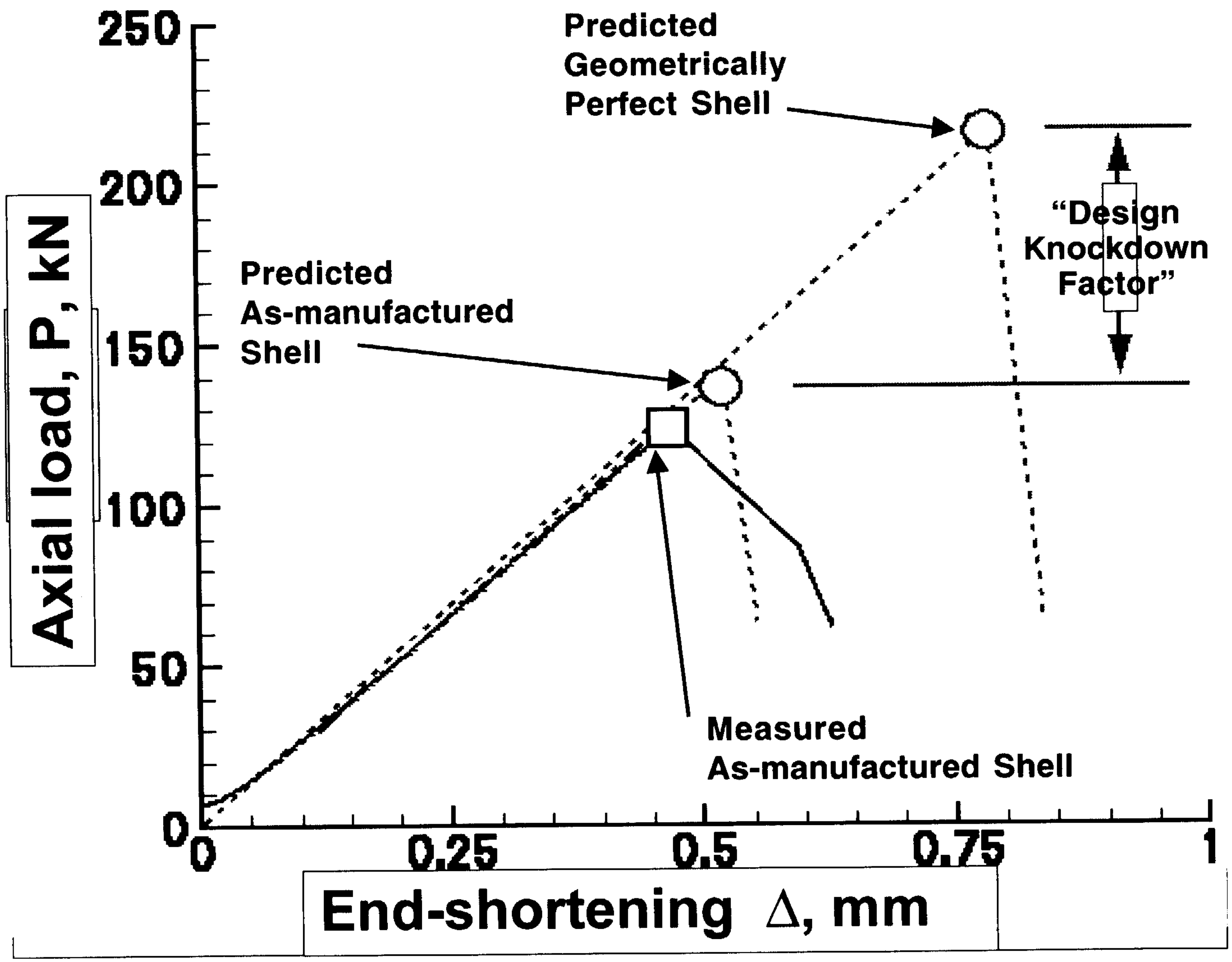




Technologies:
- High fidelity modeling
- Rapid and accurate analysis tools
- Prediction capability for all failure mechanisms
- Progressive failure methods for residual strength
- Intelligent testing approaches

2nd Gen Airframe/TPS - Structures and Materials:

High Fidelity Non-Linear Structural Analysis for Predicting Complex Structural Phenomena

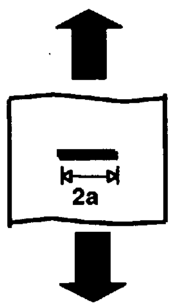


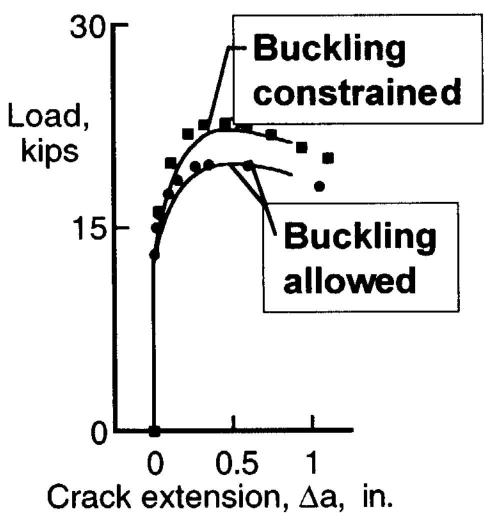
2nd Gen Airframe/TPS - Structures and Materials:

Predicted and Measured Response of a Composite Shell Structure

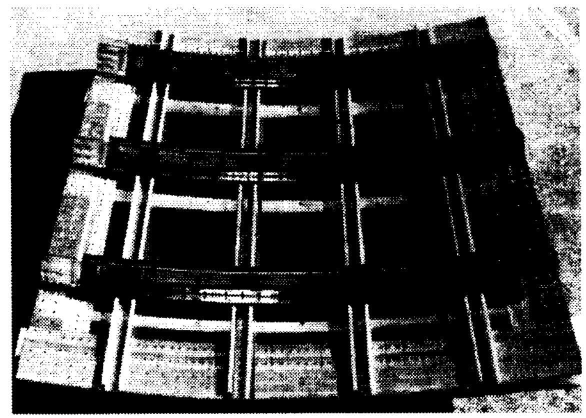
Laboratory Coupons

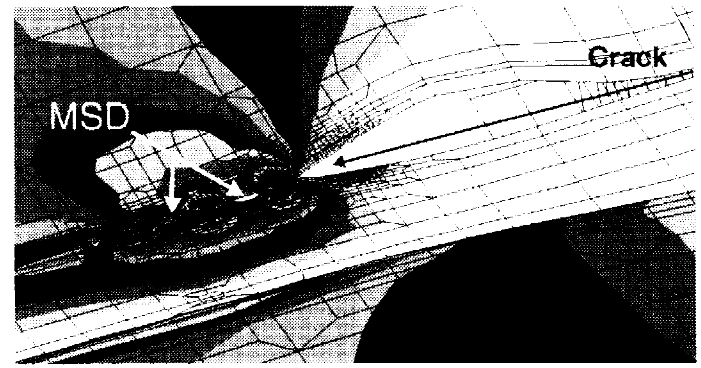
M(T) 12.0 in., 2a = 4 in.

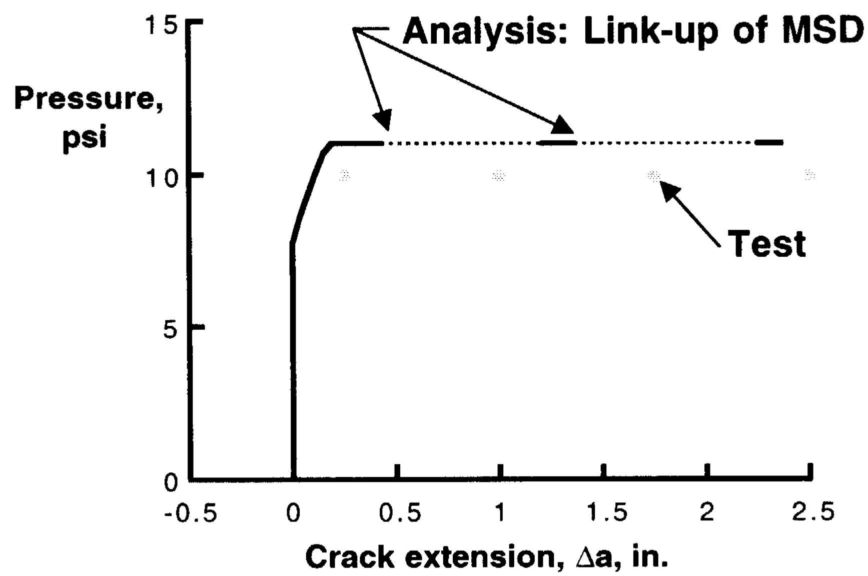




Fuselage Panel with Multiple Site Damage (MSD)



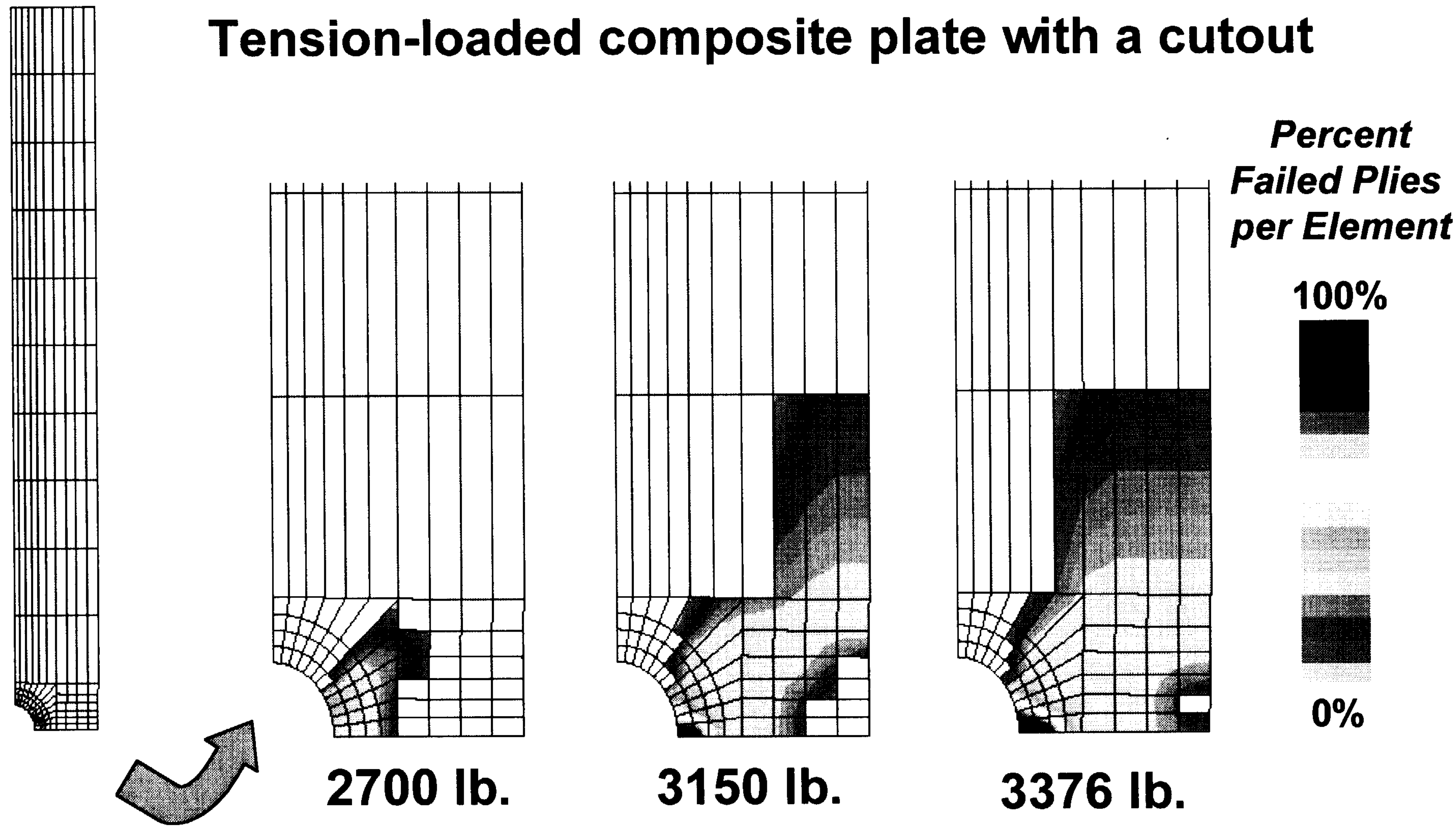




2nd Gen Airframe/TPS - Structures and Materials:

Applying Advanced Methods for Residual Strength Predictions

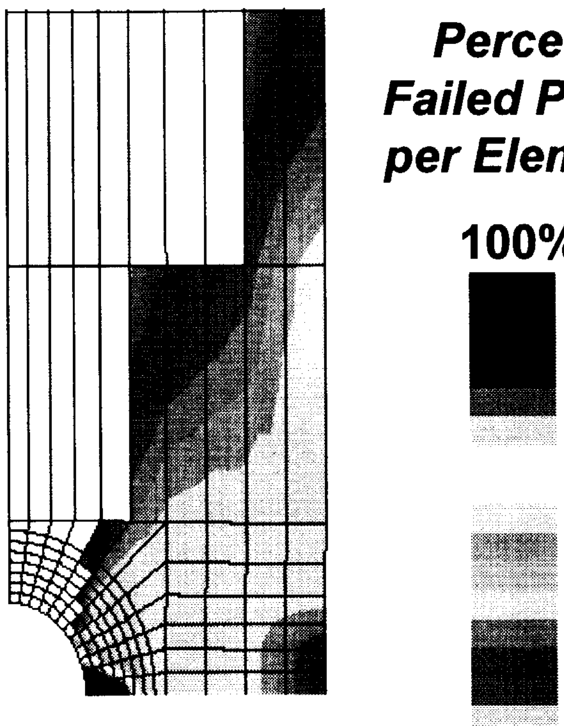
Tension-loaded composite plate with a cutout



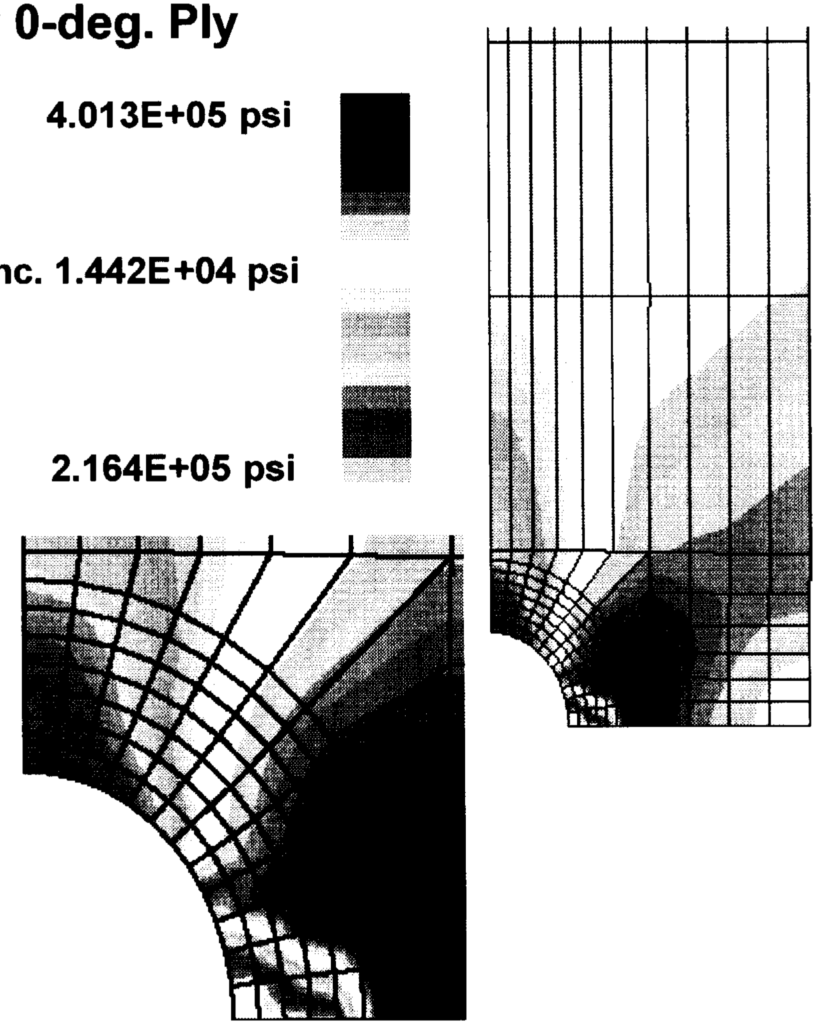
2nd Gen Airframe/TPS - Structures and Materials:

Progressive Failure Analysis

Maximum load solution for a composite plate with a cutout



3430 lb.



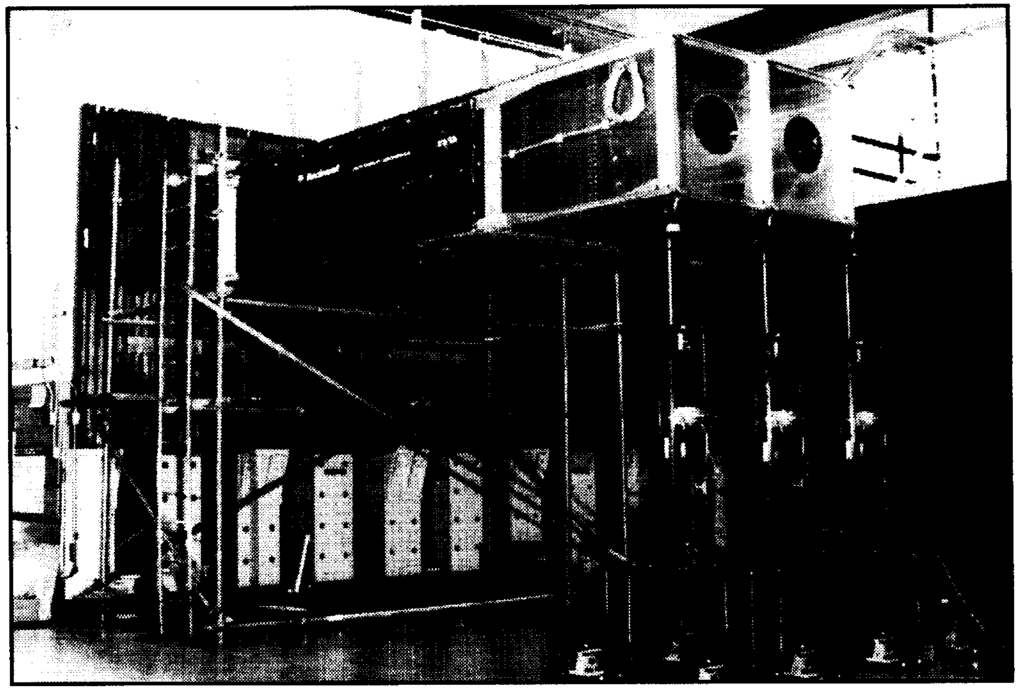
2nd Gen Airframe/TPS - Structures and Materials:

Progressive Failure Analysis - Cont.

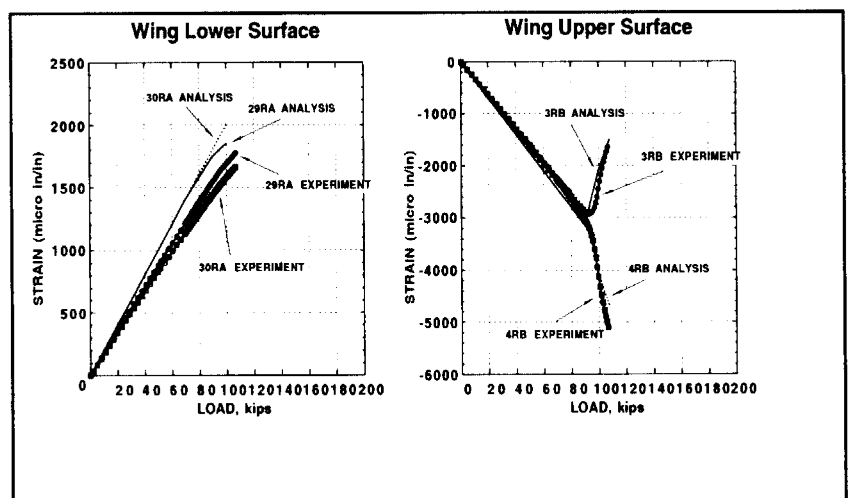
2nd Gen Airframe/TPS - Structures and Materials:

X-33 Phase I Graphite Composite Wing Box Design Validation Test

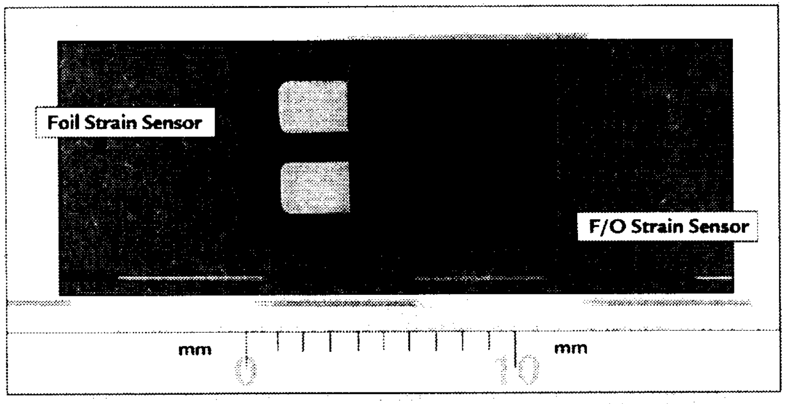
RLV wing box test setup

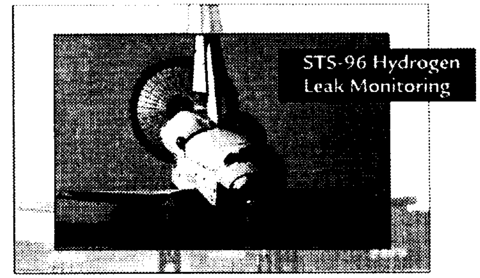


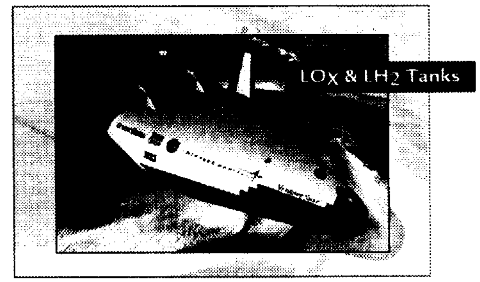
Measured and calculated strains on an RLV wingbox upper and lower surfaces



Distributed Fiber-Optic (F/O) Sensing for Structures IVHM

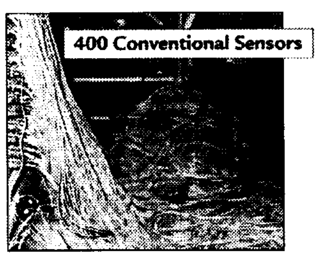


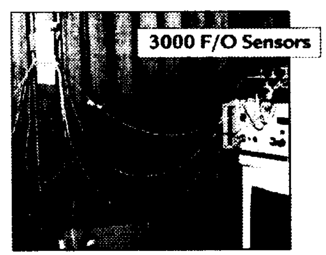


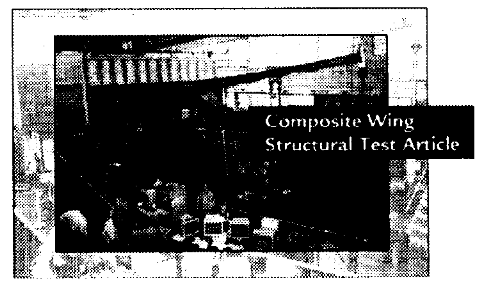


High Density Structural Sensors

- 10,000 Sensors < 1 pound
- Strain, Temperature, & Hydrogen (Propellant Leaks)
- Future Research - Vibration, Shape, Acoustic Emission, Chemistry (Corrosion)
- < $10/Sensor







2nd Gen Airframe/TPS - Structures and Materials:

Distributed Fiber Optic Sensing

2nd Gen Airframe/TPS - Structures and Materials:

Cryogenic Pressure Box Facility

Capabilities:

Loads

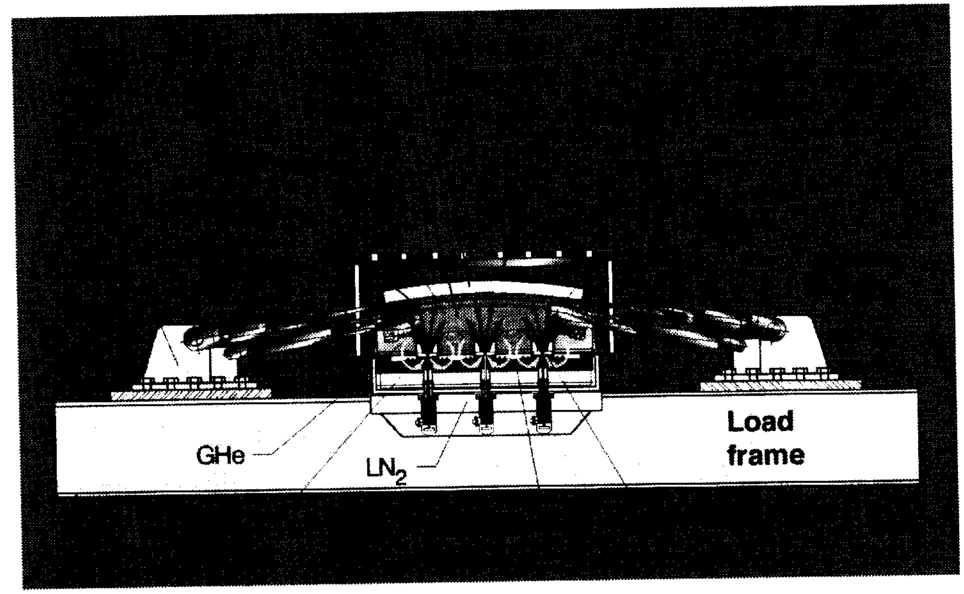
- Bi-axial tension is applied
- Max. axial load is 450 kips
- Max. internal pressure is 45 psig
- Internal cooling to -400°F
- Internal heating to 250°F
- External heating to 1000°F

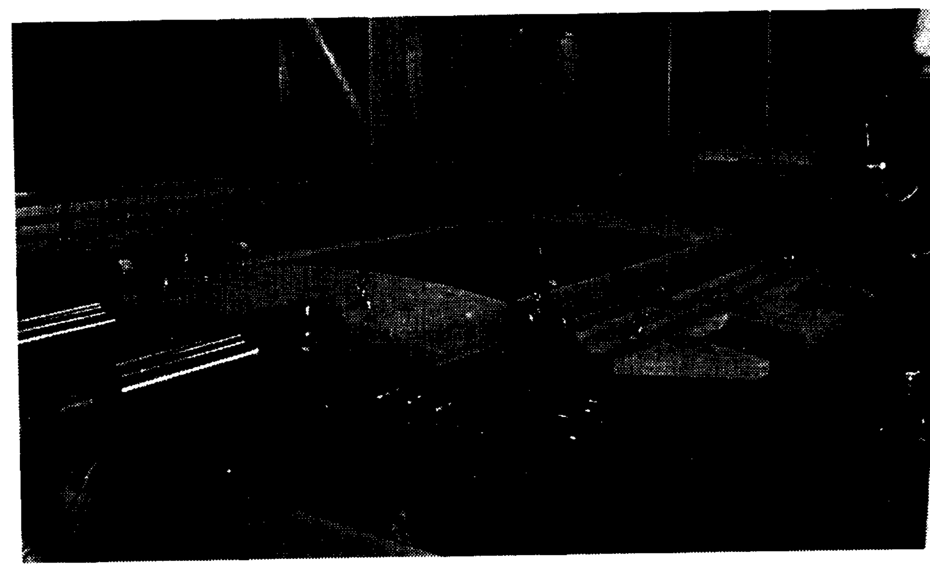
Geometry

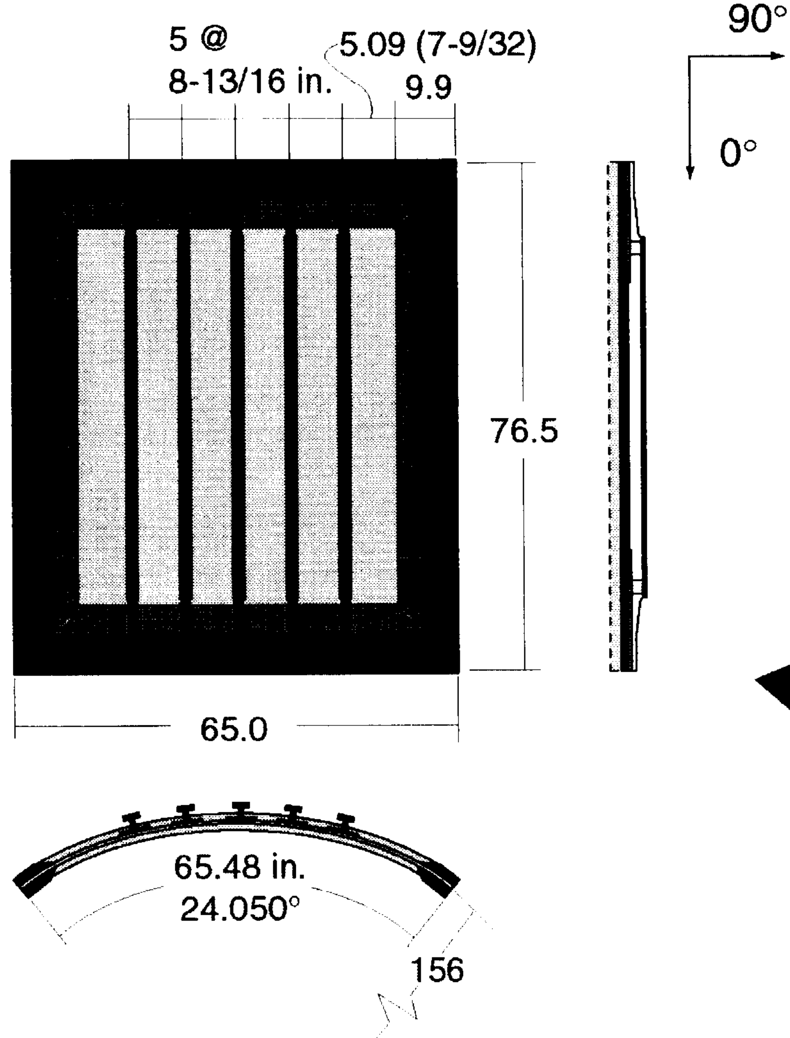
- Panel size is 65 in. x 76 1/2 in.
- Panel radii from 130 in. to 266 in. (80 in. is possible)
- Panels can have internal and external ring frames and stringers

Benefit

s
- Full-scale tank features
- Testing at subcomponent costs

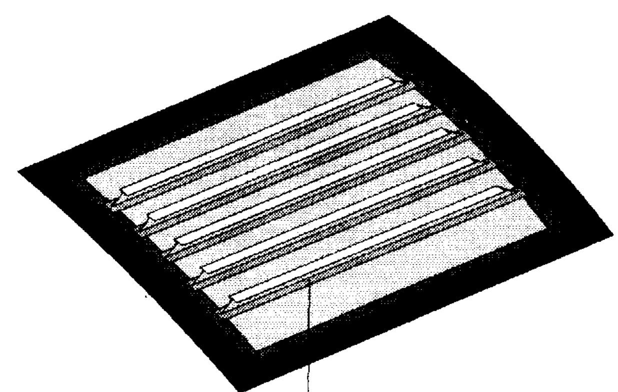






Langley
Composite LH_2 Tank
Panel

Radius: 156 in.
Material: Gr-Ep; IM7/977-2 Tape
& Fabric



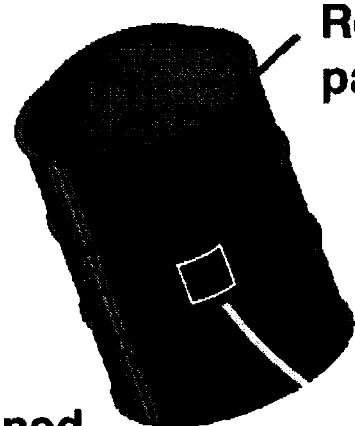
2nd Gen Airframe/TPS - Structures and Materials:

Cryogenic Pressure Box Panel

- Combined thermal and structural analysis
- Traceable solutions to flight articles

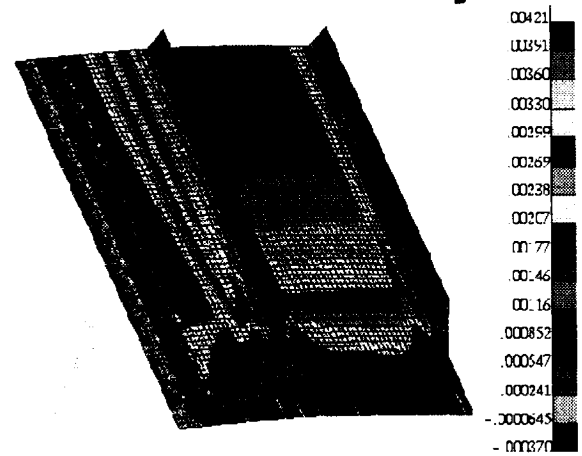
Full sized articles

Tank geometry modelled as a cylinder

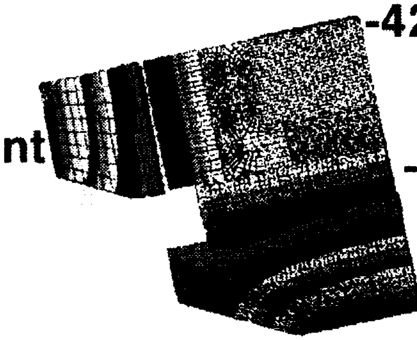


Graphite-Epoxy Externally stiffened LH_2 tank

Structural Analysis

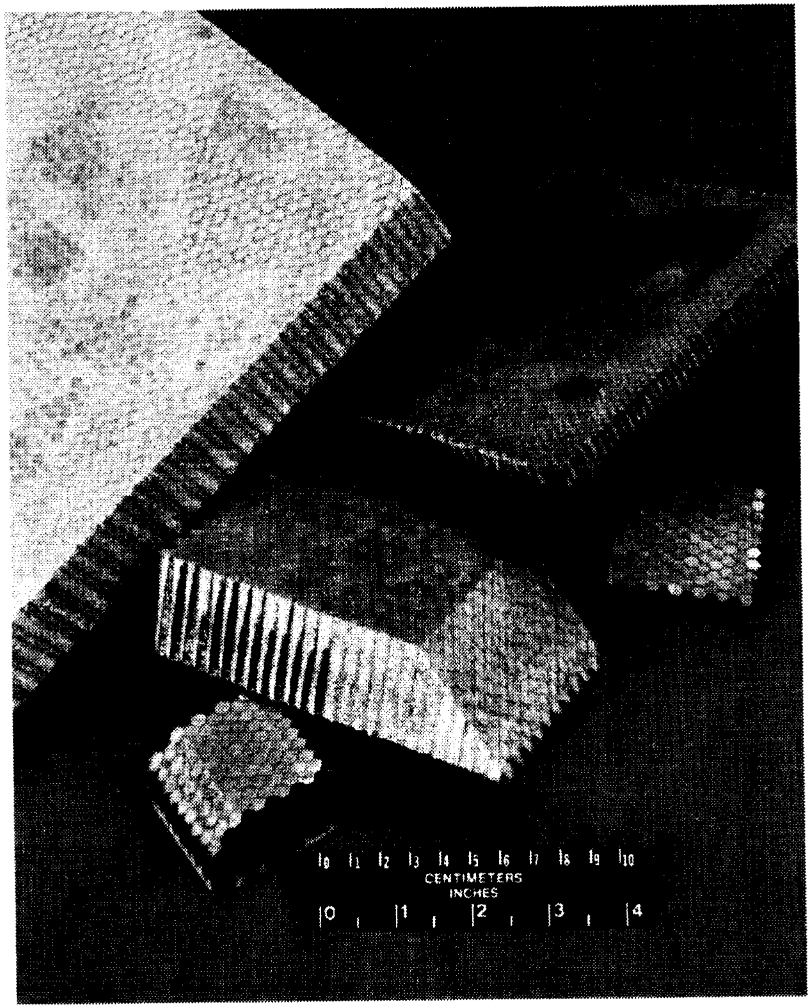


Thermal Analysis



2nd Gen Airframe/TPS - Structures and Materials:

Correlation of Analysis to Test

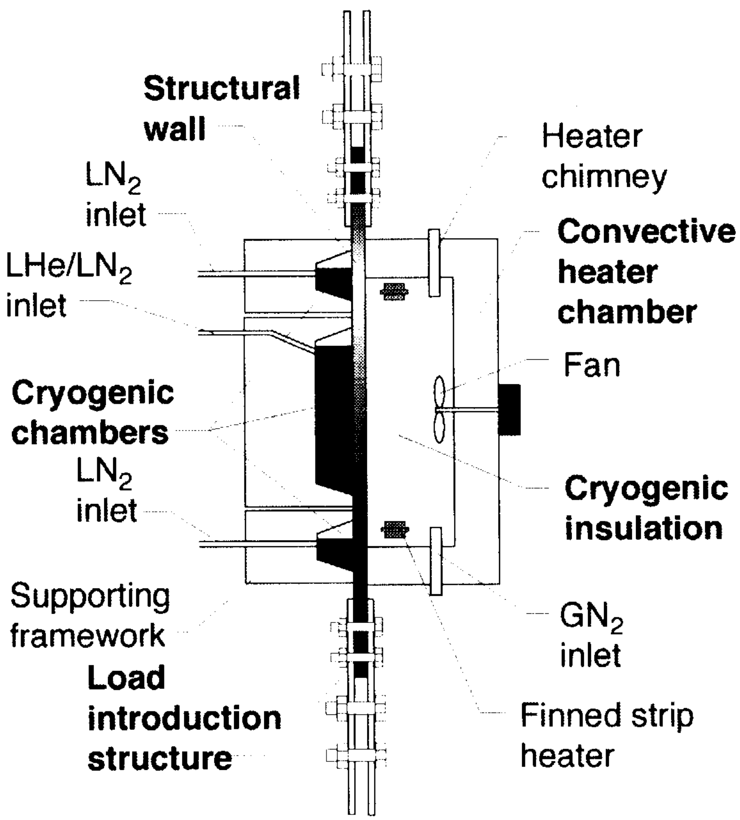


- Any honeycomb material can be foam filled - Korex, Nomex, Graphite, etc.
- Honeycomb cell size from 1/8” and larger can be foam filled.
- Honeycomb core thickness from 1/4” and larger.
- Foam densities ~2.6 pcf.

2nd Gen Airframe/TPS - Structures and Materials:

TEEK Foam Filled Honeycomb Materials

Cross-Section of fixture



Specimens

Substrate: 1' x 2' & 1' x 4'

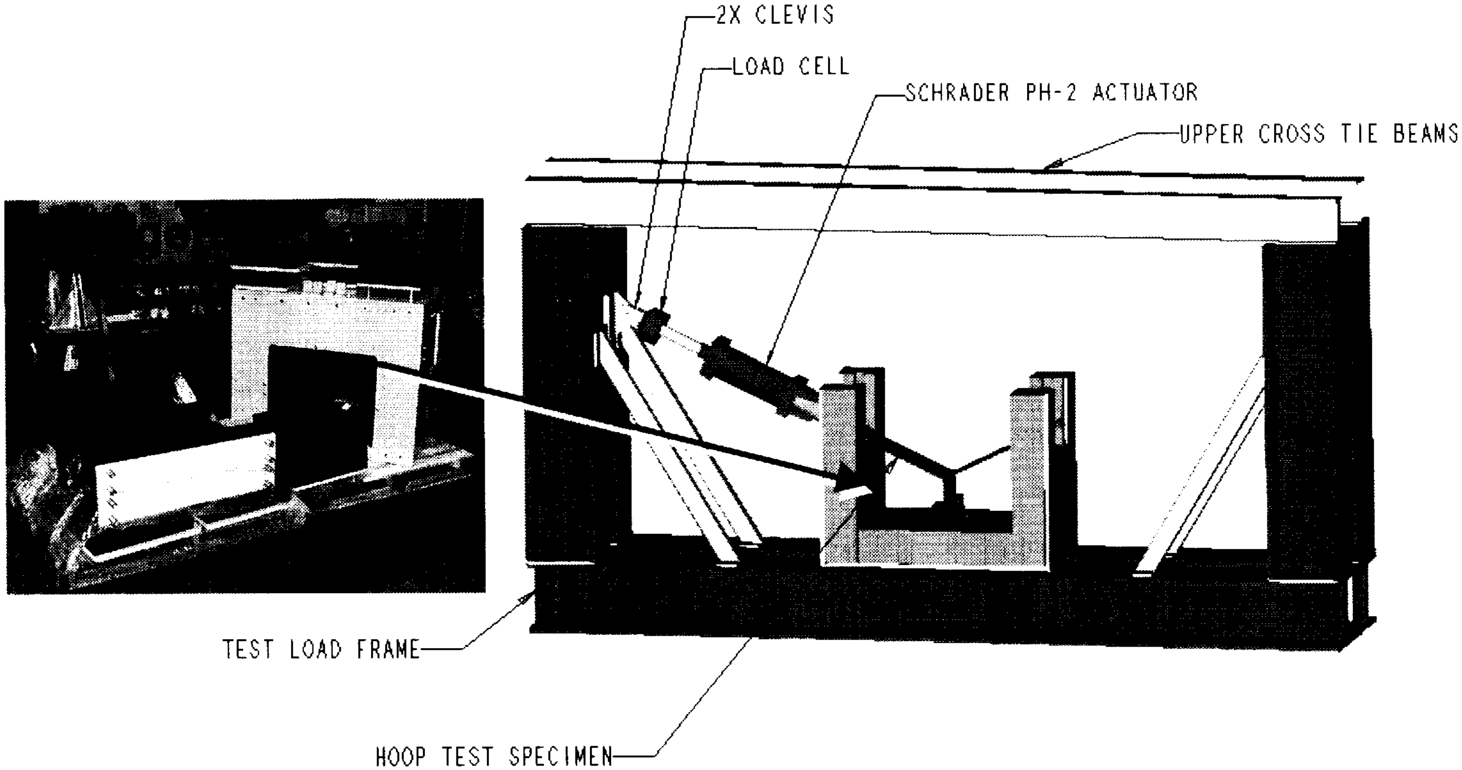
Min. Temp.
- **-423°F (Cryo. side)**
- **10°F (Foam surface)**

Max. Temp.
- **250°F (Cryo. side)**
- **450°F (Foam surface)**

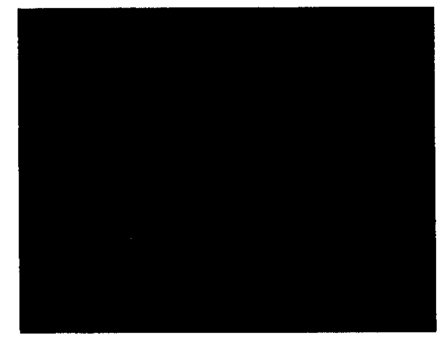
Max. Load: 110 kips

2nd Gen Airframe/TPS - Structures and Materials:

Thermal/Mechanical Tension Test



Hoop Y-joint



Axial Y-joint

Specimens

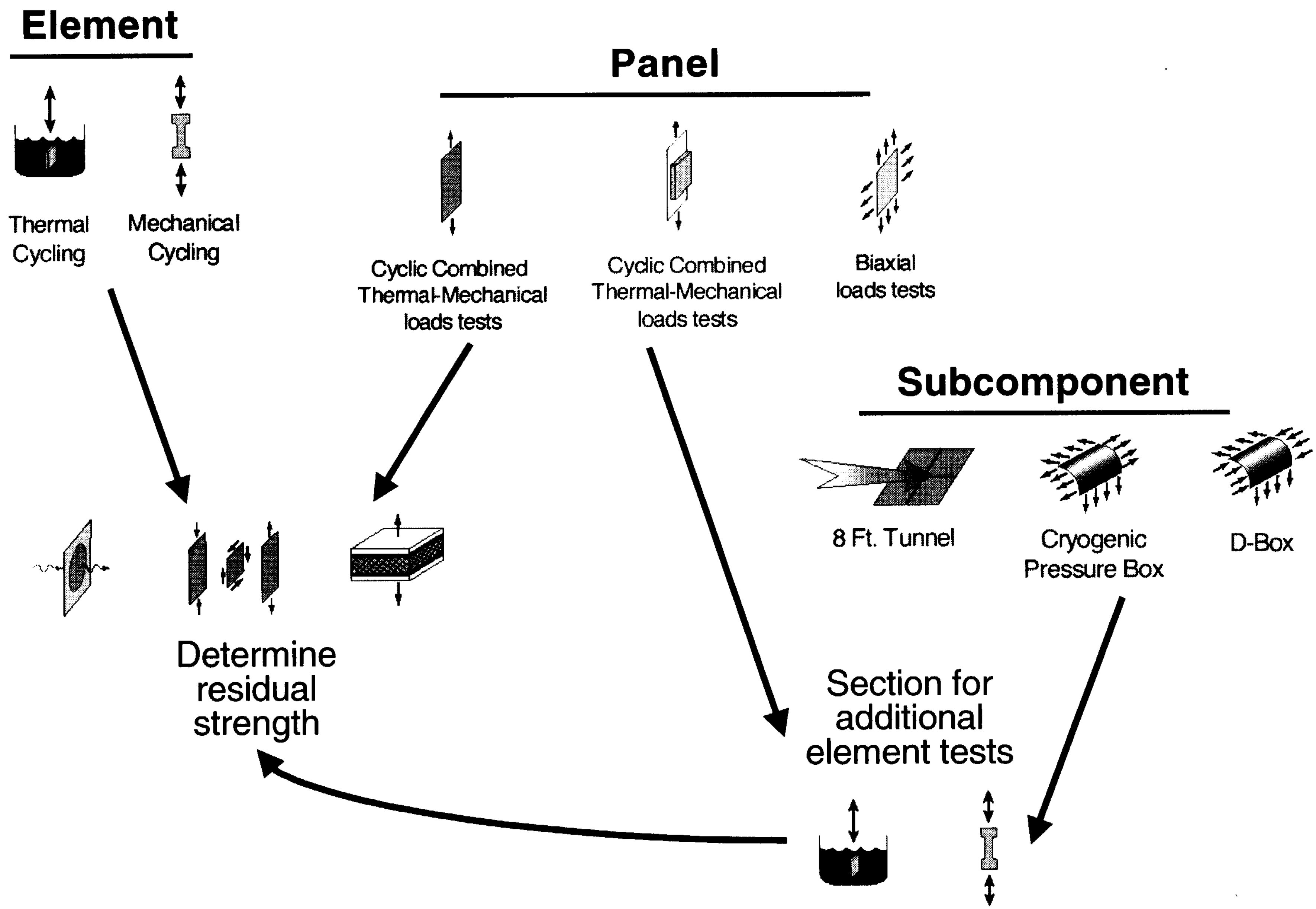
- 2 Hoop Tension Y-Joints
  - Arm-to-Barrel step joint
- 2 Axial Tension Y-Joints
  - Axial and Arm-to-Barrel step joint

Test Plan

- 10 Thermal Cycles (-423°F to +250°F)
- Pull to failure at -423°F
- Record failure load, failure mode

2nd Gen Airframe/TPS - Structures and Materials:

Hoop & Axial Y-Joint Tests



2nd Gen Airframe/TPS - Structures and Materials:

Materials in Structural Applications

- **NASA's Thermal Protection System (TPS) Technologies**
  - RLV Focused Projects
  - Recent or Emerging Technologies
- **NASA's TPS Research, Development & Testing Capabilities**
  - TPS Development Approach
  - Laboratories
  - Modeling
  - Databases
  - Test Facilities
- **TPS POC**

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NASA Ames Research Center
(650) 604-6395
mrezin@mail.arc.nasa.gov

TPS Technologies & Capabilities

- **Constituents and Fabrication Techniques for Metallic TPS** - *LaRC*
  - Advanced joining techniques
  - Surface property characterization
  - Durable, lightweight coating development
- **Metallic TPS Concepts** - *LaRC*
  - Improved metallic TPS concepts
  - Lower risk, subsurface panel-to-panel seals, cooler subsurface attachments
- **Advanced Durable Blanket TPS** - *ARC Partnership w/ Industry*
  - Lower fabrication and maintenance unit costs
  - Suitable for application to windward vehicle surfaces
- **High Temperature Integrated Structures** - *LaRC Partnership w/ Industry*
  - Structurally integrated high temperature wing design
  - Reduced manufacturing costs and improved load bearing characteristics

RLV Focused Project of the ASTP

- **Durability**
  - TUFI & White TUFI on AETB Ceramic Tiles - *ARC*
  - Structural Seals & Thermal Barriers - *GRC*
  - Toughened LI-900 - *ARC*
  - Metallic Sandwich Panel TPS - *LaRC*
  - Metal Covered Ceramic Blankets (DurAFRSI) - *ARC*
  - CMC Covered Ceramic Tiles - *LaRC*
  - Advanced Durable Ceramic Blankets - *ARC with Industry Partner*
- **Lower Thermal Conductance**
  - Reduced Conductivity AETB Ceramic Tiles - *ARC*
  - Nano-Phase Ceramic Insulations - *ARC*
    - Aerogel & other xerogel composites

Recent or Emerging Technologies

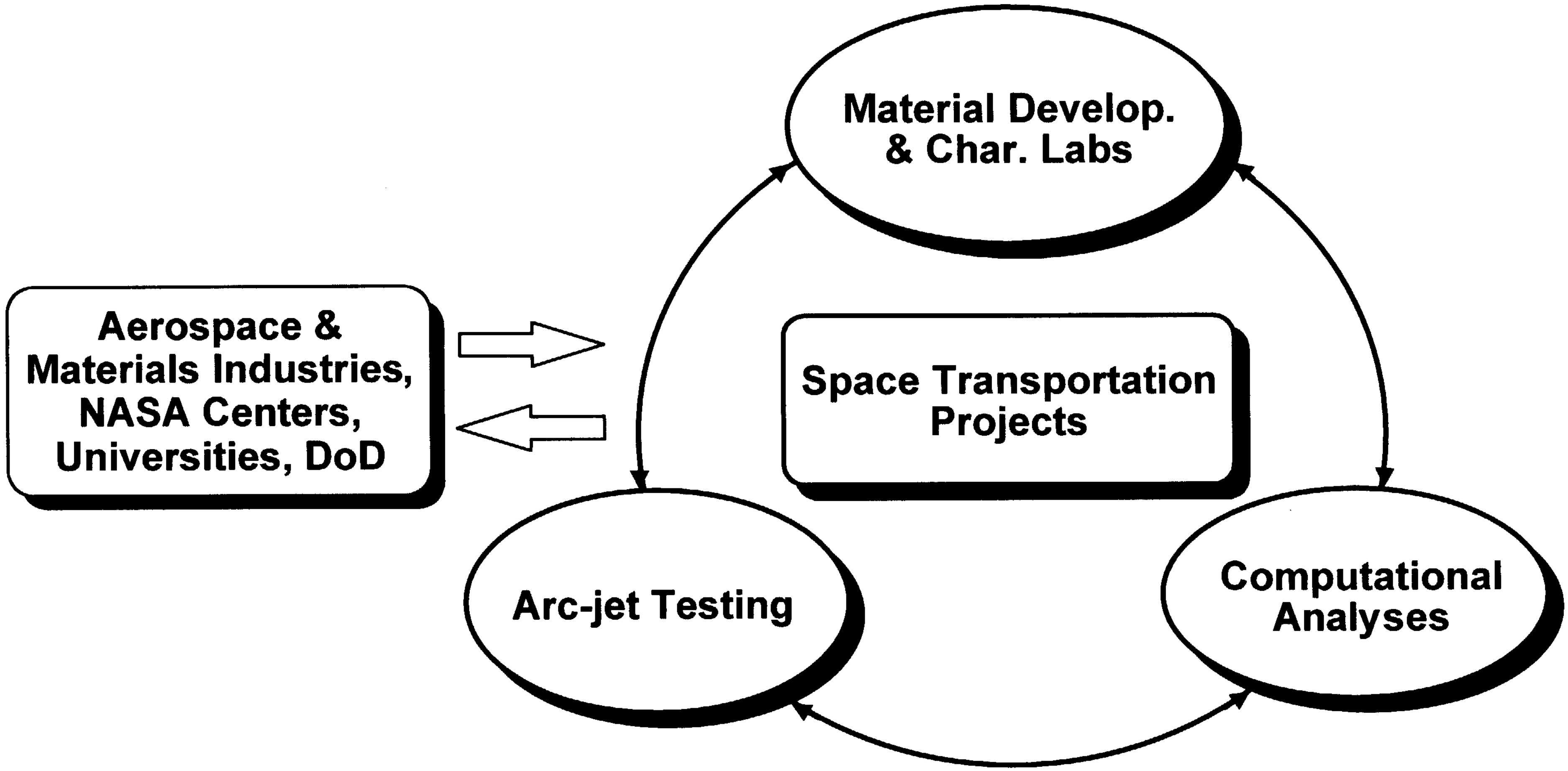
♦ Higher Temperature Capability

- Ultra-High Temperature Ceramics - *ARC, GRC, LaRC*
  - including Zr & Hf based ceramic composites
- High Temperature Seals - *GRC*
- Heat Pipe Cooled Leading Edges - *LaRC*
- TUFI-HT, Ultra-TUFI on AETB Ceramic Tiles - *ARC*
- Higher Temperature Coatings for CMCs - *JSC, LaRC*
- Light-weight Ceramic Ablators - *ARC*
  - SIRCA, PICA, SPLIT

♦ Lower TPS Life Cycle Costs

- TPS Health Monitoring Techniques - *ARC, KSC, & Industry Partners*
  - Remote scanning with distributed passive sensors
- Organo-ceramic Materials - *ARC*
  - QUIC-Fix, QUIC-Stick, QUIC-TUFI
- Higher-Temperature Felts - *ARC*
- Integral Cryogenic Insulation / TPS - *ARC, MSFC*

Recent or Emerging Technologies, ctd.



A Synergistic, Multidisciplinary Approach, Combining National Arc-jet Facilities, Material Development Labs, and Analysis Capabilities

Extensive Industry Interaction, Collaboration and Technology Transfer

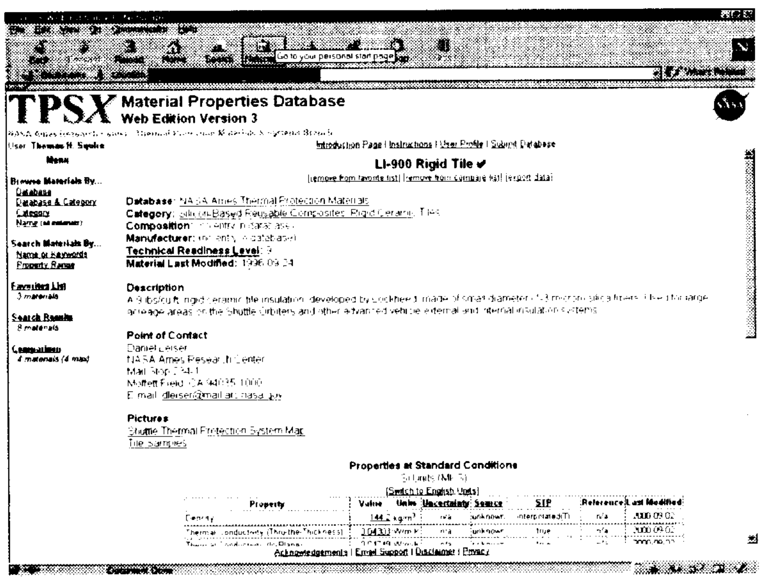
TPS Development Approach

- **Materials Development & Characterization Laboratories**
  - *ARC, GRC, JSC, LaRC*
  - Material Processing & Optimization
  - Material Structure Analysis
  - Thermo-mechanical Properties
  - Thermo-chemical Stability
  - Optical Properties
  - Heat Transfer Properties
- **Modeling** - *ARC, GRC, LaRC*
  - Vehicle Flow Environments, Aerodynamic & Aerothermal Predictions
  - TPS Material Response Analysis & Sizing
  - Ground Test Facility Flow Characterization for Optimal Testing
  - Test Model Design Optimization
  - Post-test Data Analysis & Interpretation

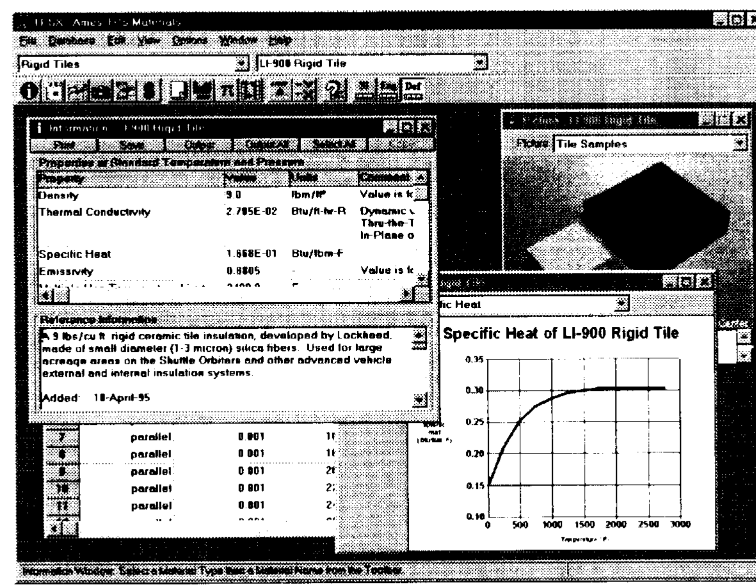
Material & Analytical Capabilities

http://tpsx.arc.nasa.gov

- TPS*X* is an engineering design tool that provides material property and performance data on a variety of thermal protection system materials.
- TPS*X* contains data on over 500 materials and allows users to search, display and output the information in several formats .
- TPS*X* is available as a downloadable Windows program and on the Web.
- TPS*X* has nearly 1000 registered users and the web site receives ~1200 hits per week.



TPS*X* Web Edition



TPS*X* Windows Program

Space Transportation Technology Workshop - Airframe Section

Thermal Protection Systems Expert & Material Property Database

- **Arc Jets**
  - ARC, JSC
- **Radiant Heating Facilities**
  - ARC, JSC
- **Wind Tunnels**
  - ARC, LaRC, MSFC
- **Aircraft-based Testbeds**
  - DFRC
- **Impact Durability Assessment**
  - ARC
- **Vibro-acoustic Facilities**
  - ARC, LaRC

Test Facilities

Stephen Scotti

s.j.scotti@larc.nasa.gov

757-864-5431

METALS AND THERMAL STRUCTURES BRANCH

NASA LANGLEY RESEARCH CENTER

HAMPTON, VA 23681

SPACE TRANSPORTATION TECHNOLOGY WORKSHOP

MARSHALL SPACE FLIGHT CENTER

OCTOBER 11-12, 2000

Airframe/TPS

AIRFRAME DESIGN AND INTEGRATION

- **Integrated Design Tools and Methods**
- **Integrated Airframe Trade Studies**
  NRA 8-21 Overview
- **Risk and Reliability Assessment**
  LaRC Points of Contact:

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Analytical and Computational Methods Branch, Structures and Materials
w.j.stroud@larc.nasa.gov
757-864-2928

Tom Zang
Multi-Disciplinary Design and Optimization Branch
t.a.zang@larc.nasa.gov
757-864-2307

Airframe/TPS

AIRFRAME DESIGN AND INTEGRATION: Major Areas

- Decompose operational, safety, and cost requirements into a comprehensive and consistent set of design criteria for different structural and material concepts for Reusable Launch Vehicles (RLVs)
- Develop compliance methods to ensure that different structural and material concepts are assessed at a consistent and adequate level of fidelity and safety
- Develop and assess weight reduction potential of integrated airframe concepts for RLVs, e.g. Thermal Protection System (TPS)/ TPS Support (TPSS)/ Cryogenic Tank (CT) System
- Compare performance and weight of various airframe structural and material concepts and structural arrangements and identify technology development needs
- Develop high fidelity parametric models that include airframe structural interactions and major design drivers

AIRFRAME INTEGRATION TRADE STUDIES
GENERAL OBJECTIVES

- Define vehicle requirements, definition, packaging
- Define airframe structural design requirements and develop compliance methods
- Define load conditions, loads, factors of safety, and materials
- Define integrated concepts
- Develop methods, perform analysis, and sizing
- Calculate system weights
- Assess concepts

Airframe/TPS

TRADE STUDIES: GENERAL APPROACH

RLV Requirements

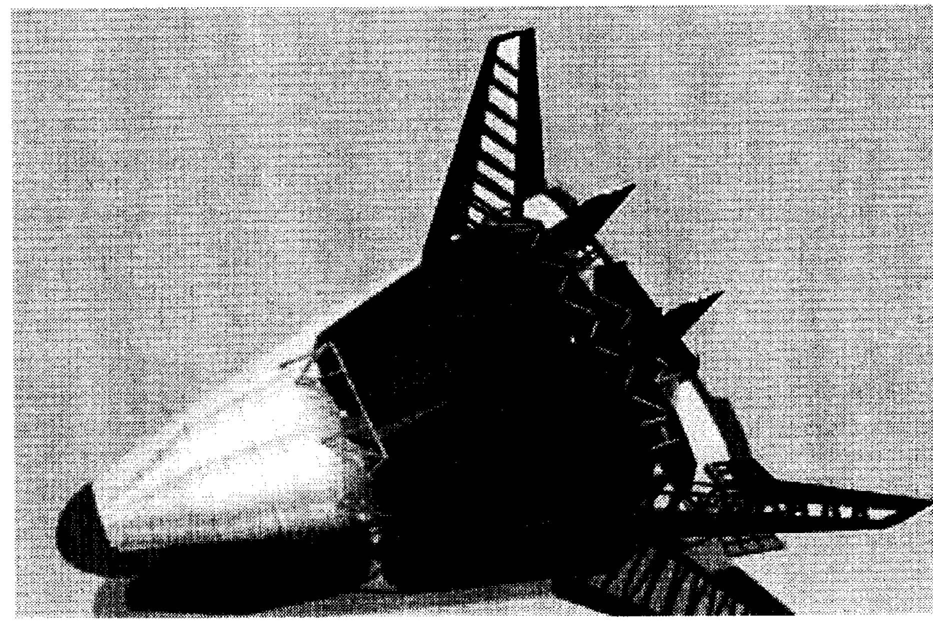
- Lightweight
- Fully reusable
- Easily maintained

Vehicle Definition

- Single Stage to Orbit (SSTO)
- Lifting body

Major Components

- Aerospike engines
- Engine Thrust Structure (integrates engines, fins, tanks, and main landing gear)
- Liquid Oxygen (LOX) Tank
- Liquid Hydrogen (LH2) Tanks
- Intertank
- Metallic Thermal Protection System and support structure



Airframe/TPS

SYSTEM DEFINITION

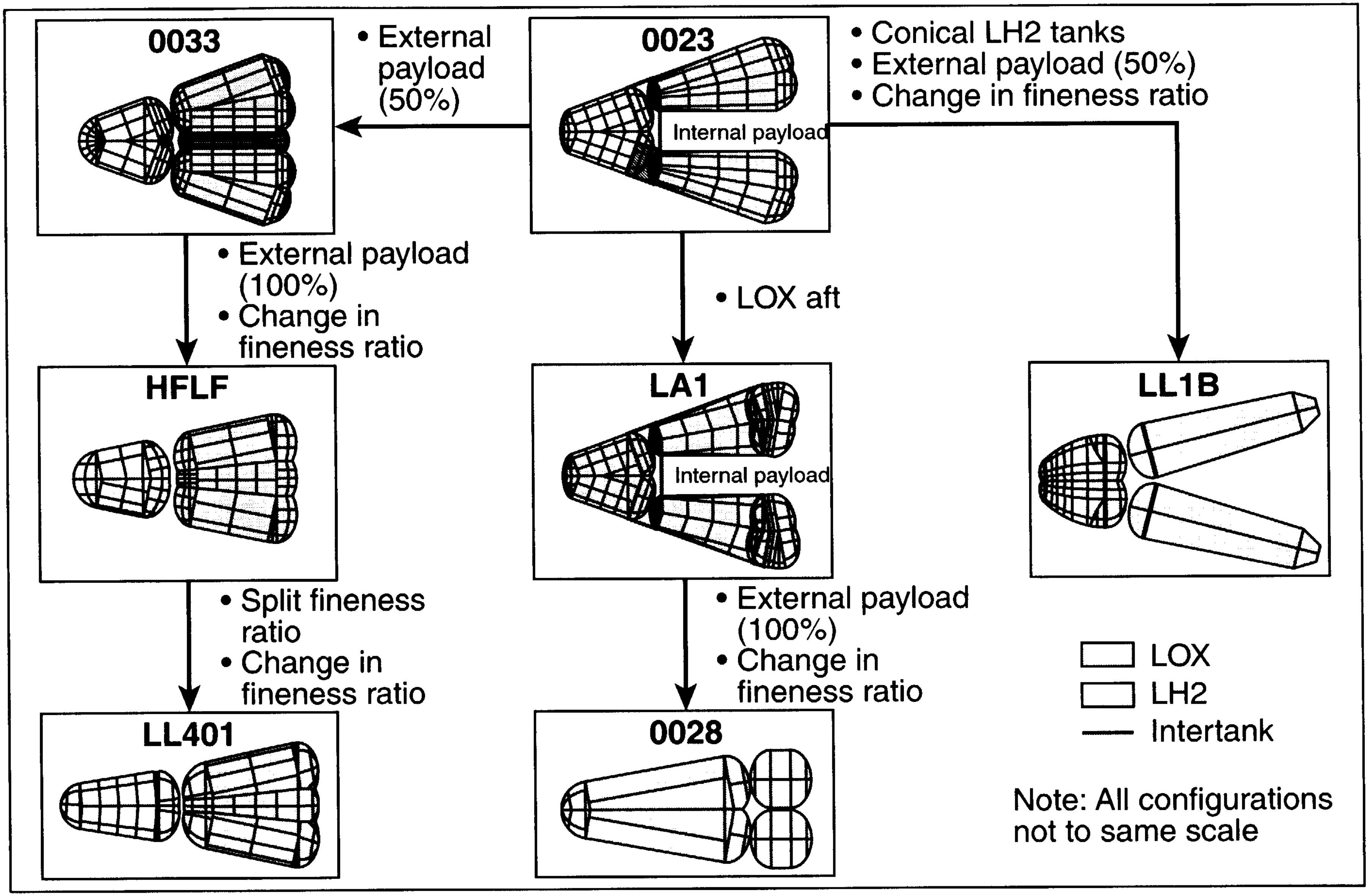
♦ **John T. Dorsey**	Airframe Integration & Concepts, Vehicle Loads, Weights (Study Lead, NRA 8-21)
♦ **Max Blosser**	TPS Concepts (TPS Team Lead)
♦ **Carl Poteet**	TPS Thermal Analysis and Sizing, TPS Concepts
♦ **Roger Chen**	TPS Panel Acoustic, Fatigue, Creep Analysis & Sizing
♦ **Irv Schmidt**	TPS Panel and Tank Stiffening Design
♦ **John Wang**	Semi-Conformal & Lobed Tank Analysis and Sizing
♦ **Su-Yuen Hsu**	TPS Panel Structural Analysis and Sizing
♦ **Lynn Bowman**	Non-Optimum and Vehicle Weights
♦ Jeff Cerro	Material Properties, Vehicle Loads
♦ Nani Balakrishnan	TPS Panel Structural Analysis and Sizing
♦ David Myers	Packaging, Weights, & TPS
♦ **Kevin Rivers**	2nd Gen RLV Airframe Integration and Trades Lead
♦ **Kim Bey**	Aerothermal Loads, Thermal Analysis, TPS Sizing

Airframe/TPS

TRADE STUDY TEAM

- Tank Packaging and Geometry
  - Packaging configurations
  - Lobed versus conformal tanks
  - Minimize Distance between Outer Mold Line (OML) and Tank
- Component Trade Studies
  - Tanks
  - TPS and support structure
- Integrated TPS, TPS support, and tanks
  - Applicable to several architectures
  - In progress

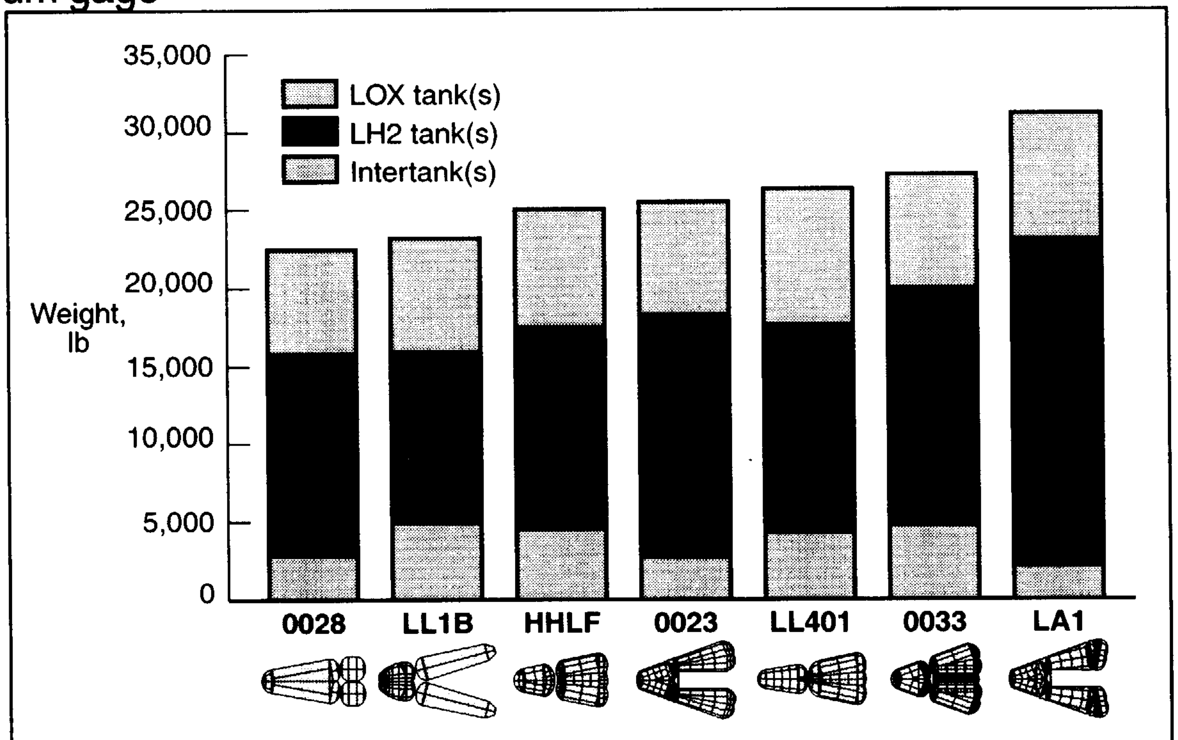
TRADE STUDIES FOR NRA 8-21: MAJOR CATEGORIES



Airframe/TPS

PACKAGING CONFIGURATIONS

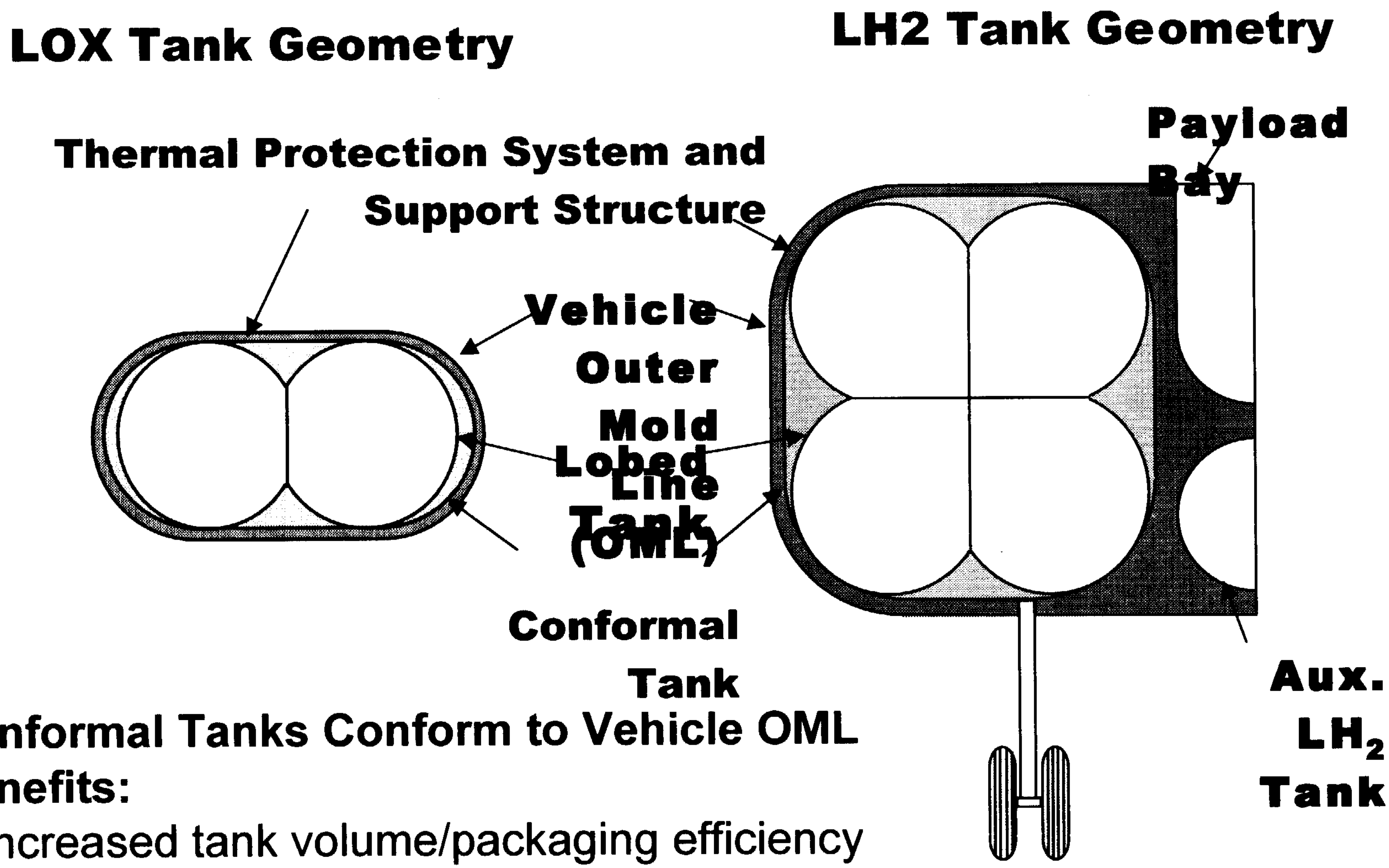
- **Material Specifications**
  - Quasi-isotropic PMC laminates
  - Limit strain 6000 µin./in.
  - Minimum gage
- **Load Cases**
  - Launch (1.355 g's)
  - Max acceleration (3 g's)



- **Interactions:**
  - LOX-aft: reduced LH2 ullage pressure for tank stabilization changes engine operating requirements
  - External payload and aerodynamics

Airframe/TPS

CONFIGURATION SIZING



Conformal Tanks Conform to Vehicle OML

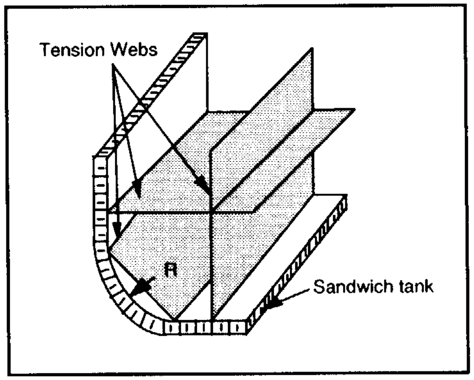
Benefits:

- Increased tank volume/packaging efficiency
- Reduced TPS support structure
- Improved thrust load paths

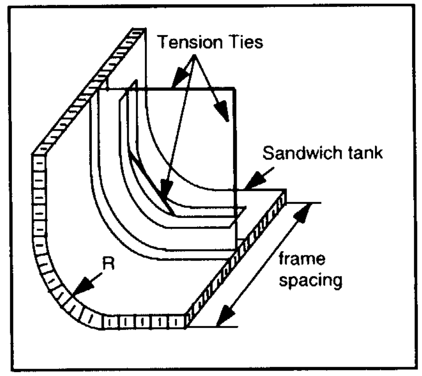
Airframe/TPS

TANK GEOMETRY TRADE STUDIES

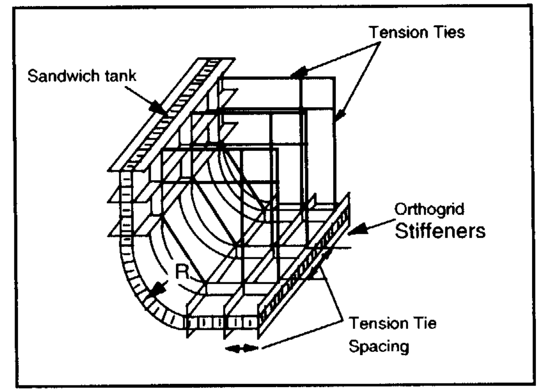
Axial Tension Webs



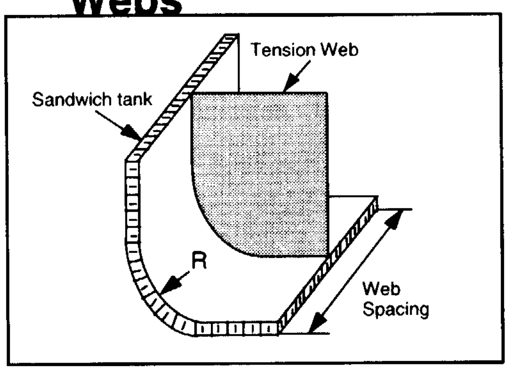
Frames & Ties



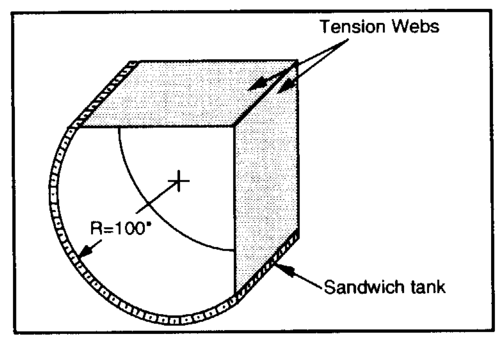
Orthogrid & Ties



Transverse Webs



Quad-lobe & Webs

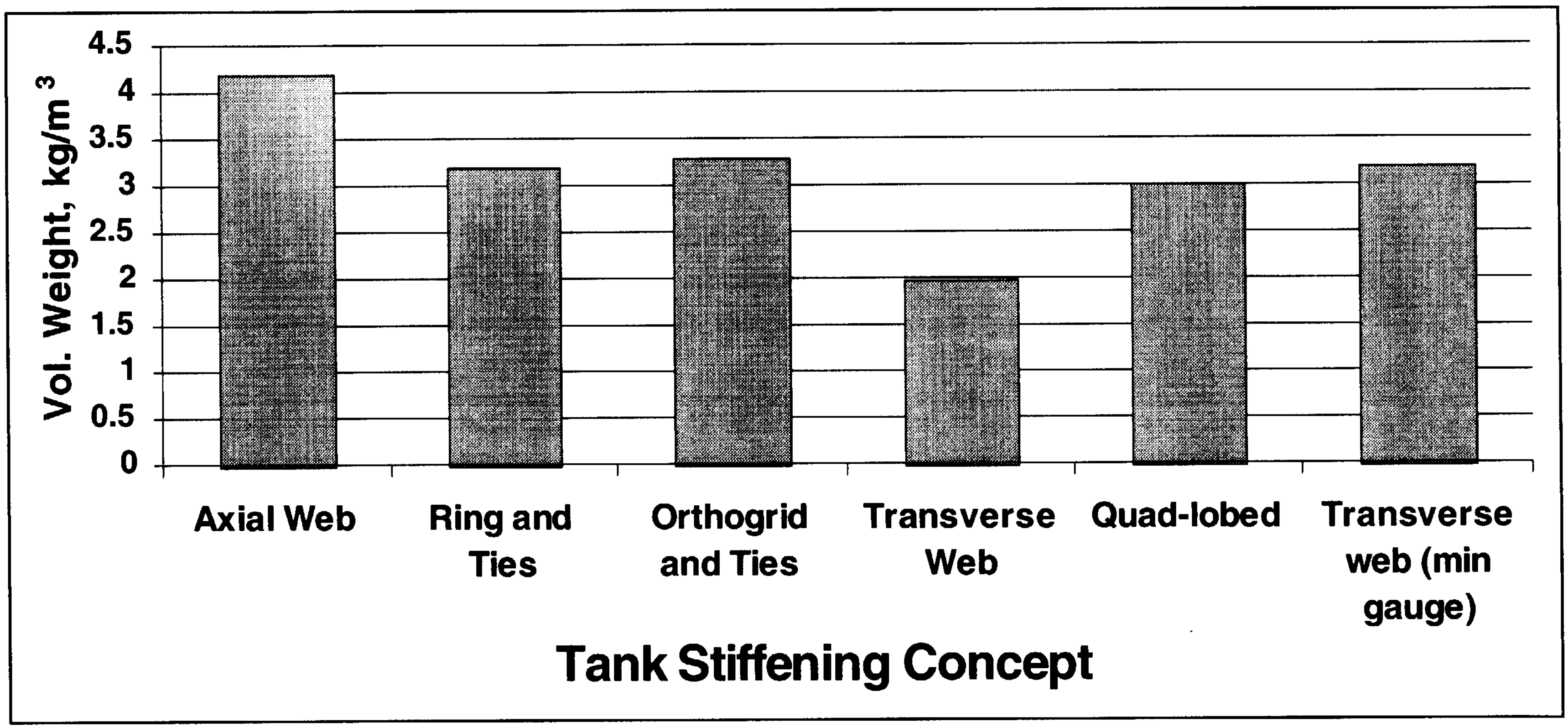


Airframe/TPS

TANK STIFFENING CONCEPTS CONSIDERED

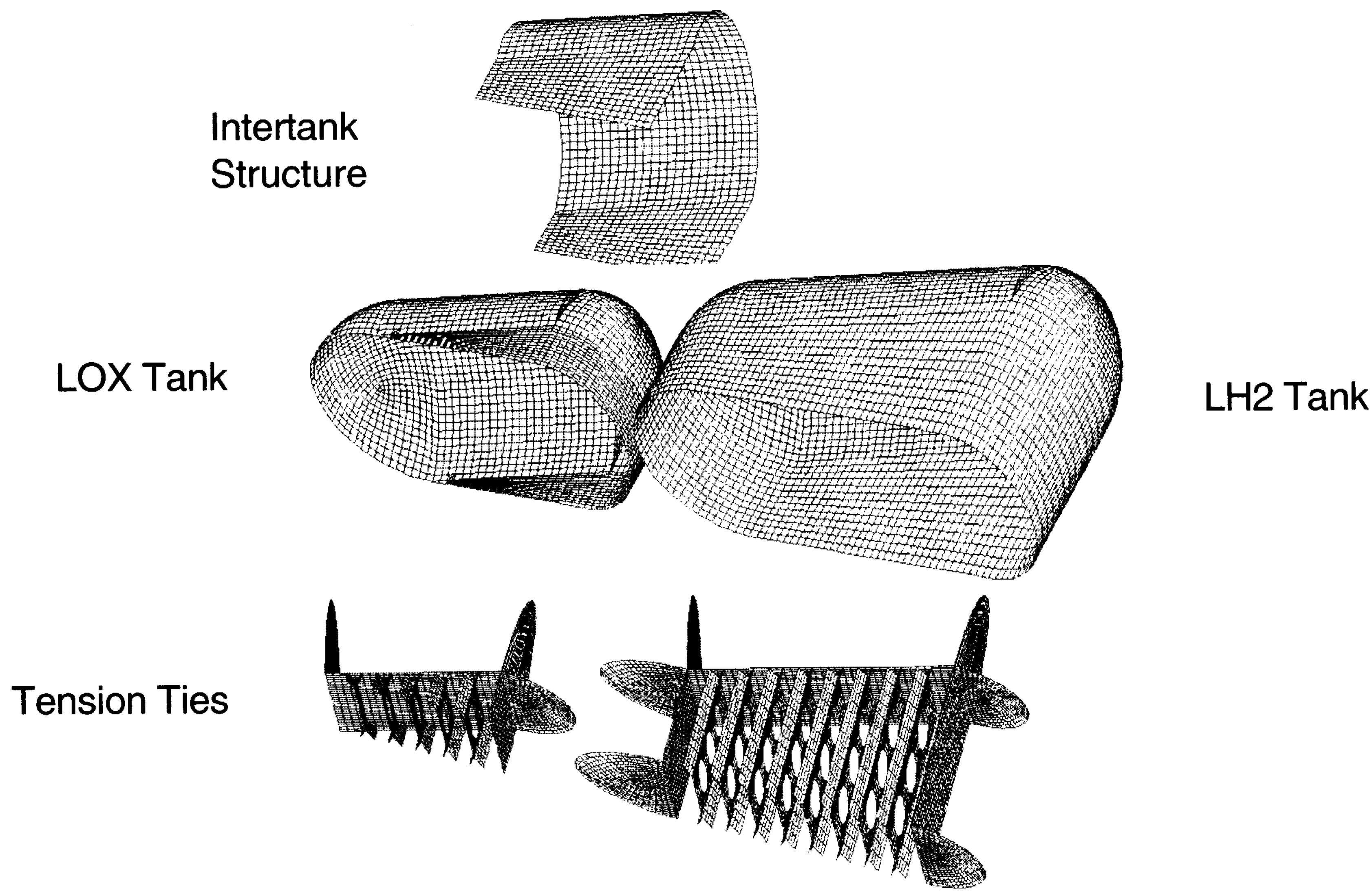
Corner radius = 0.635 m
Pressure = 137.9 KPa

No manufacturing min. gauge



Airframe/TPS

TANK STIFFENING WEIGHTS COMPARISON

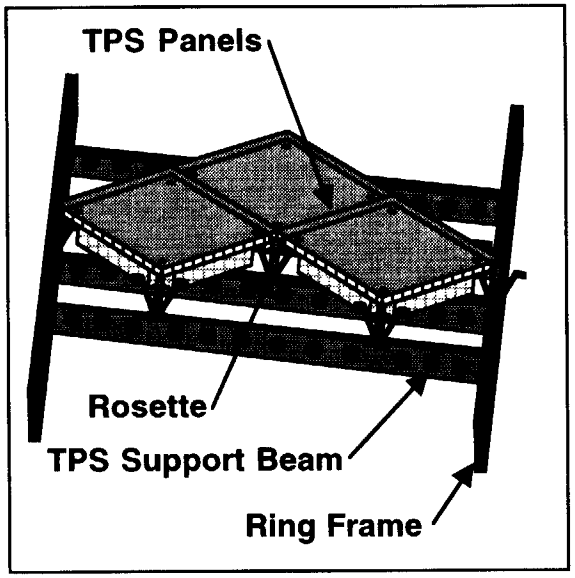


Airframe/TPS

SEMI-CONFORMAL SANDWICH TANK SYSTEM: FEM FOR SIZING (In Progress)

Metallic TPS Concepts for Windward Aeroshell Surfaces

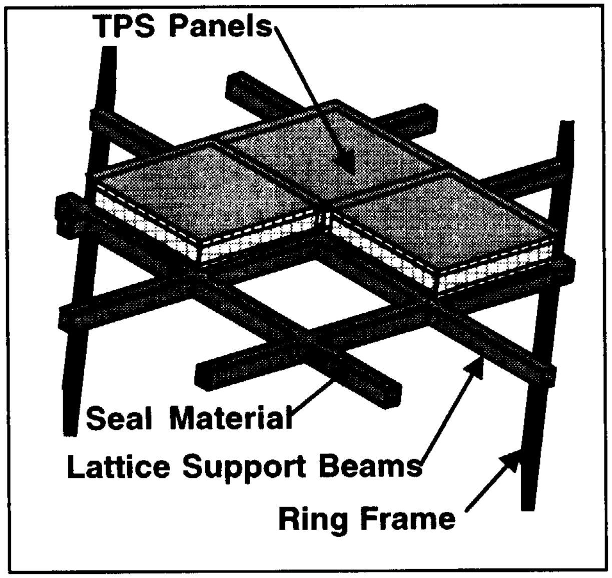
Rohr X-33 Concept (baseline)



- Thermal stresses minimized
- Light weight system
- Simplified manufacturing

- Seals on hot surface
- Hot surfaces carry aero pressures
- Panel damage/loss potentially catastrophic

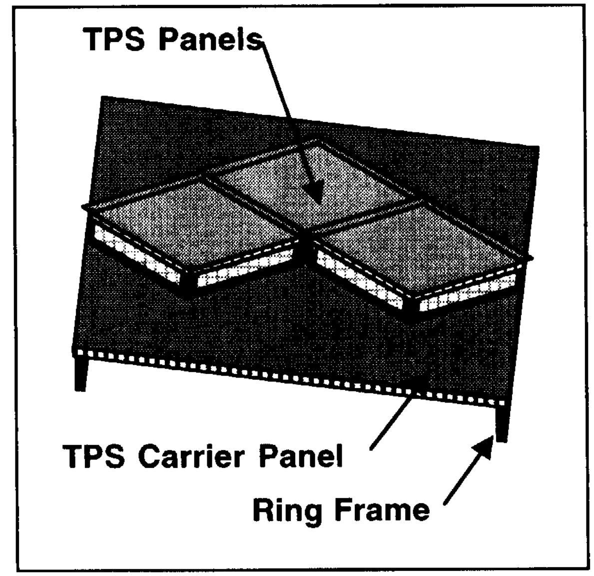
LaRC-Type TPS Panels with Lattice Seal & Support Frames



- Seals and pressure bearing surface moved to cooler region
- Tolerant to outer surface damage

- More complex support structure
- More costly TPS panel
- Panel loss potentially catastrophic

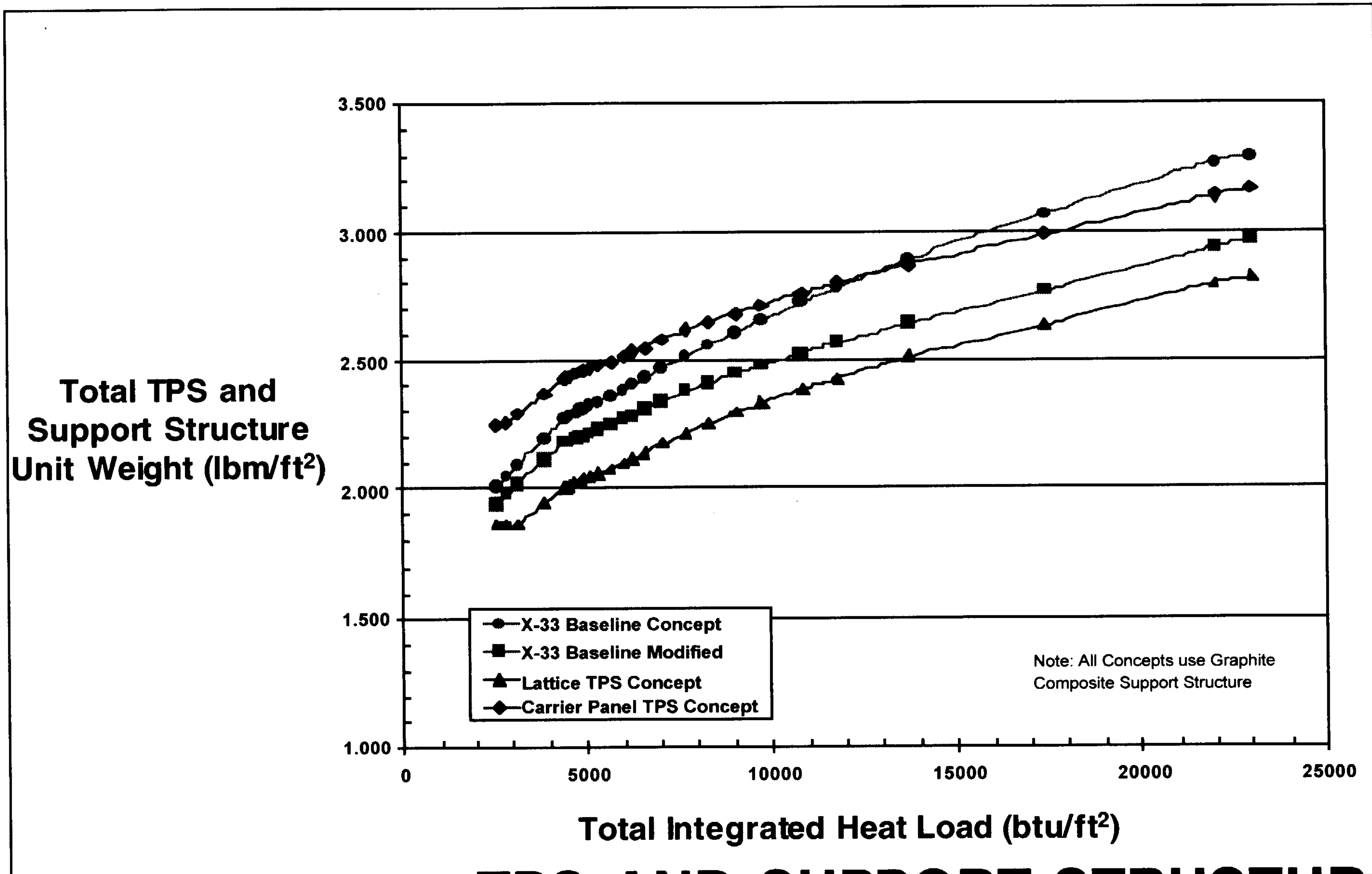
LaRC-Type TPS Panels Mounted to Carrier Plates



- Carrier panel increases TPS options
- Improved damage tolerance
- Reduces number of seals
- Pressure carried on large, cool panel

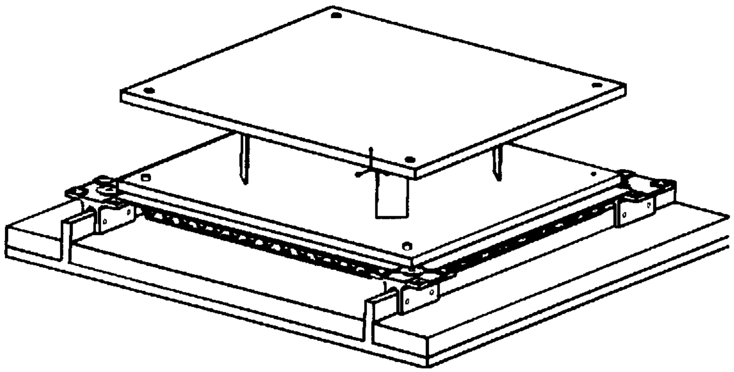
- Heavier than other concepts
- Complicates removal for inspection
- Potential thermal stress issues

TPS TRADE STUDY CONCEPTS

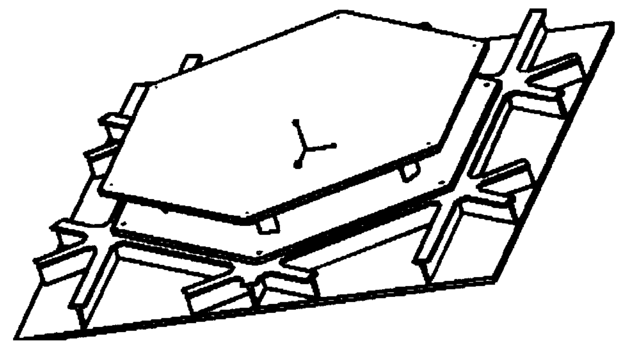


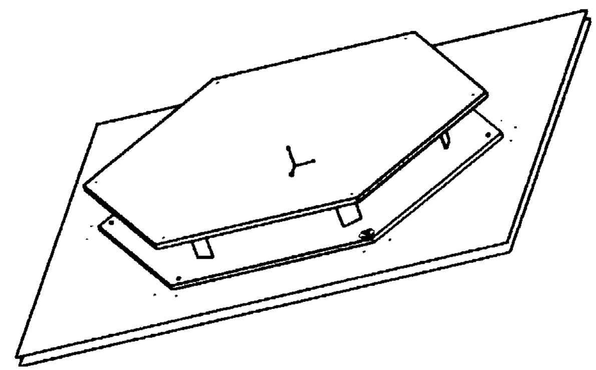
TPS AND SUPPORT STRUCTURE WEIGHTS

REPRESENTATIVE STRUCTURAL CONCEPTS



FEATURES
- Metallic TPS
- TPS Support Structure
- Purge Gap
- Cryogenic Foam
- Sandwich or Stiffened Skin Tank Wall





FEATURES
- Metallic TPS
- Direct Attach TPS
- Cryogenic Foam
- Sandwich, Stiffened Skin, or Integrally-Stiffened Tank Wall

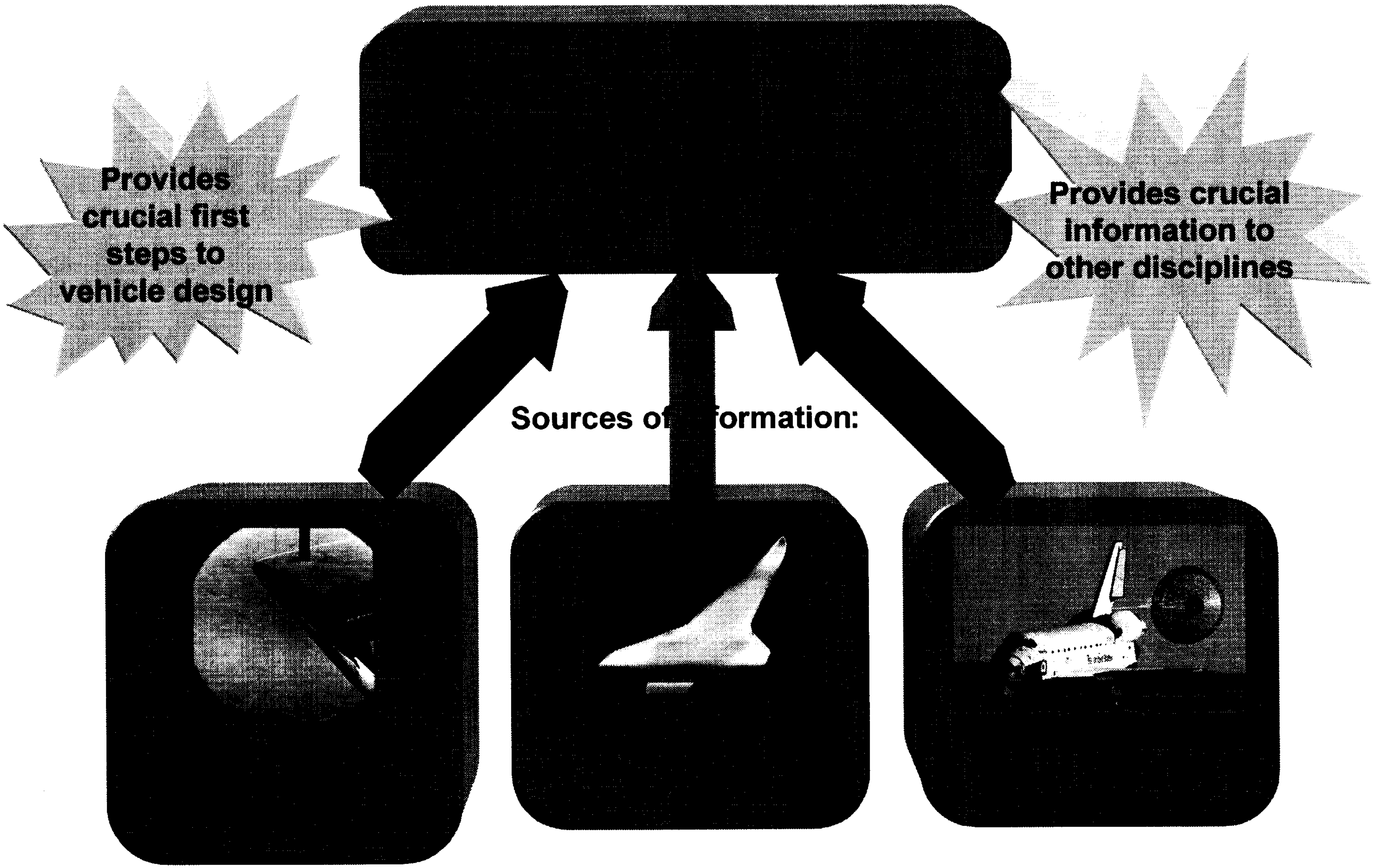
- Hierarchy of sizing methods are needed to support trade studies and concept assessment. Even low fidelity sizing must capture effect of major design drivers (e.g. geometry, size, load, ...)

- Major deficiencies exist in the types of material data needed to optimize integrated airframe (TPS/TPS Support/Tank systems) for both metallic and polymeric composite systems

- Critical interactions exist within airframe systems, and between airframe and vehicle systems. New analytical formulations and/or tools are needed to take advantage of those interactions which significantly improve or enable vehicle/system viability.

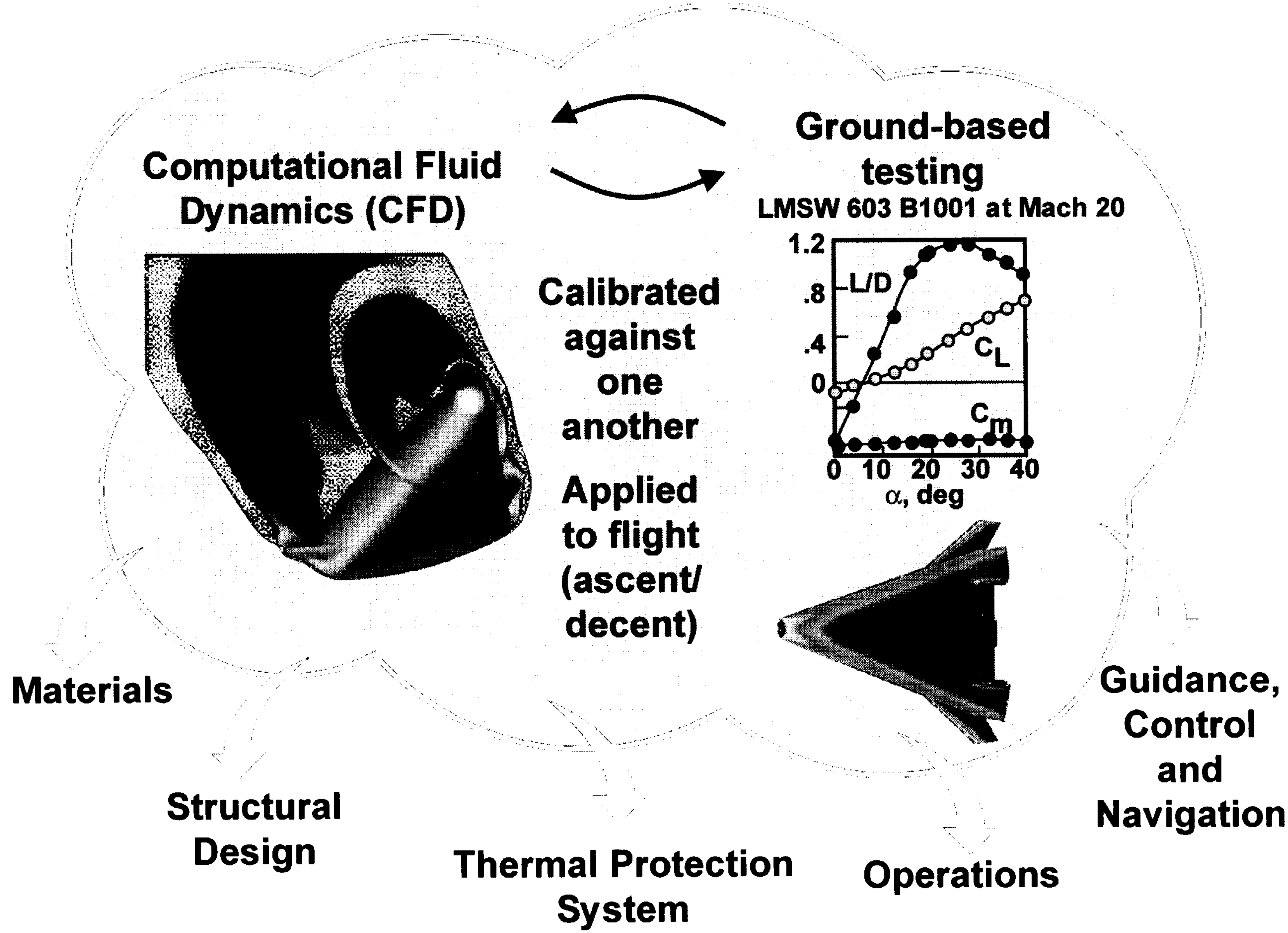
Airframe/TPS

CONCLUDING REMARKS



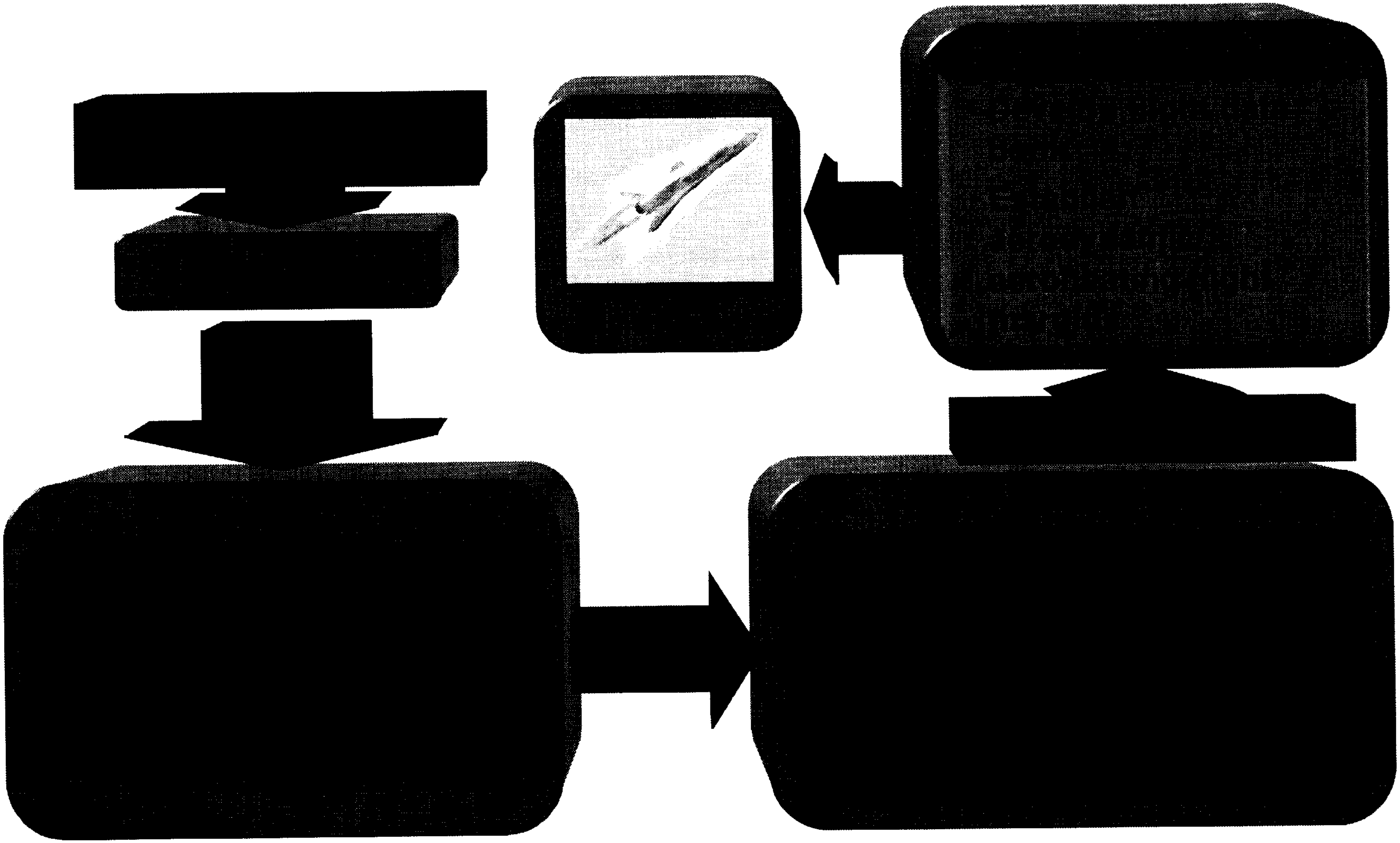
Airframe/TPS - Aerothermodynamics

Aerothermodynamics



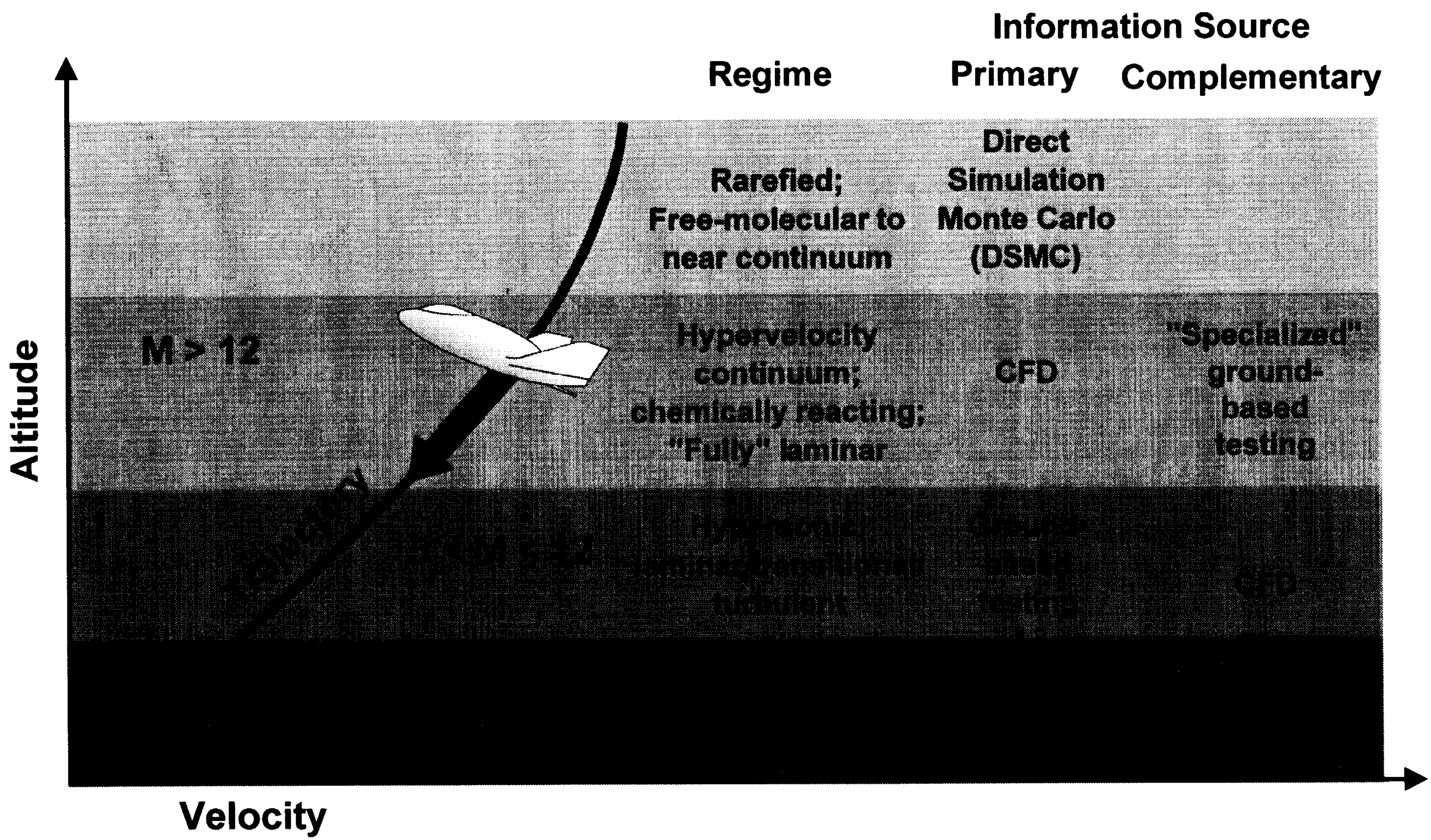
Airframe/TPS - Aerothermodynamics

Aerothermodynamics Provides Critical - Path Information



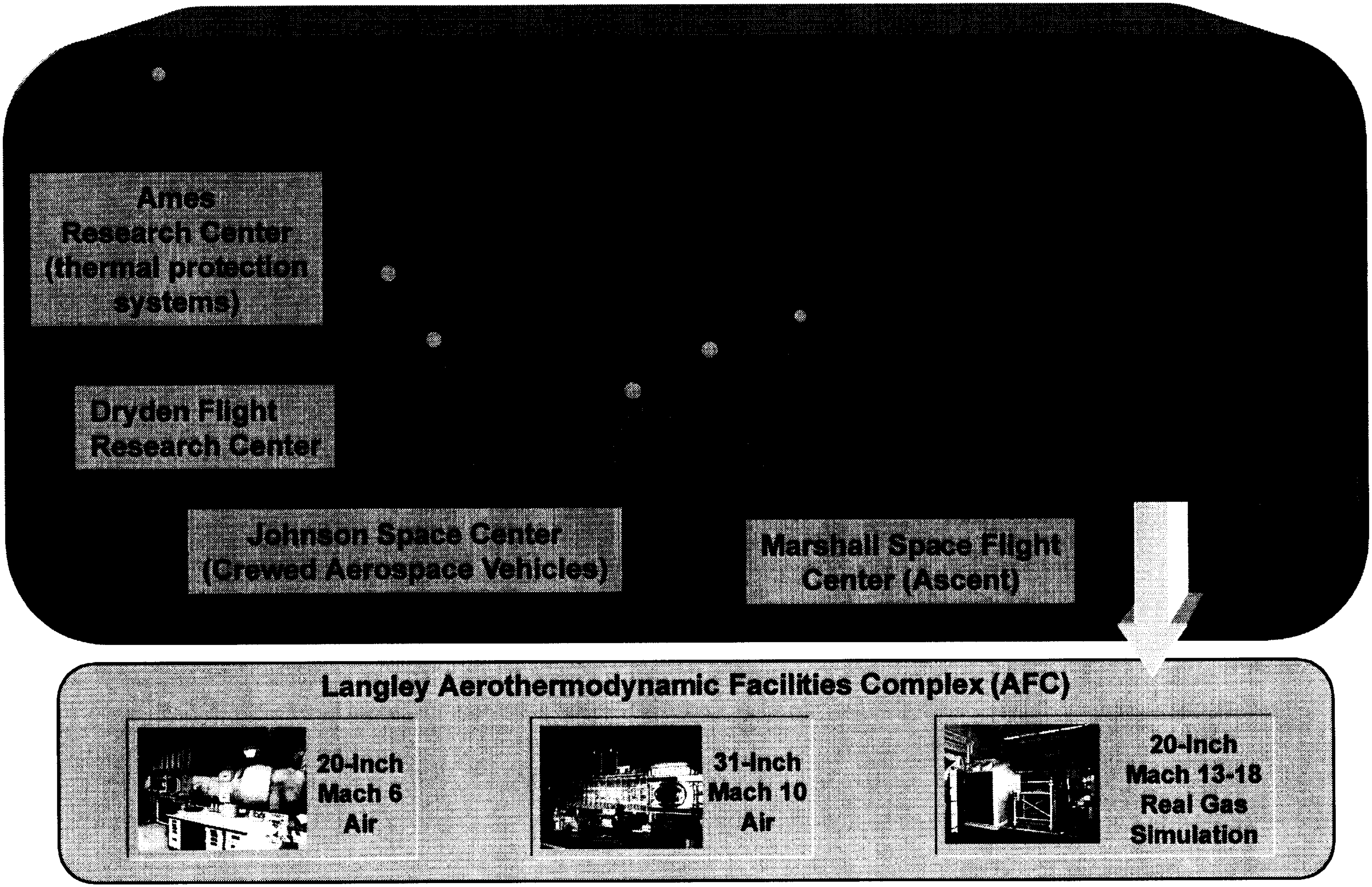
Airframe/TPS - Aerothermodynamics

Aerothermodynamic Process

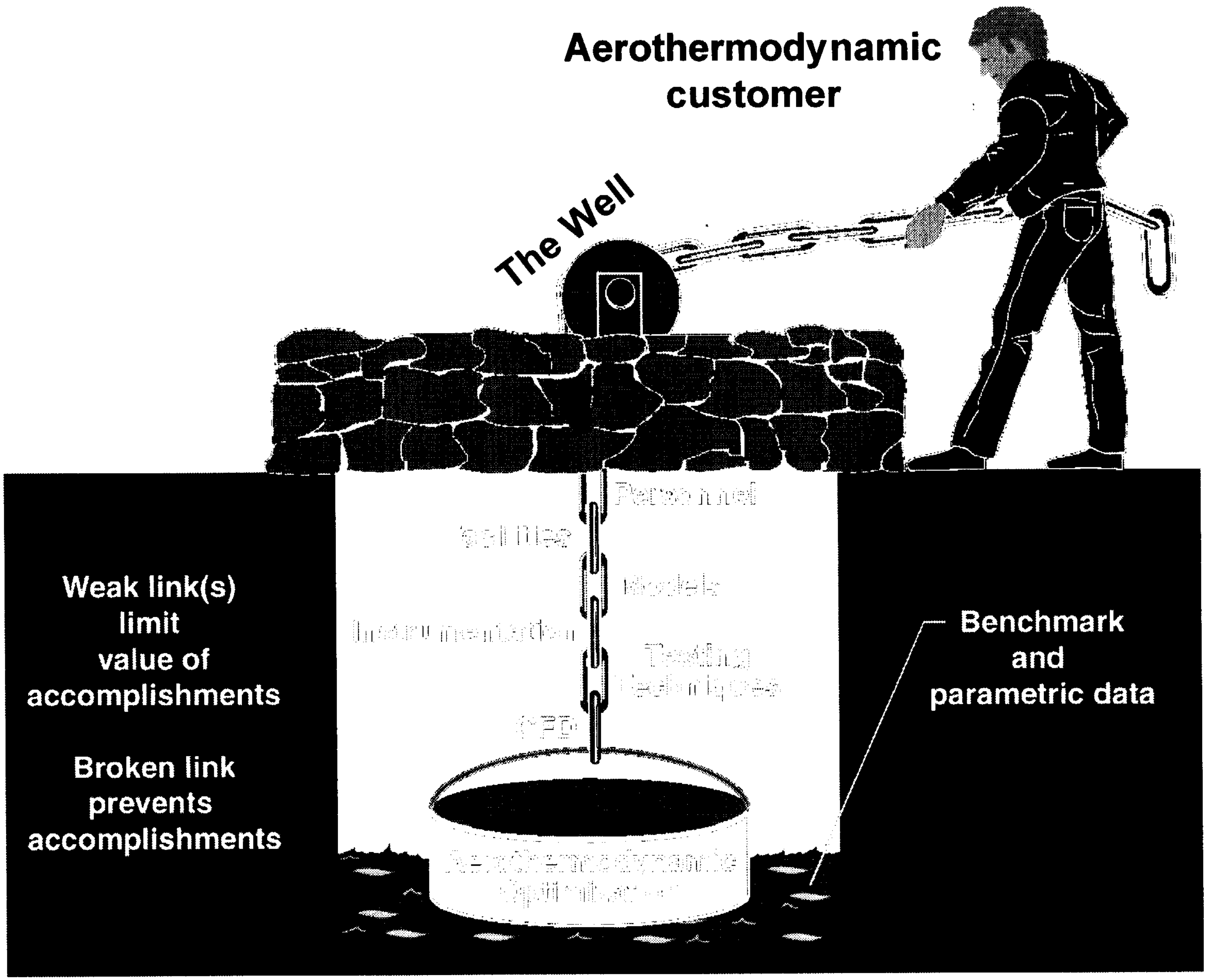


Airframe/TPS - Aerothermodynamics

Aerothermodynamic Methodology

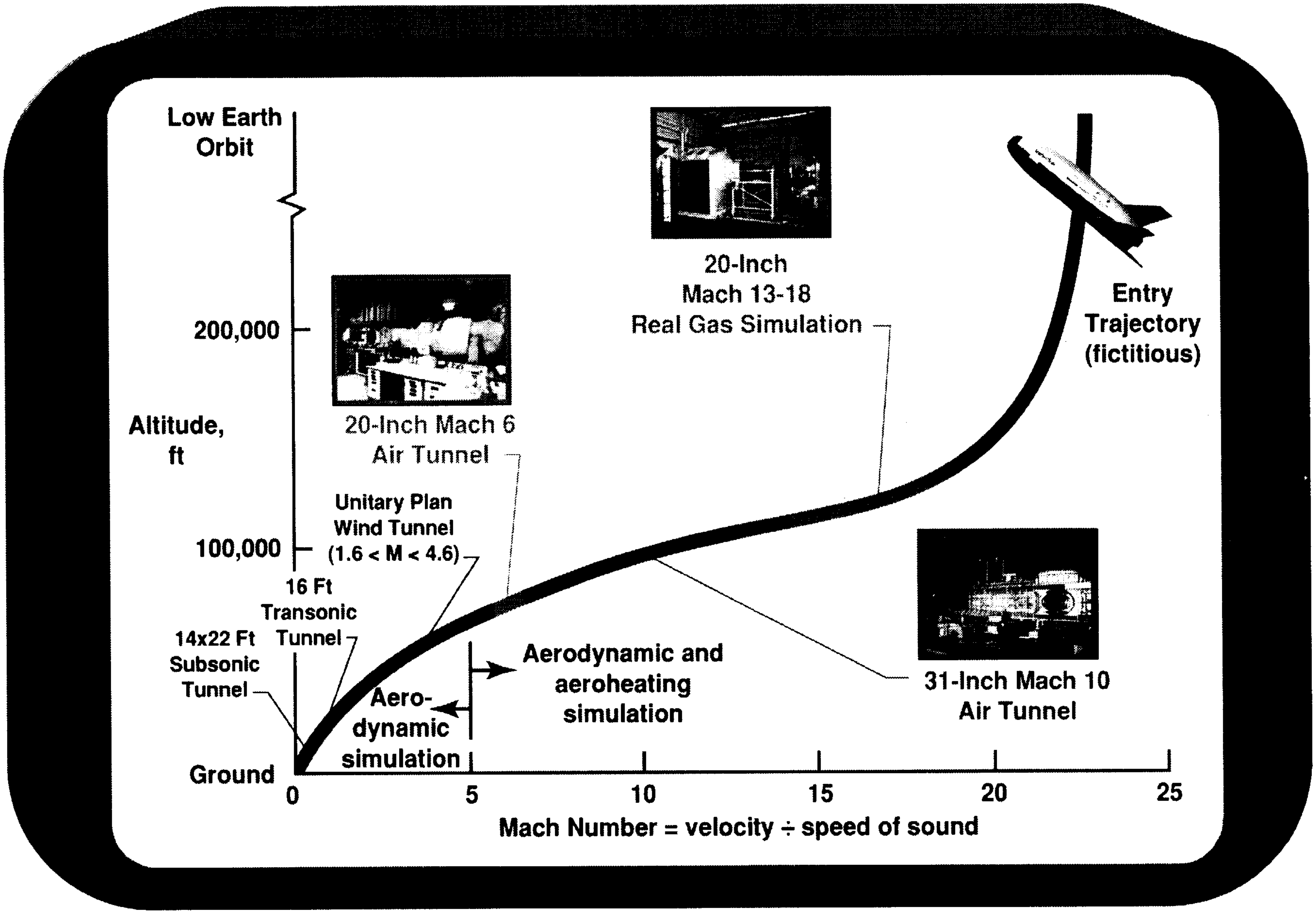


LaRC is NASA Lead For Aerothermodynamics



Airframe/TPS - Aerothermodynamics

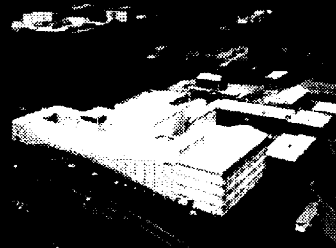
Aerothermodynamic "Chain"



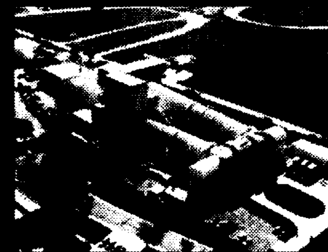
Airframe/TPS - Aerothermodynamics

Aerothermodynamic Flight Simulation Capability

Low Turbulence Pressure Tunnel

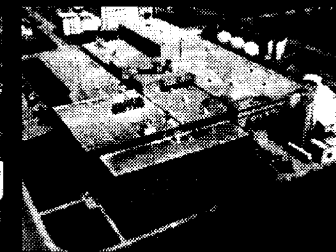


14-by 22-Foot Subsonic Tunnel

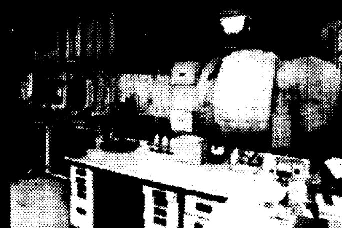


16-Foot Transonic Tunnel

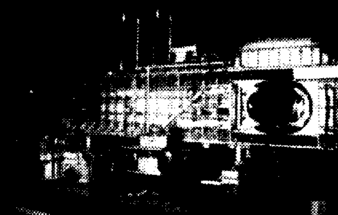
National Transonic Facility



Unitary Plan Wind Tunnel



20-Inch Mach 6 Air Tunnel

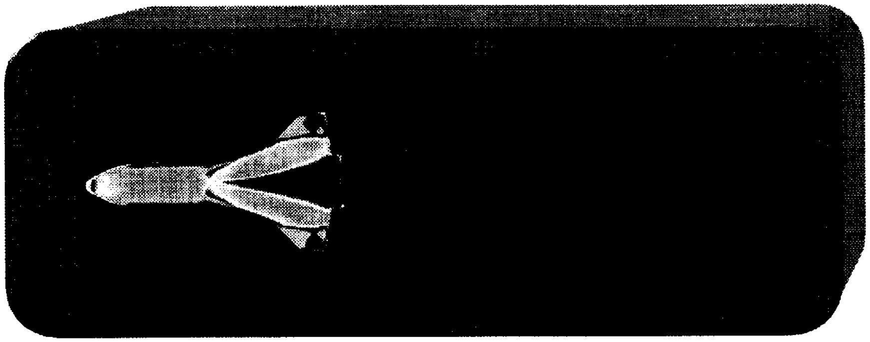


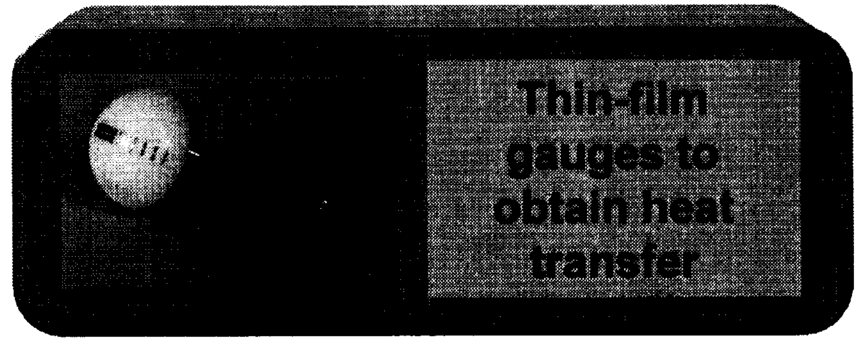
31-Inch Mach 10 Air Tunnel

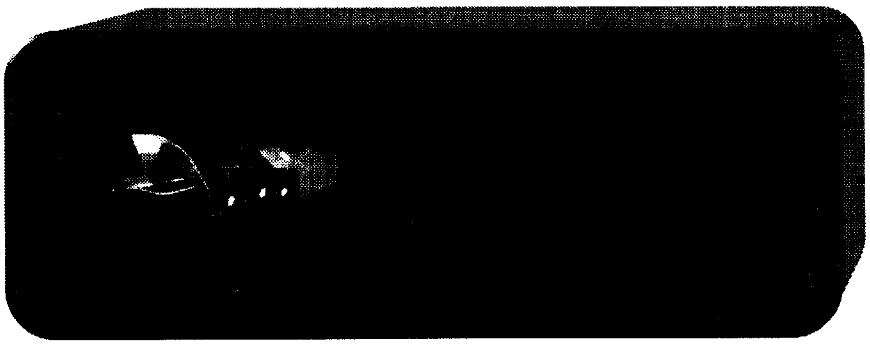
20-Inch Mach 6 CF_4 Tunnel (Mach 13-18 Real Gas Simulation)

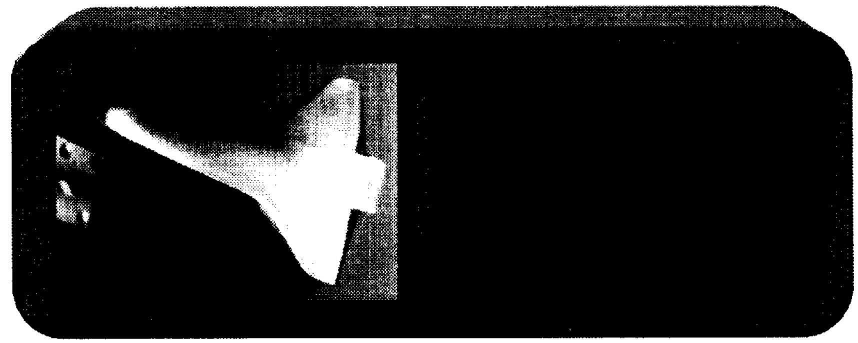
Airframe/TPS - Aerothermodynamics

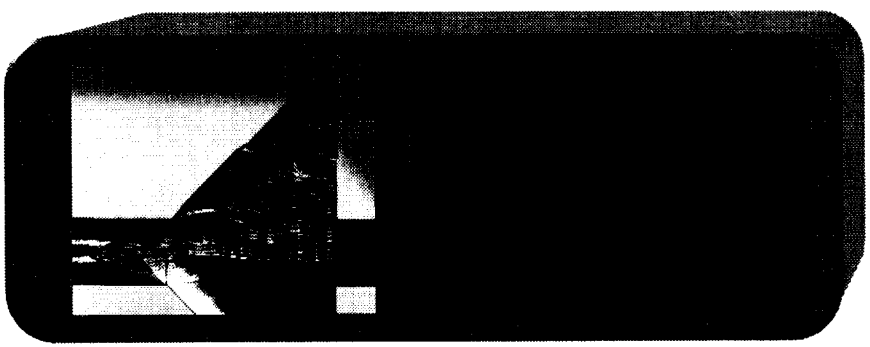
LaRC Subsonic-to-Hypersonic Wind Tunnels

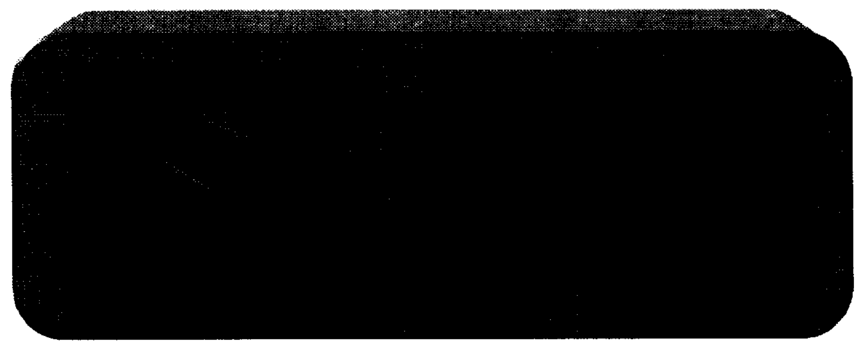












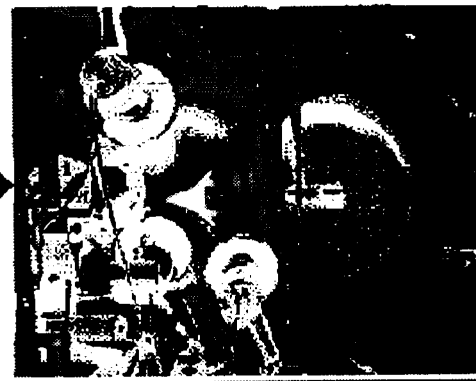
Airframe/TPS - Aerothermodynamics

Testing Techniques

Vehicle Concept

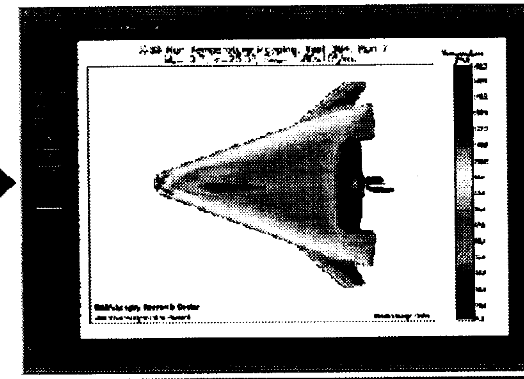
Model Fabrication

- Casting of ceramic models
- Rapid turnaround
- Complex shapes



Wind Tunnel Testing

- Two-color fluorescence
- State-of-art computerized acquisition system



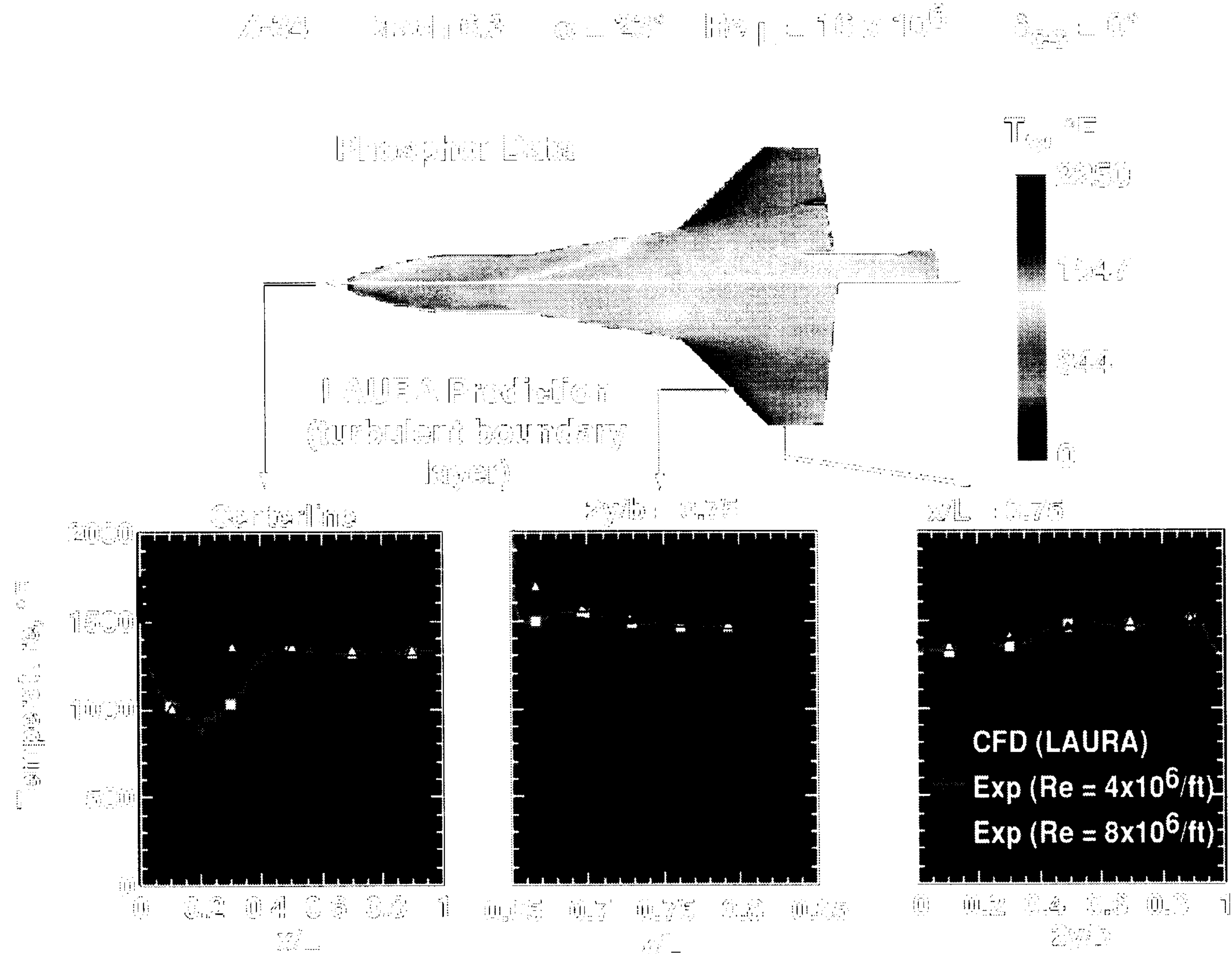
Analysis of Measurements

- Nonlinear theory to infer accurate temperatures
- User-friendly computer program (IHEAT)

Aeroheating data to customers

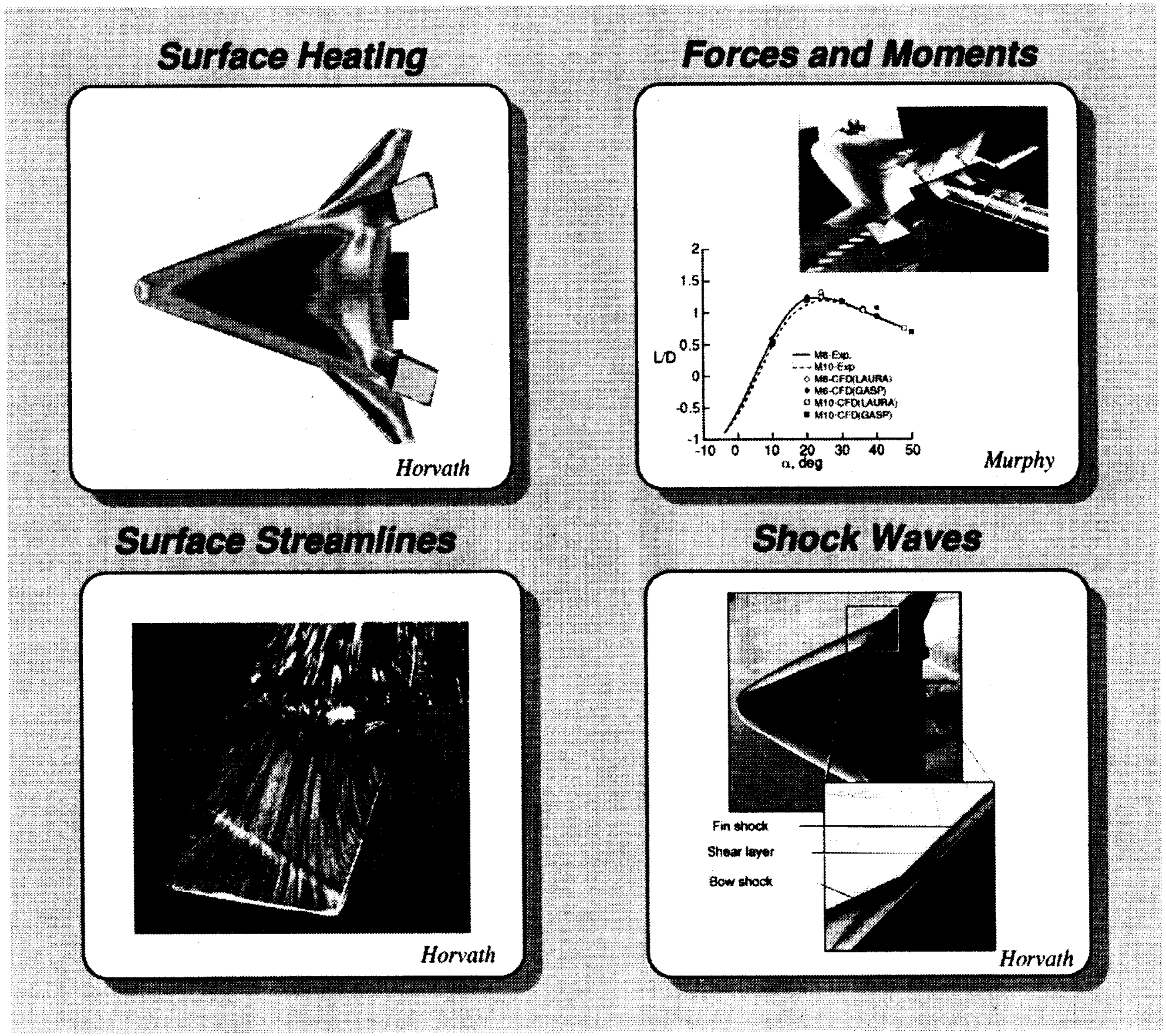
Airframe/TPS - Aerothermodynamics

Phosphor Thermography Process



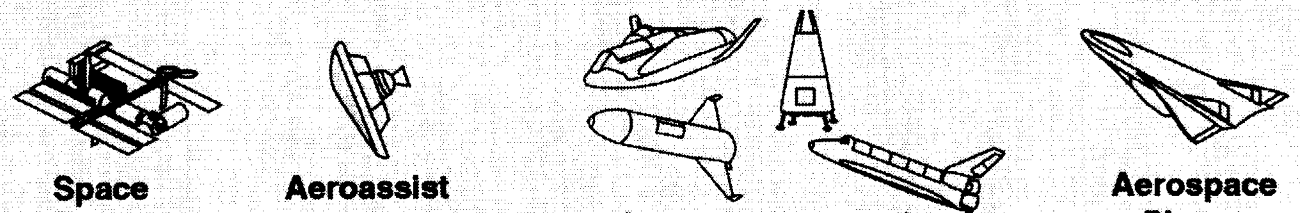
Airframe/TPS - Aerothermodynamics

Extrapolation of Measurements to Flight



Airframe/TPS - Aerothermodynamics

Complementary Measurements: X-33



Space Station | Aeroassist Orbital Transfer | Space Transportation | Aerospace Planes

Free Molecular Flow | Transitional Flow | Continuum Flow

LaRC Workhorse Codes for X-33/X-34/X-37

[illegible]

[illegible]

[illegible]

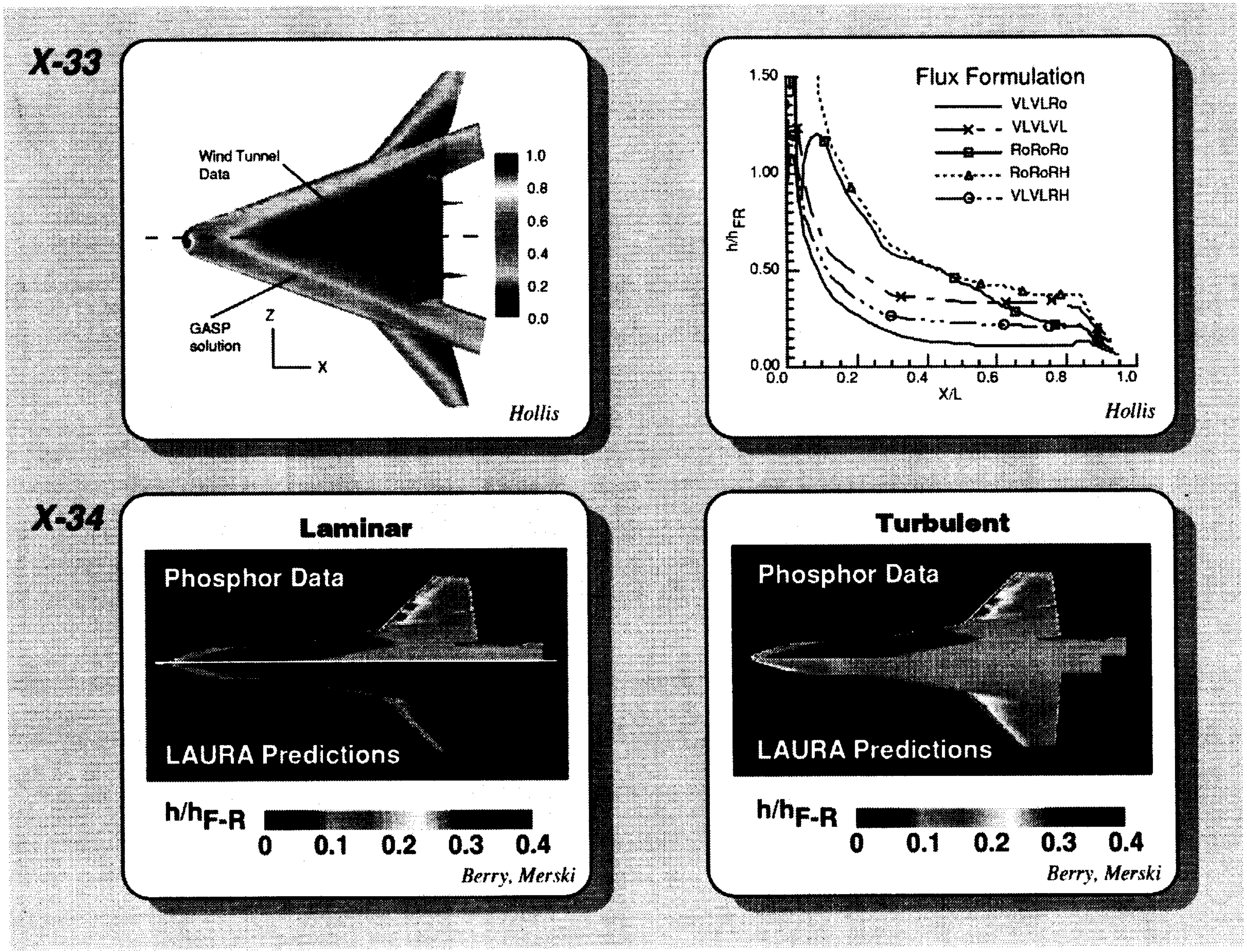
- Navier Stokes*
- Viscous Shock Layer
- Inviscid/Boundary Layer
- Direct Simulation Monte Carlo

DSMC Analysis Code (DAC); 3D capability developed by Jay LeBeau (JSC) and Dr. Richard Wilmoth; physical modeling per Dr. Graeme Bird, Univ. of Sydney

* Also, GASP, registered trademark of AeroSoft, Inc.

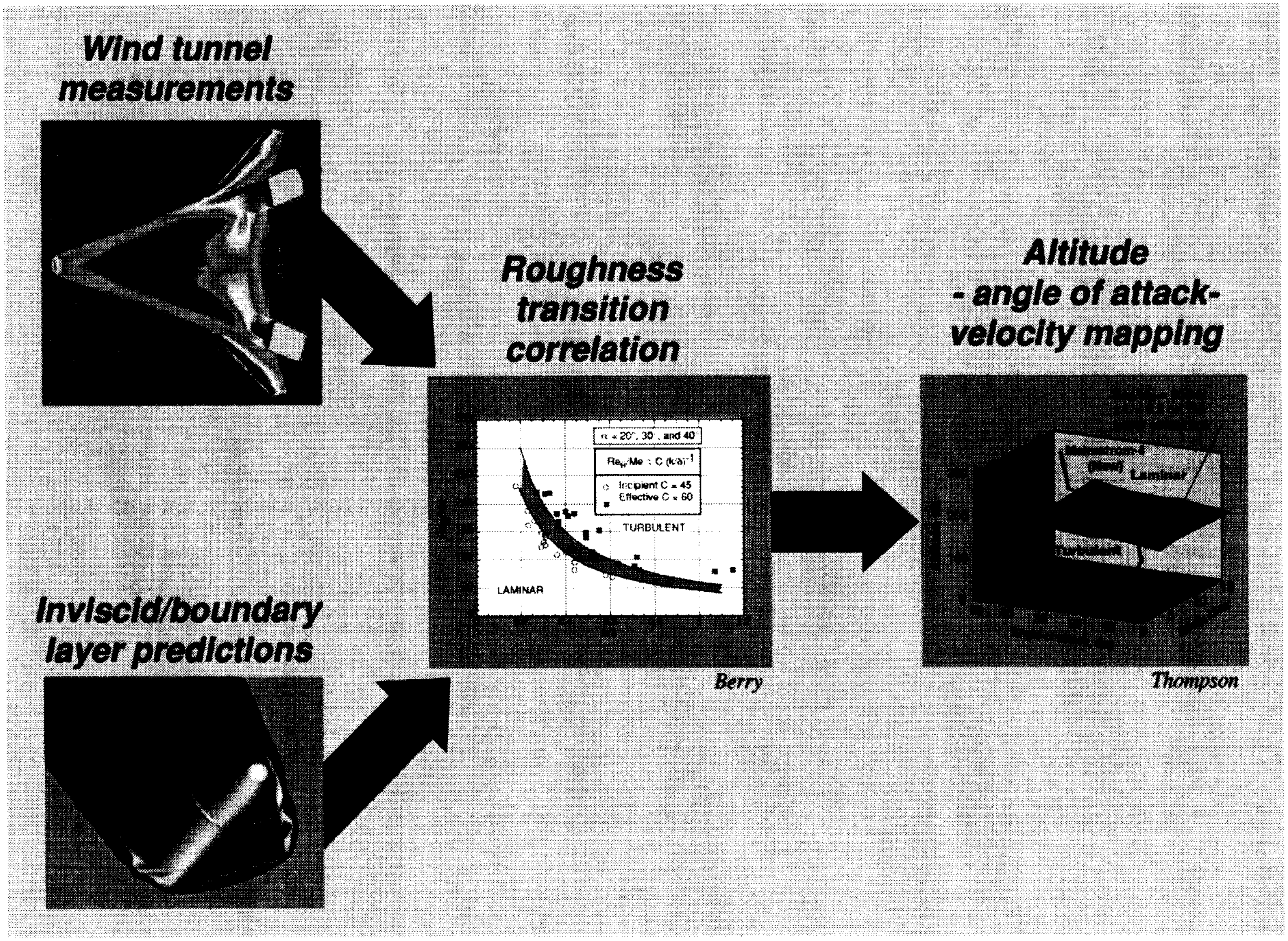
Airframe/TPS - Aerothermodynamics

Computational Fluid Dynamics (CFD)



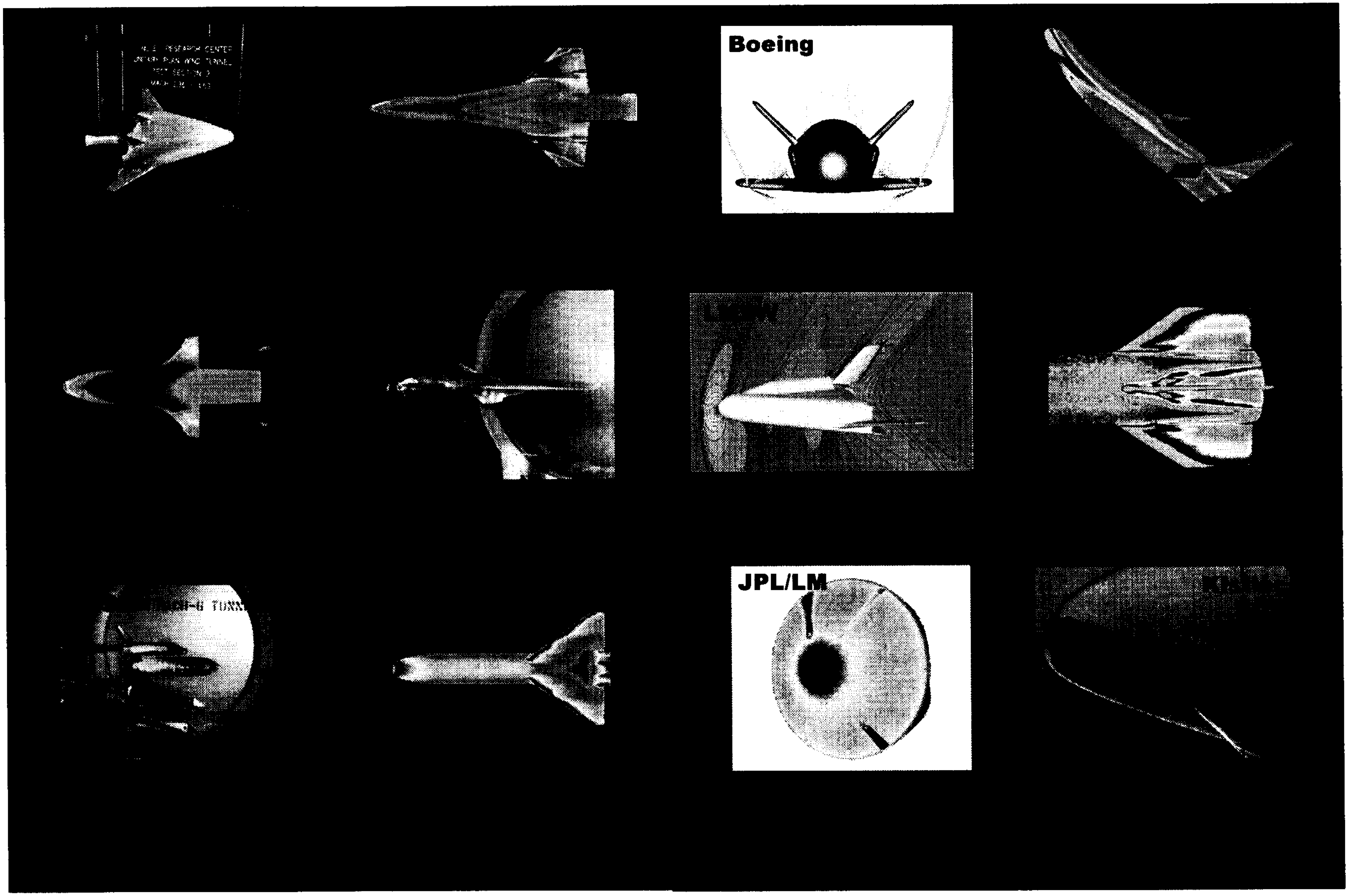
Airframe/TPS - Aerothermodynamics

Computational - Experimental Synergism



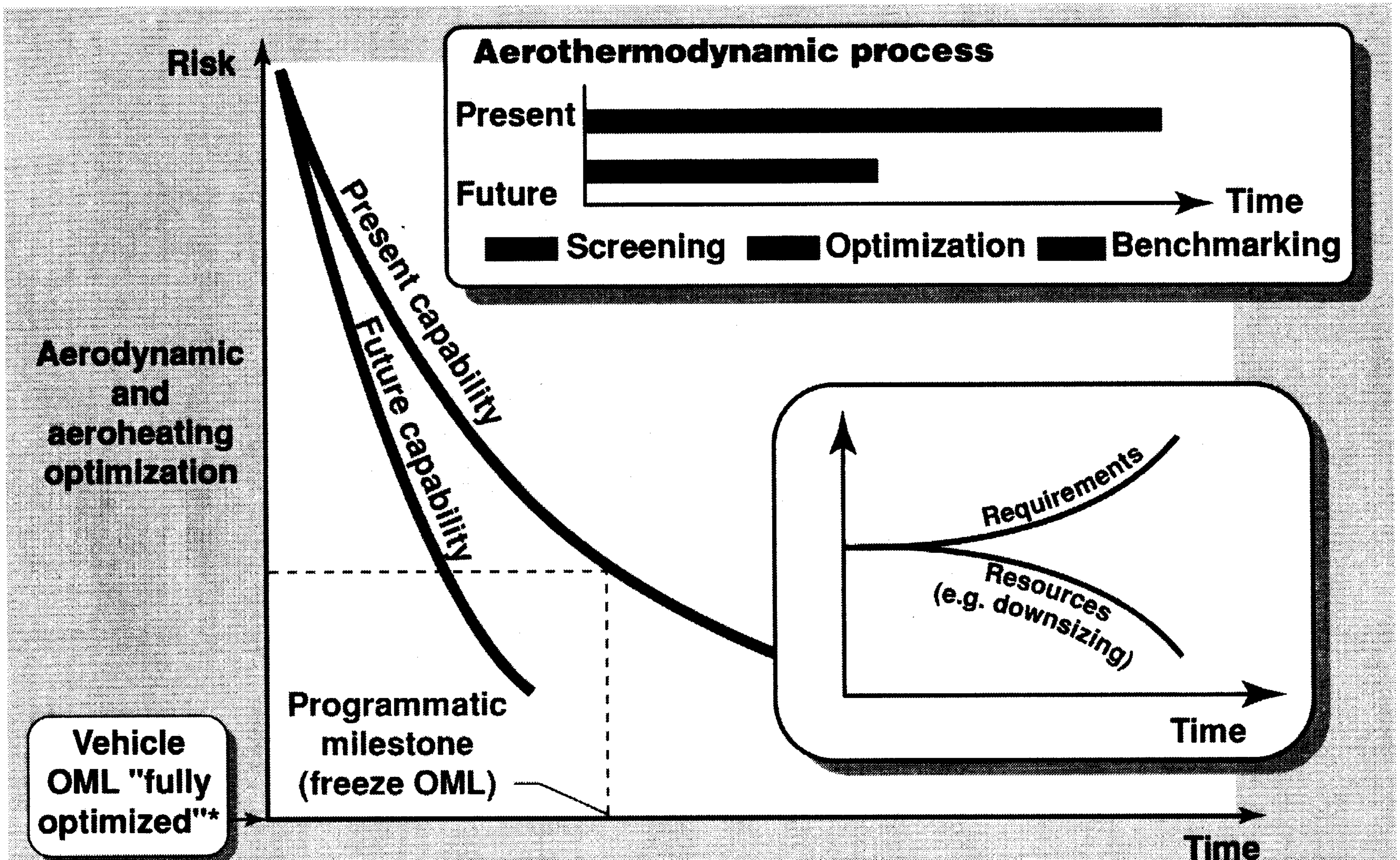
Airframe/TPS - Aerothermodynamics

X-33 Boundary Layer Transition Methodology



Airframe/TPS - Aerothermodynamics

Recent LaRC Aerothermodynamic Contributions



* "Fully optimized" corresponds to maximum aerodynamic performance across subsonic-to-hypersonic speed regime and minimum aeroheating

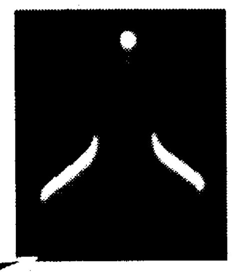
Airframe/TPS - Aerothermodynamics

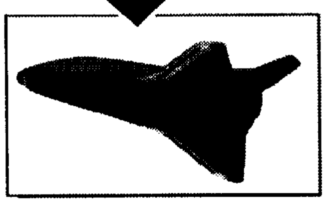
Aerospace Vehicle Design: Risk vs. Time

Calibration/validation of experimental and computational tools via comparisons to flight data

- **Aerodynamic performance/aeroheating characteristics extracted from flights**

BMDO/ISTEF IR Image of STS-96





LaRC Mapping Code

Demonstrate on Orbiter prior to X-33 application

On-board and off-board aeroheating measurements

Airframe/TPS - Aerothermodynamics

Future Plans

- **"Review of X-33 Hypersonic Aerodynamic and Aerothermodynamic Development"; ICA-0323**
  Richard A. Thompson, NASA Langley Research Center
  Presented at 22nd International Congress of Aeronautical Sciences, August 27 - Sept 1, 2000, Harrogate, United Kingdom

  Paper available:

  http://techreports.larc.nasa.gov/ltrs/PDF/2000/mtg/NASA-2000-22cicas-rat.pdf

  Extensive list of references

- **Journal of Spacecraft and Rockets; Vol. 36, No. 2, Mar-Apr 1999**
  Special Section: X-34; pages 153-239
  (collection of nine papers)

Airframe/TPS - Aerothermodynamics

Reference Sources for Recent RLV Studies

♦ 12:45 - 1:00 Introduction 2nd Gen RLV Airframe	S. Welch
♦ 1:00 - 1:20 Airframe Design and Integration	S. Scotti
♦ 1:20 - 1:40 Aerothermodynamics	C. Miller
♦ 1:40 - 2:00 Structures and Materials	T. Johnson
♦ 2:00 - 2:20 Tanks	D. Smith
♦ 2:20 - 2:40 Thermal Protection Systems	M. Rezin
♦ 2:40 - 3:00 Integrated Airframe Demonstrations	D. Glass
♦ 3:00 - 3:05 BREAK	
♦ 3:05 - 3:30 Introduction 3rd Gen RLV Airframe	D. Bowles
♦ 3:30 - 3:55 Integrated Design and Analysis	T. Gates
♦ 3:55 - 4:20 Integrated Thermal Str. & Materials	B. Jensen
♦ 4:20 - 4:45 Thermal Protection Systems	S. Johnson

2nd Gen Airframe/TPS - Structures and Materials:

Agenda