

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

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| 1. AGENCY USE ONLY (Leave blank)  |  | 2. REPORT DATE<br>02-JUL-2003                            | 3. REPORT TYPE AND DATES COVERED<br>FINAL (15-SEP-2002 TO 14-JAN-2003) |                            |
| 4. TITLE AND SUBTITLE<br>AFOSR WORKSHOP ON MULTIFUNCTIONAL AND HYBRIDIZED AEROSPACE MATERIALS AND STRUCTURES  |  |  | 5. FUNDING NUMBERS<br>F49620-02-1-0432                                 |                            |
| 6. AUTHOR(S)<br>PROFESSOR C. T. SUN   |  |  |  |                            |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>PURDUE UNIVERSITY<br>SPONSORED PROGRAM SERVICES<br>610 PURDUE MALL<br>WEST LAFAYETTE, IN  |  |  | 8. PERFORMING ORGANIZATION REPORT NUMBER                               |                            |
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| 13. ABSTRACT (Maximum 200 words)<br>The "Microstructure Testing and Analysis Laboratory" is a new facility for the mechanical testing of small specimens, soft material, and small structures. The main components of the laboratory are a low force electrostatically actuated test frame for axial/torsion and combined loading, a digital image correlation system for the measurement of displacement fields, and a stereovision system for investigations of fracture surface<br><br>The facilities have been used successfully in research projects on carbon-carbon composites, and in investigations of porous polymeric materials, as well as for projects in a graduate course on "Micromechanics of Materials." In all experiments performed so far the experimental facilities have performed satisfactory. |  |  |  |                            |
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**38 ATTENDEES:**  
26 Speakers, Panelists & Discussion Leaders;  
1 Moderator; 1 Organizer;  
10 Invited Guests

MODERATOR:

\*C. T. Sun (Purdue U)

OPENING REMARK:

<sup>01</sup> Les Lee (AFOSR) "AFOSR Perspective"

**Background Overview** (2:30 - 4:00 PM, 23 October 2002; Stewart Center Room 214C)

KEYNOTE SPEAKERS:

*15 min. presentation & 5 min. question per each*

- <sup>02</sup> Brian Sanders (AFRL/VA) "Overview of Research at AFRL Air Vehicles Directorate"
- <sup>03</sup> David Banks (Boeing Phantom Works) "Overview of Multifunctional Structures Research"
- <sup>04</sup> Steve Donaldson (AFRL/ML) "Overview of Research at AFRL Materials Directorate "
- <sup>05</sup> Jeff Welsh (AFRL/VS) "Overview of Research at AFRL Space Vehicles Directorate "

**1<sup>st</sup> AIR FORCE WORKSHOP ON  
“MULTIFUNCTIONAL AEROSPACE MATERIALS”**

October 23-24, 2002, Purdue University, W. Lafayette, IN  
*(Immediately following the 17<sup>th</sup> Technical Conference of American Society for Composites)*

**ORGANIZING COMMITTEE:**

Les Lee (AFOSR), *Chair*  
Steve Donaldson (AFRL/ML)  
Tom Hahn (UCLA)  
Brian Sanders (AFRL/VA)  
C. T. Sun (Purdue U)

**DISTRIBUTION STATEMENT A**

Approved for Public Release  
Distribution Unlimited

**Multifunctional Design** (4:00 - 6:00 PM, 23 October 2002; Stewart Center Room 214C)

**DISCUSSION LEADER:** Bill Baron (AFRLVA)

**KEYNOTE SPEAKERS:**

*15 min. presentation*

- <sup>06</sup> Bill Baron (AFRLVA) "Conformal Load Bearing Antenna Structures"
- <sup>07</sup> Barton Bennett (Odysian) "Multifunctional Structures with Embedded Subsystem Functionality"
- <sup>08</sup> Jim Thomas (NRL) "Design Issues for Multifunctional Materials and Structures"

**PANELISTS (Expertise):**

*10 min. comments or alternative opinion per each*

- <sup>09</sup> Jim Mason (Notre Dame U) "Circuit Integration and Thermal Management"
- <sup>10</sup> Greg Schoeppner (AFRL/ML) "Design Issues for Multifunctional Composites"
- <sup>11</sup> David Banks (Boeing Phantom Works) "Health Monitoring of Multifunctional Structures"

**OPEN DISCUSSION:** 45 min

**(DINNER SERVED)**

Self-Diagnosis (8:00 - 10:00 AM, 24 October 2002; Stewart Center Room 313)

**DISCUSSION LEADER:** Munir Sindir (**Boeing Rocketdyne**)

**KEYNOTE SPEAKERS:**

*15 min. presentation per each*

- <sup>12</sup> Munir Sindir (**Boeing Rocketdyne**) "Health Management System Needs - Space Transportation Perspective"
- <sup>13</sup> Mark Derriso (**AFRL/VA**) "Structural Health Monitoring"
- <sup>14</sup> David Green (**Physical Sciences**) "Materials That Sense Their Environment"

**PANELISTS (Expertise):**

*10 min. comments or alternative opinion per each*

- <sup>15</sup> Bill Curtin (**Brown U**) "Self-diagnosis of Damage in CFRP by Electrical Resistance"
- <sup>16</sup> Fu-Kuo Chang (**Stanford U**) "Demand and Challenges in Structural Health Monitoring"
- <sup>17</sup> Alex Bogdanovich (**3Tex**) "3-D Woven Composite Structures with Integrated Fiber Optic Sensors"
- <sup>18</sup> Steve Kreger (**Blue Road Research**) "Multi-axis Fiber Grating Strain Sensors"

**OPEN DISCUSSION:** 45 min

**Self-Cooling** (10:15 AM - 12:25 PM, 24 October 2002; Stewart Center Room 313)

**DISCUSSION LEADER:** Roger Morgan (Texas A&M U)

**KEYNOTE SPEAKERS:**

*15 min. presentation*

- <sup>19</sup> David Brown (AFRL/VA) "Thermal Protection Systems"
- <sup>20</sup> Keith Bowman (AFRL/ML) "Thermal Management Issues and Program Directions"
- <sup>21</sup> Roger Morgan (Texas A&M U) "Self Fast Cooling Mechanisms"

**PANELISTS (Expertise):**

*10 min. comments or alternative opinion per each*

- <sup>22</sup> Patrick Kwon (Michigan State U) "Micro Heat Exchanger"
- <sup>23</sup> Jim Sutter (NASA Lewis) "Thermal Management and High Temperature Polymers"
- <sup>24</sup> Khalid Lafdi (AFRL/ML) "Graphite Foams as Heat Carrier for Thermal Control"

**OPEN DISCUSSION:** 45 min

(LUNCHEON SERVED)

**Self-Healing** (1:15 PM - 3:15 PM, 24 October 2002; Stewart Center Room 313)

**DISCUSSION LEADER:** Scott White (U Illinois)

**KEYNOTE SPEAKERS:**

*15 min. presentation*

- <sup>25</sup> Nancy Sottos (U Illinois) "Autonomic Healing of Polymers and Polymer Composites"
- <sup>26</sup> Scott White (U Illinois) "Next Generation of Autonomic Healing Process"
- <sup>27</sup> Xiangxu Chen & Fred Wudl (UCLA) "Remendable Polymeric Materials"

**PANELISTS (Expertise):**

*10 min. comments or alternative opinion per each*

- <sup>28</sup> Michael Wisnom (U Bristol, UK) "Novel and Multi-functional Composites"
- <sup>29</sup> Andrew Skipor (Motorola) "Self-healing and Electronic Assemblies"
- <sup>30</sup> Roger Morgan (Texas A&M U) "On Self-healing Mechanisms"

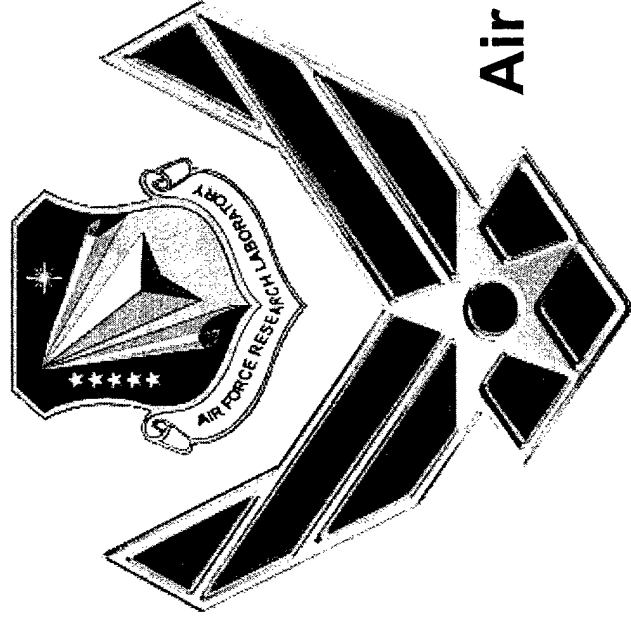
**OPEN DISCUSSION:** 45 min

\*\*\*\*\*

**SPECIAL GUESTS INVITED:**

Jaycee Chung (**Global Contour**)  
Krishna Jonnalagadda (**Motorola**)  
Doug Adams (**Purdue U**)  
Tom Farris (**Purdue U**)  
Hyonny Kim (**Purdue U**)  
Thomas Siegmund (**Purdue U**)  
John Starkovich (**TRW**)  
Stephen Hallett (**U Bristol, UK**)  
Brian Rice (**U Dayton**)  
Philippe Geubelle (**U Illinois**)

# **MECHANICS OF MATERIALS AND DEVICES: AFOSR PERSPECTIVE**



**B. L. ("Les") Lee**

**Program Manager**

**Mechanics of Materials & Devices**

**Air Force Office of Scientific Research**



# MISSION



**Establish the science base for  
*integration of advanced materials and  
devices into future Air Force systems.***

Materials/Devices



Processing/  
Manufacture

Mechanics  
of Materials  
& Devices

Design

Structures

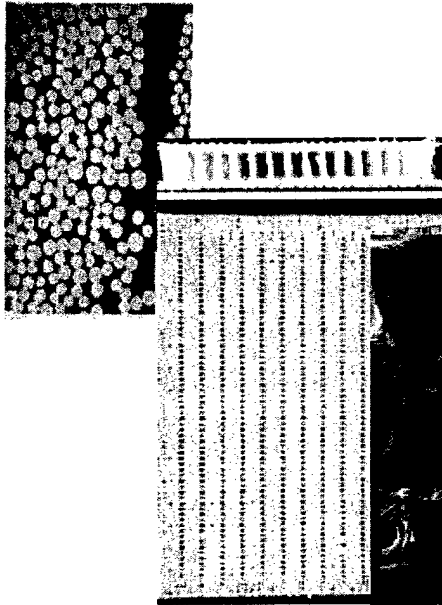
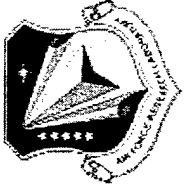


Properties

Performance



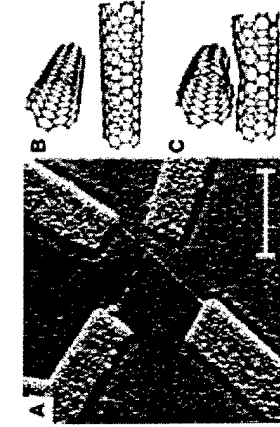
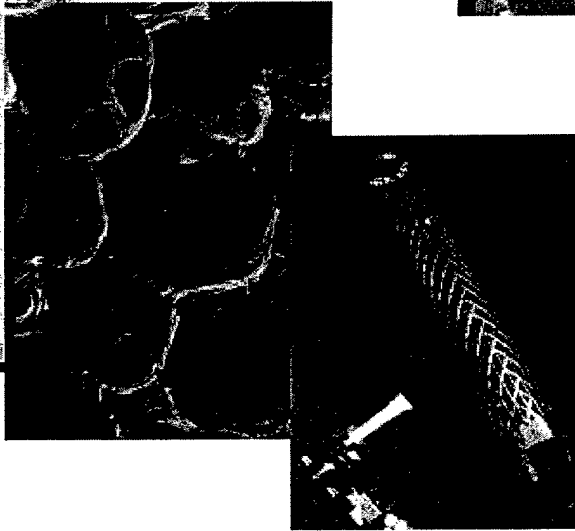
# MECHANICS ISSUES IN Design, Manufacturing & Sustainability:



*\*Advanced Fiber Composites  
Stealthy Materials  
High-Performance Metals*

*\*Structural Ceramic Composites  
Propellants: particulate composites*

*\*Carbon Foam  
Shape-Memory Alloy  
Functionally Graded Materials*



*\*Multifunction Composites  
\*Nano-materials  
Self-Diagnosing Structures  
\*Self-Healing Materials*

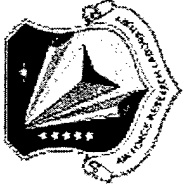
*Adhesives & Joints*



*Sensors  
Micro-devices incl. MEMS  
Nano-devices*



# THRUST AREAS vs. STRATEGIC RESEARCH AREAS



## THRUST AREAS -

Affordable Processing

Vibration Mitigation 1

(Materials Aspects)

Durability

Damage Tolerance

Micromechanics

Life Prediction



Nano-materials 2

Multifunctional Behavior:

Multifunction Materials 1

Micro- & Nano-devices 1

Self-Diagnosis 1

Self-Healing 1,3

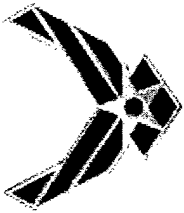
Multi-scale Model

Life Extension

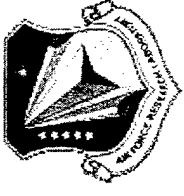
1 Smart Materials/Structures - SRA

2 Nano Science - SRA

3 Biomimetics - SRA



# VISION



**Biomimetics**

**Design for Coupled  
Multi-functionality**

**Nano-materials**

**Concurrent  
Multi-scale Model**

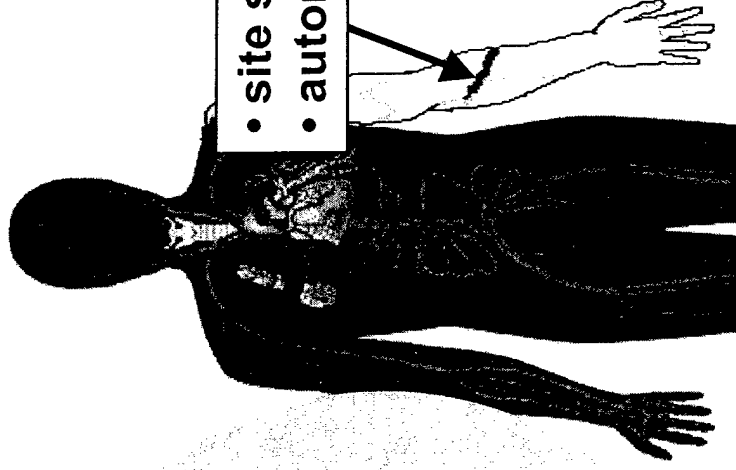
**Micro- & Nano-  
Devices**

**Manufacturing Sci**

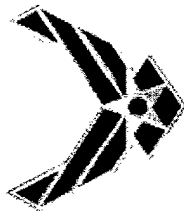
**Neural Network &  
Information Sci**

**AUTONOMIC  
AEROSPACE  
STRUCTURES**

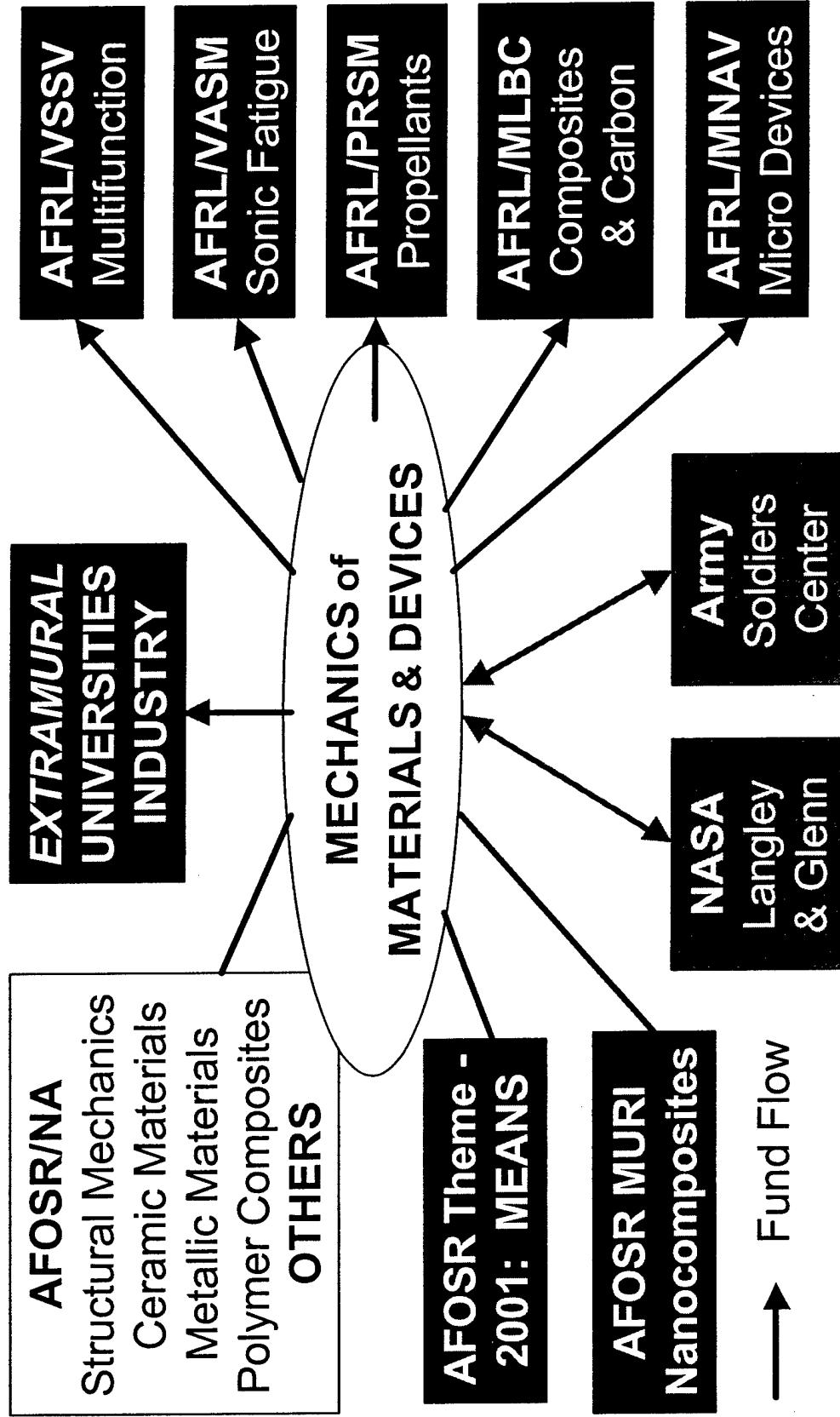
- Self-Diagnosis
- Self-Healing
- Threat Neutralization
- Self-Cooling



- site specific
- autonomic



# PROGRAM INTERACTION

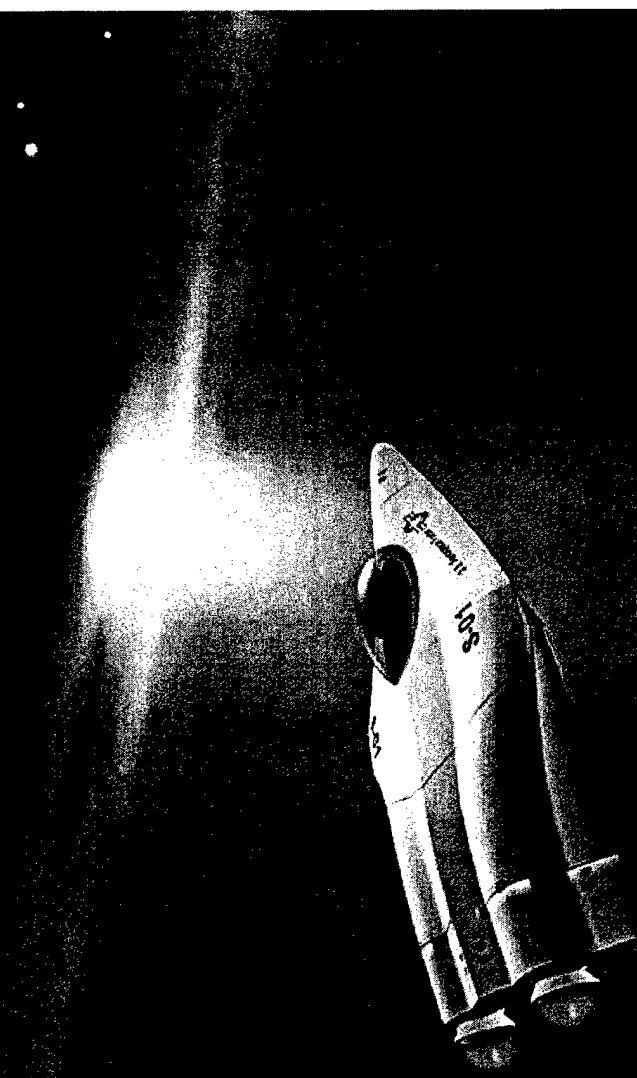




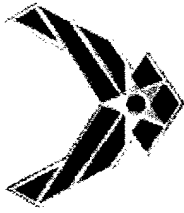
**Air Force**

**Research Laboratory | AFRL**

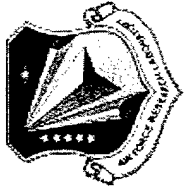
*Science and Technology for Tomorrow's Aerospace Force*



**AIR VEHICLES  
DIRECTORATE**



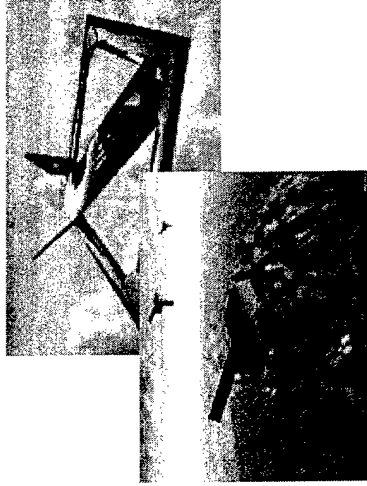
# AIR VEHICLES DIRECTORATE S&T Focus Areas



## Sustainment:

Technology insertion to enable today's fleet to meet tomorrow's warfighter needs

Increased mission capable rates  
Reduced operation and support costs



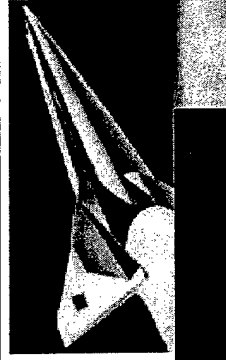
## Unmanned Air Vehicles:

Technologies to enable routine operation of high payoff UAV alternatives across the full spectrum of warfare

Seamless manned / unmanned vehicle operation

Superior mission capability at reduced cost

Intelligent control of UAV swarms



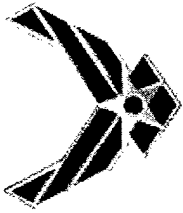
## Space Access & Future Strike Technology:

Affordable space access and quick reaction trans-atmospheric capability

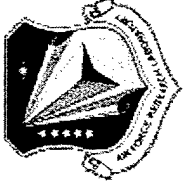
Aircraft like operation -- quick turnaround and flexible mission capability

Global engagement in less than 3 hours

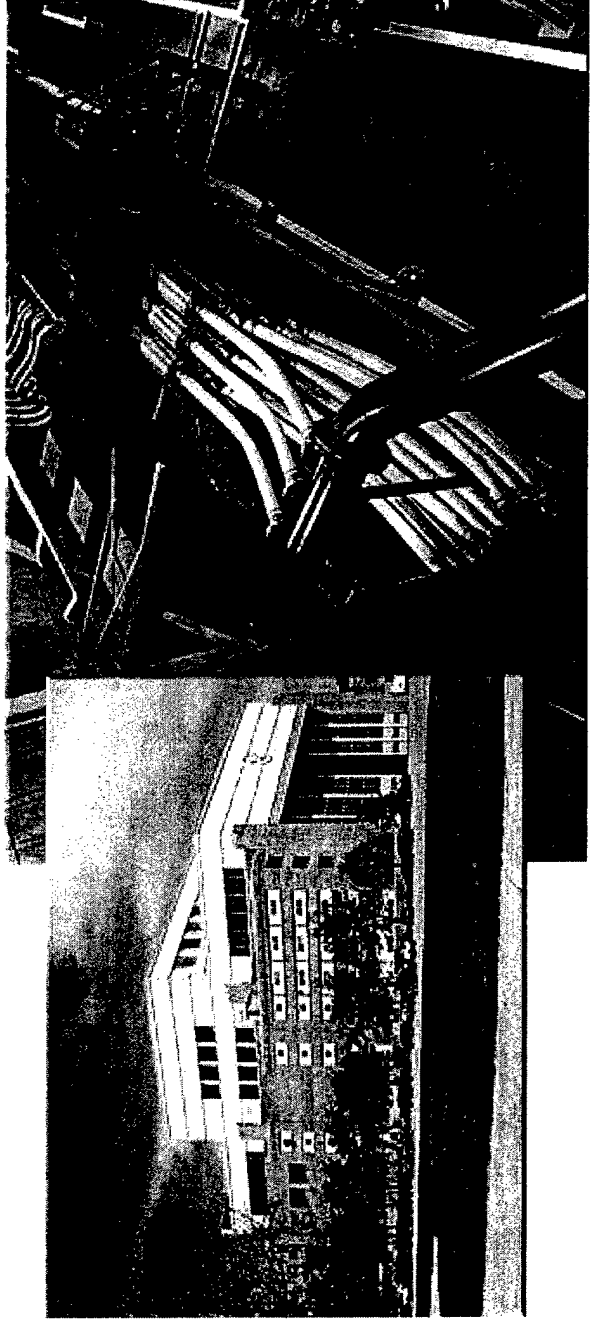
Reduced cost for access to space<sup>2</sup>



# EXPERIMENTAL FACILITIES

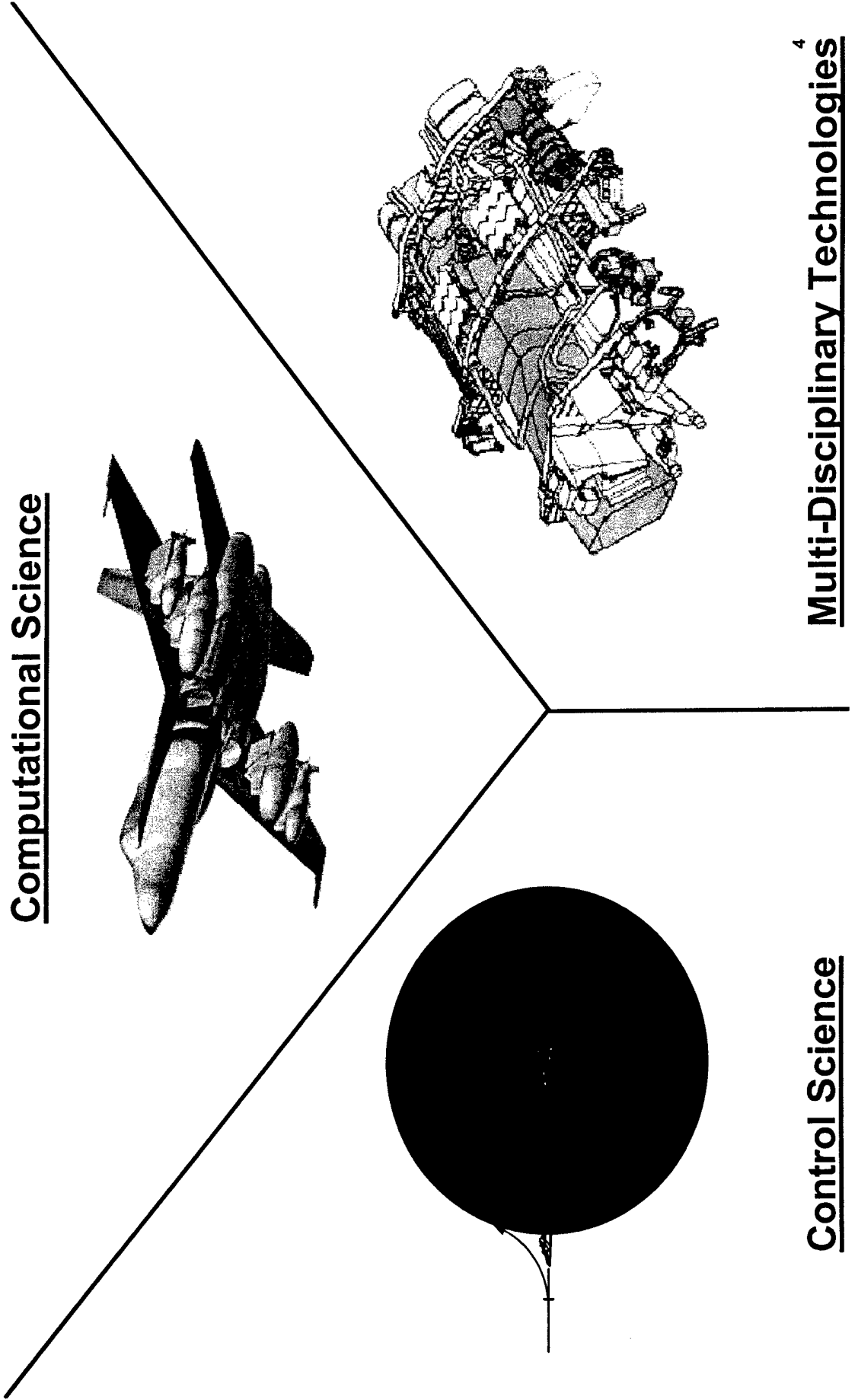
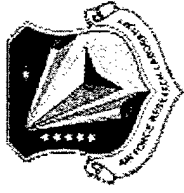


- Combined Environment Acoustic Chamber
- Simulates severe aeroacoustic and engine environments
- Only facility capable of achieving 173dB and 2500°F on a 9'x4' specimen

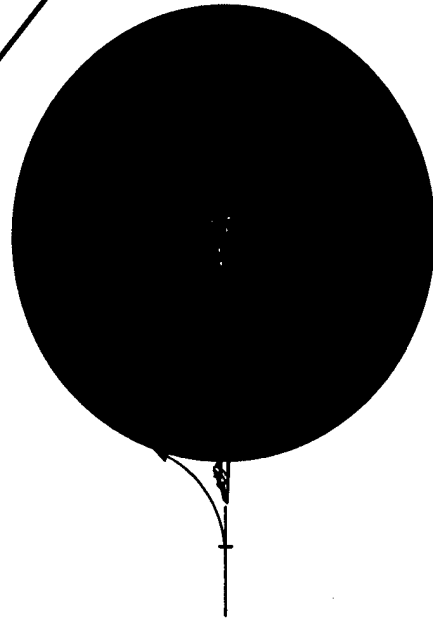
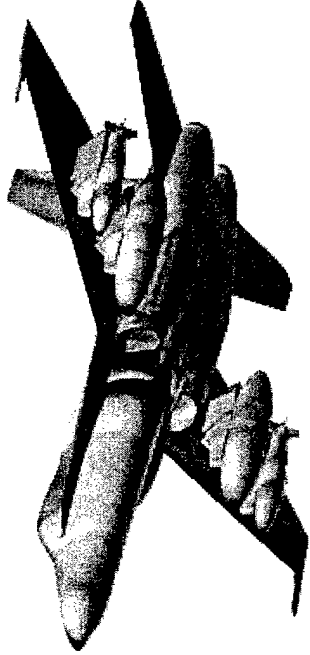




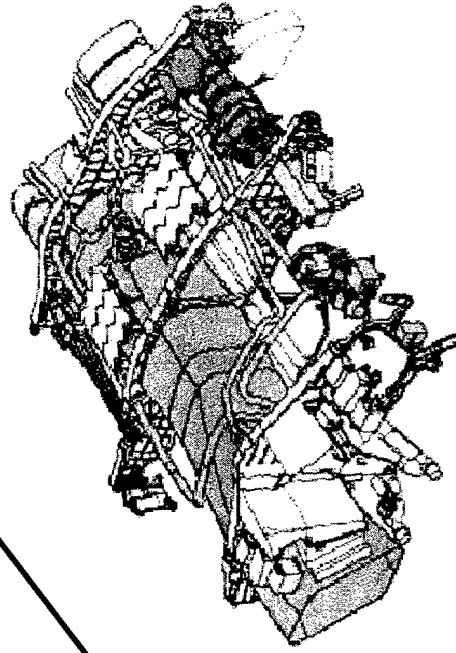
# CENTERS OF EXCELLENCE



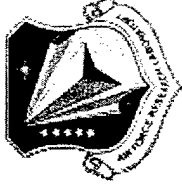
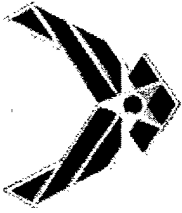
Computational Science



Control Science



Multi-Disciplinary Technologies<sup>4</sup>



**STRUCTURES DIVISION**  
**STRUCTURAL DESIGN AND DEVELOPMENT BRANCH**

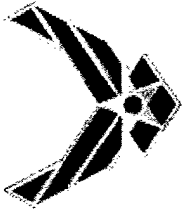
**MULTIFUNCTIONAL & ADAPTIVE STRUCTURES TEAM**  
**(MAST)**

**AFRL**

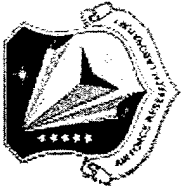
Baron, Bowman, Forster, Garner, Joo, Keihl, Washington, Ohio State University  
Reich, Sanders, Cannon (VACC)

**External Collaborators**

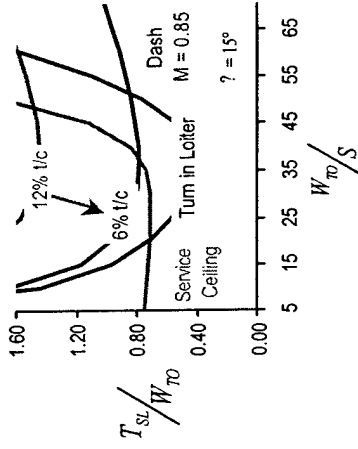
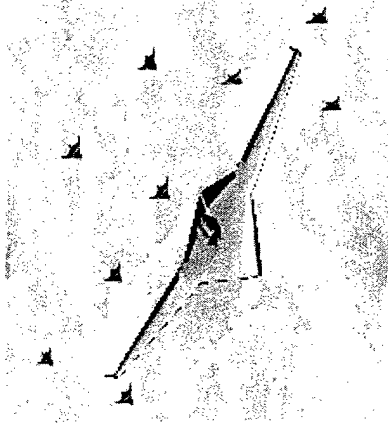
Weisshaar/ Crossley, Purdue  
Murray, Univ of Dayton  
Inman, VPI  
Alton, Univ of Dayton



# SCOPE OF PROGRAM

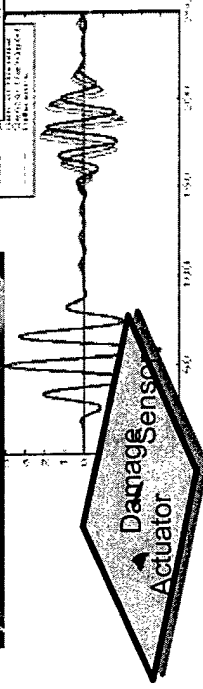
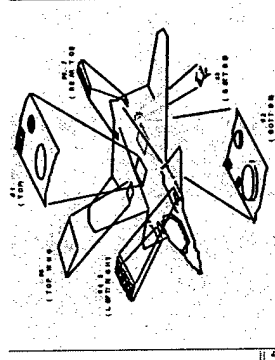


## Mission Identification & Vehicle Configuration



## Integrated Structures

- Shape Control
- Antenna Integration
- Energy Storage & Harvesting



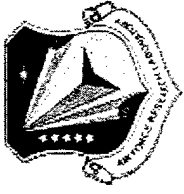
## Energy Based Design

$$\text{Exergy } ? (u ? u_o) ? T_o(s ? s_o) ? \frac{P_o(\rho ? \rho_o) ? V^2}{2g_f} ? \frac{g}{g_c} J (z ? z_o) ? ? ( ? ? ? ) N_c ? \square$$





# DARPA/AF



## MORPHING AIRCRAFT PROGRAM



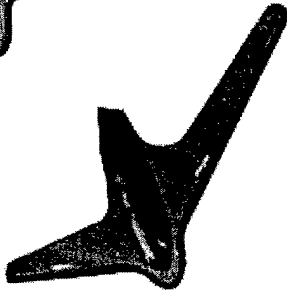
From rigid airframes to commanded, time variant, variable geometry, load-bearing structures

### Variable Geometry Wings



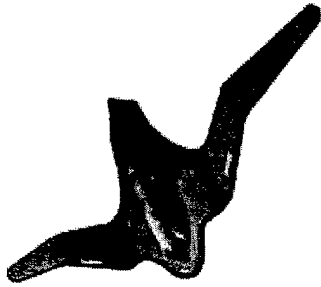
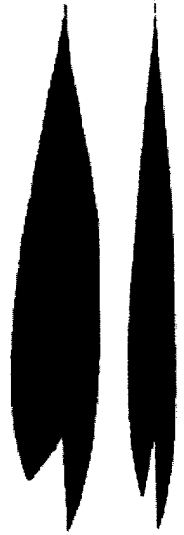
- cross section
- camber

- dihedral
- wing ?
- wing planform



- sweep
- aspect ratio
- twist

### Fuselage & Propulsion System



Aircraft are currently designed around specific missions

Can we develop aircraft capable of multiple missions?

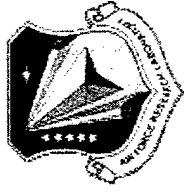
- e.g., reconnaissance air vehicles transform into effective ground attack vehicles

First challenge: Morph the wing

Technology Challenges:  
Active Skins  
Mechanism Design & Integration

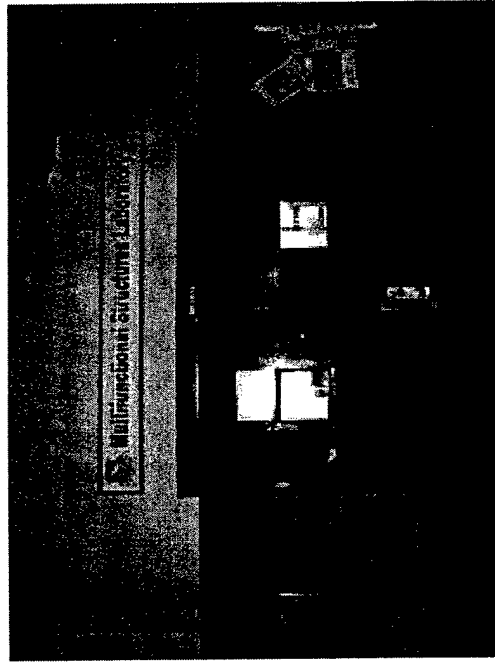


# Multifunctional Structures Laboratory

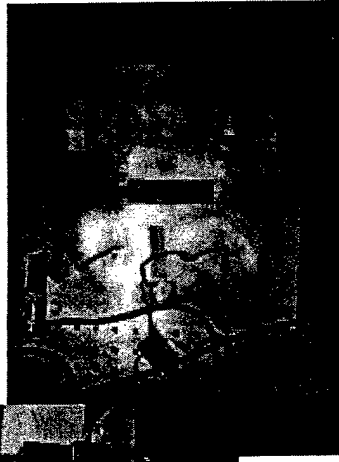
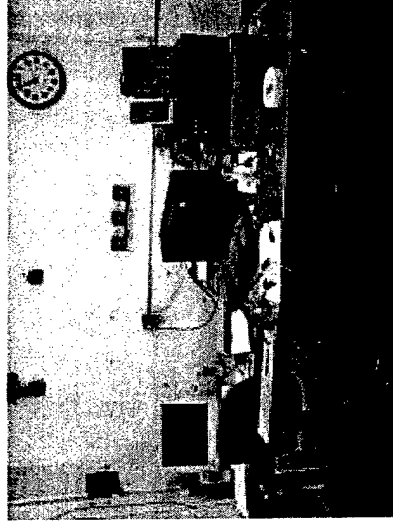


## Objective

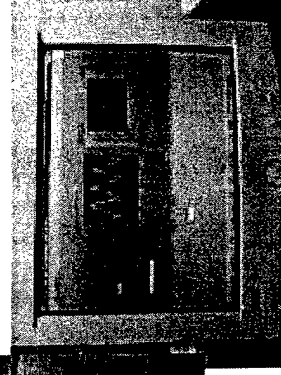
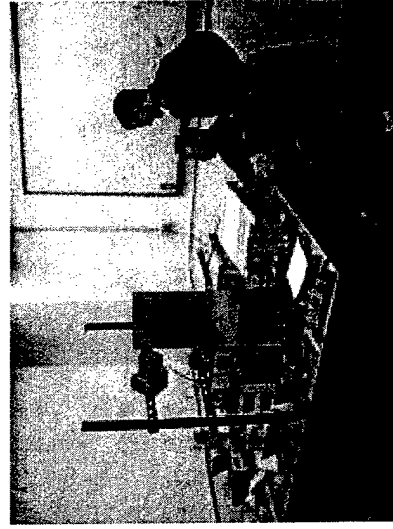
Have the capability to conduct experimental research and rapidly evaluate sensor and actuator technology for application to MFS



Located in Bldg 65



Health Monitoring



Shape Control

# 1st Air Force Workshop on “Multifunctional Aerospace Material”

Overview of Multifunctional  
Structures R&D at Boeing

Dave Banks

Boeing Phantom Works

[David.L.Banks@Boeing.Com](mailto:David.L.Banks@Boeing.Com)  
206-655-3855

# Some Definitions

Phantom Works



- **Any structure with functions beyond load carrying capabilities**
- **Possible integration features:**
  - Integrated attachments for other systems
  - Conduits (for air, fuel venting, or other fluids)
  - Energy Absorption (for vibration and acoustic noise suppression)
  - Thermal Control (cooling and heating)
  - Electrical Systems & Conductive Structures (for grounding and lightning)
  - Actuation (for aerodynamic control, fluid movement
  - Sensing (pressure, acceleration, acoustic, strain, temperature, Corrosion...)
  - Optics (for data or for light transmission)
  - Energy Generation (remote sensors & vibration suppression)
  - Self-healing structures / self-repairing structures

# Benefits

Phantom Works

BOEING

Multifunctional Structures  
Cost More ...than single-  
function structures

System Level Integration & Life cycle  
Costs are Lower

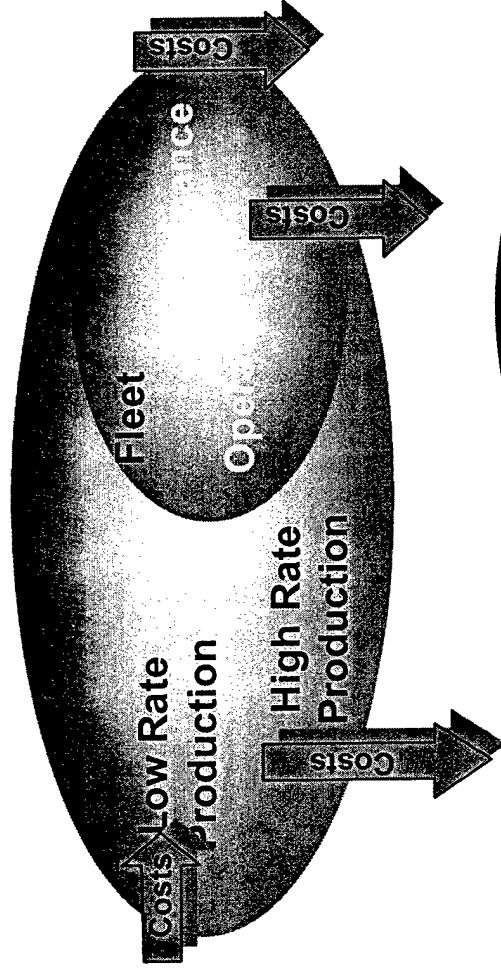
Multifunctional Structures

Prognostics & Health Management

Multifunctional Teams

Few, but more complex parts

Engineering Analysis Systems



Traditional System Installation

Reduced Part Count

Increased Flight Time

Real-time Damage Detection


Battle Damage Feedback

Autonomic Response Systems

# Multifunctional Structures Systems / Technology Development Matrix

Phantom Works



|   |                     | Technology Development Items |                                 |               |                      |           |                            |                                |                                   |  |                          |                                   |                         |
|---|---------------------|------------------------------|---------------------------------|---------------|----------------------|-----------|----------------------------|--------------------------------|-----------------------------------|--|--------------------------|-----------------------------------|-------------------------|
| Multifunctional Systems   | Fiber Optic Sensors | Fiber Optic Data Bus         | Improved Ultrasonic Fuel Sensor | Flex Circuits | Signal Bus Hi/Low BW | Power Bus | Integrated Piezo Actuators | Integrated MEMS Strain Sensors | Sensor Data Processing Algorithms | Structurally Integrated Connectors (wire & FO) | Structural Interconnects | Flat Wire through Spar/Skin Joint | Analysis Models / Tools |
| Integrated Cabling  | X                   | X                            |                                 | X             | X                    | X         | X                          |                                |                                   | X  | X                        | X                                 | X                       |
| Fuel Monitoring   |                     |                              | X                               | X             | X                    | X         |                            |                                | X                                 | X  |                          | X                                 |                         |
| Structural Health Monitoring  | X                   |                              |                                 | X             | X                    | X         | X                          | X                              | X                                 | X  | X                        | X                                 | X                       |
|  Demonstration Test System |                     |                              | X                               | X             | X                    | X         | X                          |                                | X                                 | X  | X                        | X                                 | X                       |
| Planarity Compensation  | X                   |                              |                                 |               |                      |           |                            |                                | X                                 | X  |                          | X                                 | X                       |
| Structural Test   | X                   |                              |                                 | X             | X                    | X         | X                          | X                              | X                                 | X  | X                        | X                                 | X                       |
| Integrated Manufacturing Sensors  | X                   |                              |                                 | X             | X                    |           | X                          | X                              | X                                 | X  | X                        | X                                 | X                       |
| Lightning   |                     |                              |                                 | X             |                      | X         |                            |                                |                                   | X  | X                        |                                   |                         |
| Structurally Integrated Apertures   | X                   | X                            | X                               | X             | X                    | X         | X                          |                                | X                                 | X  | X                        | X                                 | X                       |
| Active Rotor Blade  | X                   | X                            |                                 | X             | X                    | X         | X                          |                                | X                                 | X  | X                        | X                                 | X                       |

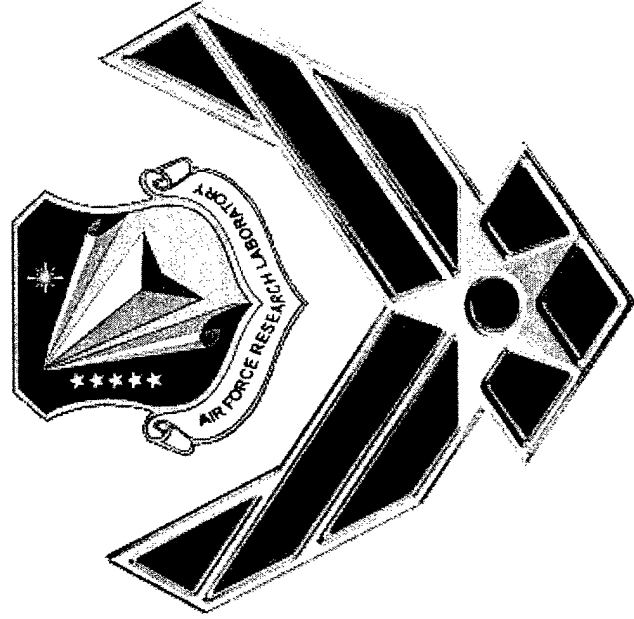
TRL 1-3

TRL 3-4

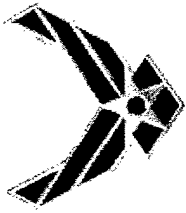
TRL 5-7

TRL 8-10

# **Organic Matrix Composites Research Activities at AFRL/MLBC**

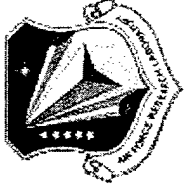


**Steven L. Donaldson**  
**Materials & Manufacturing**  
**Directorate**  
**Air Force Research Laboratory**



## **ML Mission / Vision**

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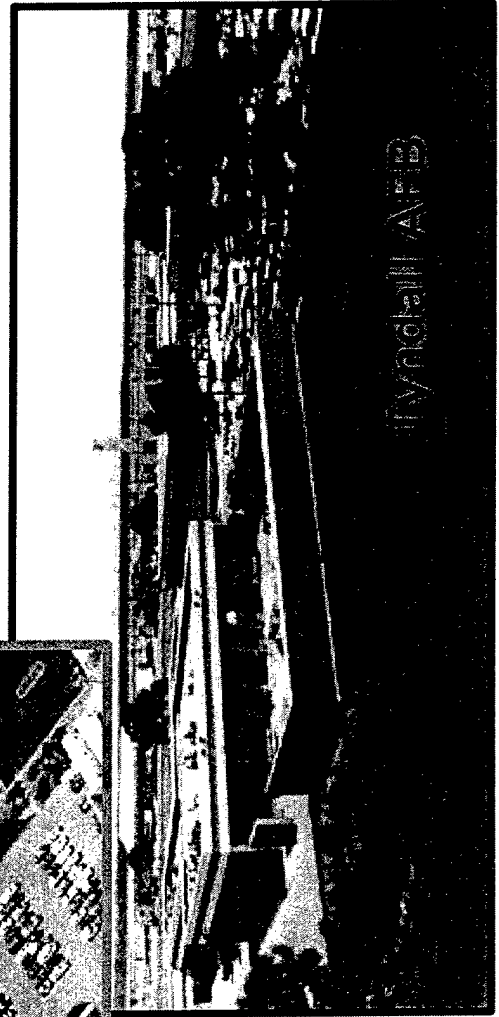
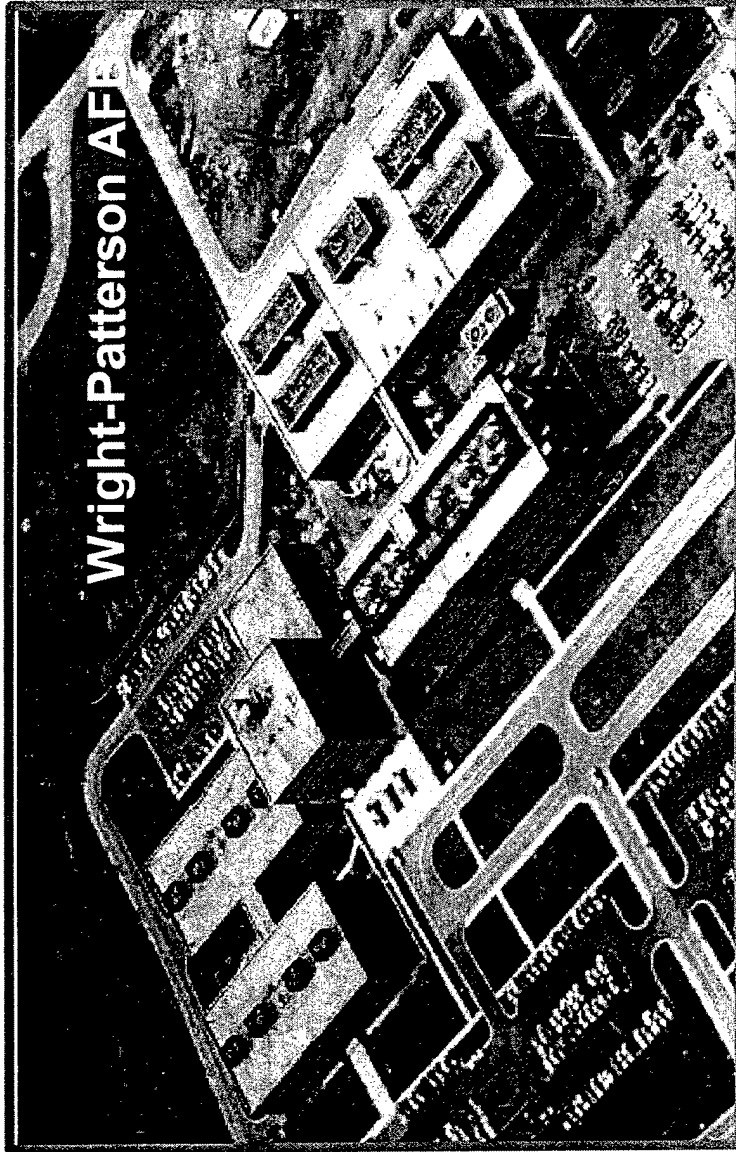
**Plan and execute the USAF program for materials and manufactory in the areas of basic research, exploratory development, advanced development and industrial preparedness. Provide responsive support to Air Force product centers, logistics centers, and operating commands to solve system and deployment related problems and to transfer expertise.**

*Aerospace materials and manufacturing leadership*

*for the Air Force and the nation.*



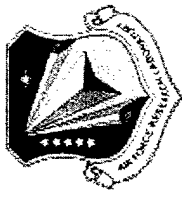
# Facilities



**Materials & Manufacturing  
Directorate**



# Key 21st Century Challenges for Aerospace M&P

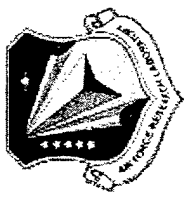


- **Maintaining “The Revolution”**
- **Increased Performance at an “Acceptable” Cost**
- **Controlling Cost With Small Production Runs**
- **Orchestrating Strategic Partnerships**
- **Reducing R&D Cycle Times Without Sacrificing Quality**
- **Accelerated Insertion of Materials**
- **Transitioning “High Risk”, but “High Performance”,  
Materials in a Risk Averse Environment**



# Revolutionary Opportunity Areas

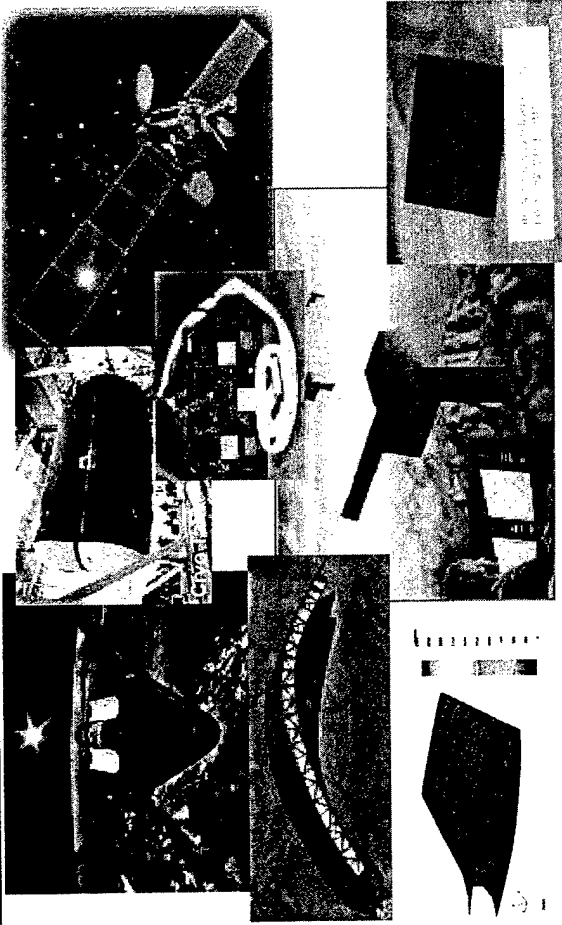
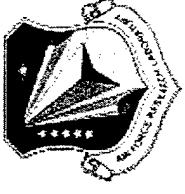
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- **Bioengineered/Bioinspired Materials**
- **Nano-Tailoring**
- **Multi-functional Materials**
- **Computational Materials Science**
- **Atomic Engineering**
- **Virtual Prototyping of M&P**
- **Virtual Databases**
- **Self-inspection Capabilities/Vehicle Health Monitoring**



# CTA-3 Organic Matrix Composites (OMCs)



## CTA DIRECTION GOALS

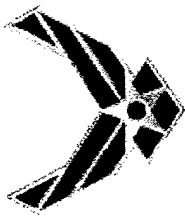
- 3.1 Develop improved, lightweight, tailored, multi-functional composite materials highly resistant to degradation in realistic severe service environments for long range, pervasive technologies
- 3.2 Develop, demonstrate, and transition new and improved OMC materials, processes, and mechanics approaches for Air Force aircraft and weapons
- 3.3 Exploit the properties of OMCs through the development of innovative, affordable processes, material forms, and supporting repair/mechanics technologies

## CTA DIRECTIONS

- 3.1 Advanced OMC Concepts
- 3.2 OMC M&P for Air Platforms
- 3.3 OMC M&P for Space Platforms

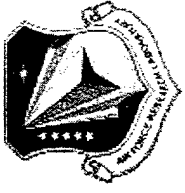
## ACCOMPLISHMENTS

- Evaluated a new family of affordable, low recession, insulative C-C for a simulated Global Reach Trajectory (CAV application)
- Demonstrated first nanocomposite matrix advanced composite with 5% to 10% increase in laminate properties
- Demonstrated a large panel component of a low cost sandwich structure for use in JASSM and UCAV applications
- Demonstrated 40% reduction in processing time of C-C for thermal management applications
- Validated a 20% improvement in energy absorption of full scale testing of phase change enhanced aircraft brakes
- Transitioned a flow model to industry for resin transfer molding of a fighter aircraft tail section with reduced fabrication time and costs



# CTA 3 OVERVIEW

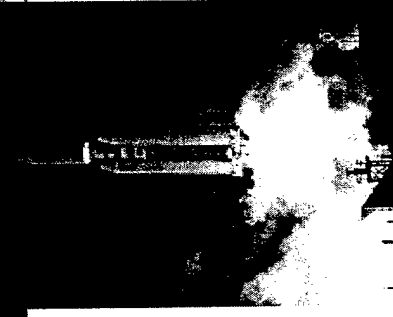
## Mission/Vision



### Mission:

To develop, demonstrate, and transition new and improved composite materials, processes, and applicable science bases for Air Force Weapons Systems:

- Performance with affordability
- Improved durability and survivability
- Reduced acquisition cost and times
- Technology transition

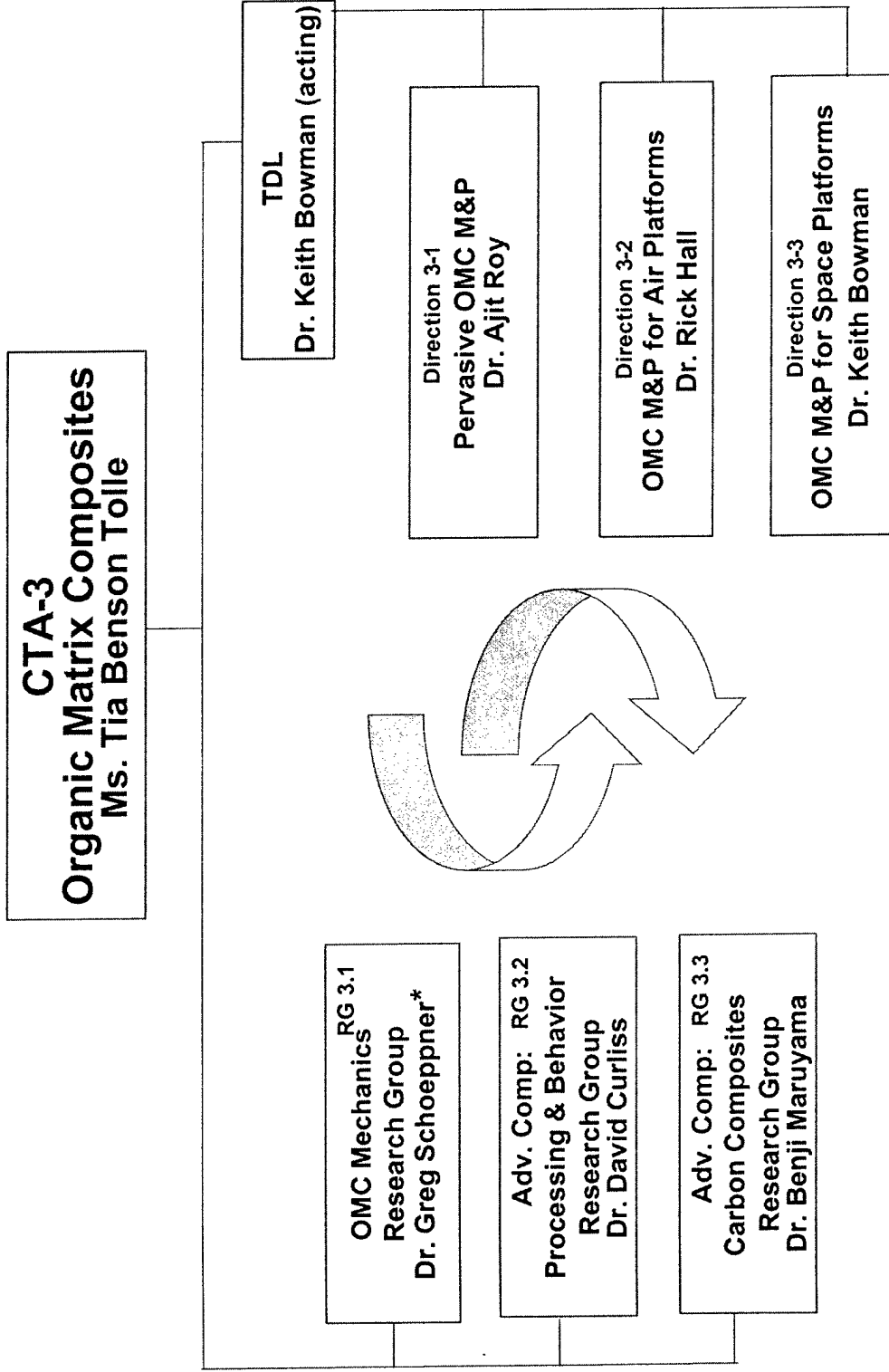
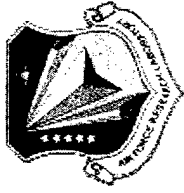


### Vision:

To develop, invest in, and implement the necessary technology for OMCs reach their full potential in affordable, flexible and mobile AF systems.



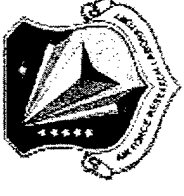
# CTA-3 Organic Matrix Composites Organization



\* CTA representative on ML Research Council



# CTA 3 Niche

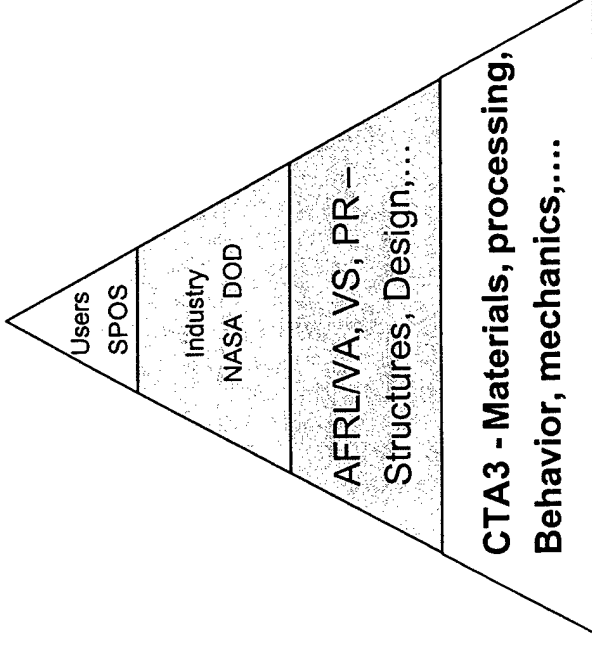


- **The S&T for USAF composites**

- Integrated group - materials, processing, chemistry, mechanics, ...
- Basic research + customer/industry interactions
- 6.3, 7.8/CAI ties
- Technical Directorates

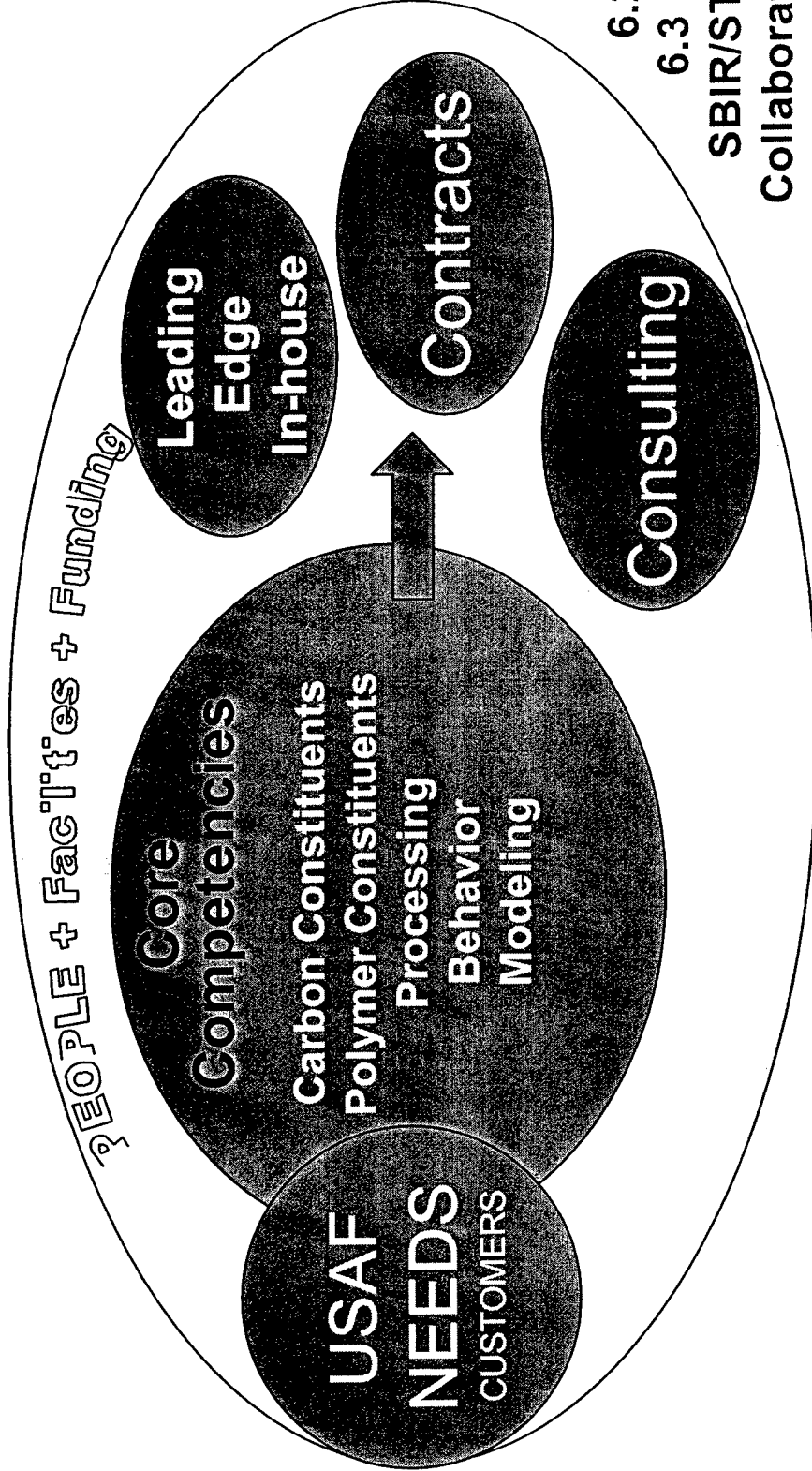
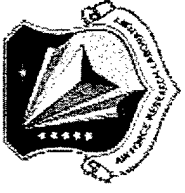
- **Technical challenges validate need**

- F119 engine: composites replaced by Ti (\$)
- SOV: composite cryotanks, TPS: durability? compatibility?
- ABL: chemical compatibility
- Realize the ‘why composites’ – full potential

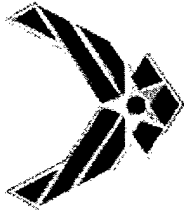




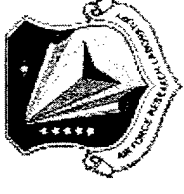
# Model: What we do



**To Guide Today's Customers, Meet Future Needs,  
and Enable Tomorrow's Weapons Systems**



# Technical Program Thrusts



- New Carbon Forms - Carbon Foams, Nano Carbon
  - Nanocomposites - Layered Silicate, CNT, Nanofibers
  - 3D Preforms (Textiles & Weaves) - Analysis, Design Tools
  - Modeling & Design Tool Development (PACT)
- 3-1: Pervasive

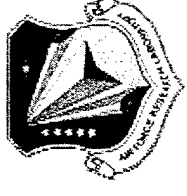
- C-C & Heat Exchangers
  - High Temperature Polymeric Composites
  - M&P for Affordability/Large Integrated Structures (P4A, Webcore, PDC)
  - Bonding & Joining
- 3-2: Air

- Thermal management for orbital applications
  - M&P for Integrated Structures – Non-Autoclave Processing
  - Thermal Protection Systems
- 3-3: Space

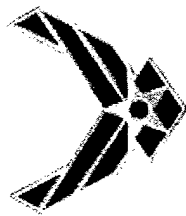


# OMC Development Emphasis

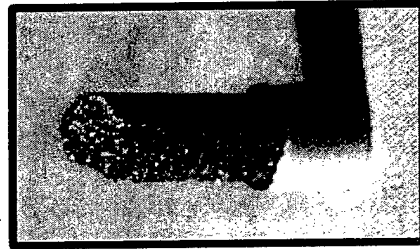
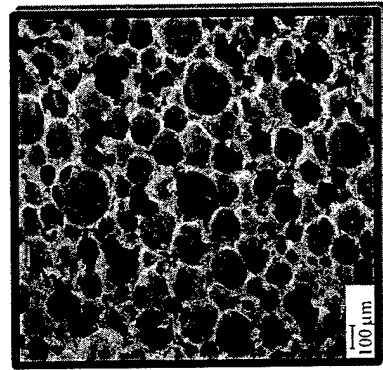
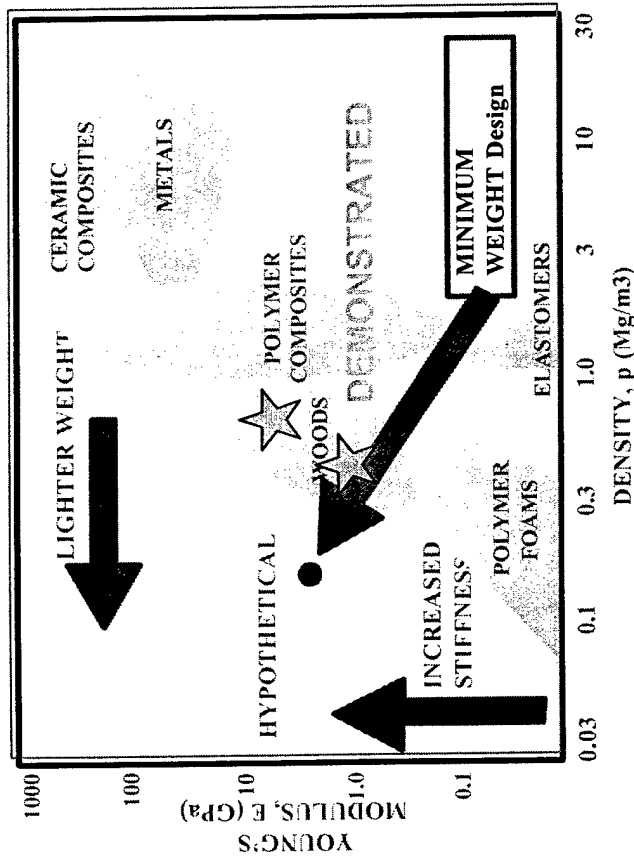
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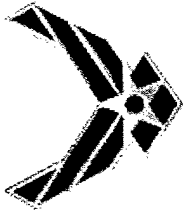
- **Pervasive Materials Development**
  - **Novel Materials Forms (Foam, Composite Preforms, NanoComposites, Bio-inspired Materials)**
- **Extreme Materials Environments**
  - **High Temperature, Cryo, LOX & GOX Compatibility**
- **Improved Capabilities**
  - **Thermal Management, Multifunctional**
- **Improved Understanding for Material Exploitation**
  - **PACT, 6.1, 6.2, Collaborations**



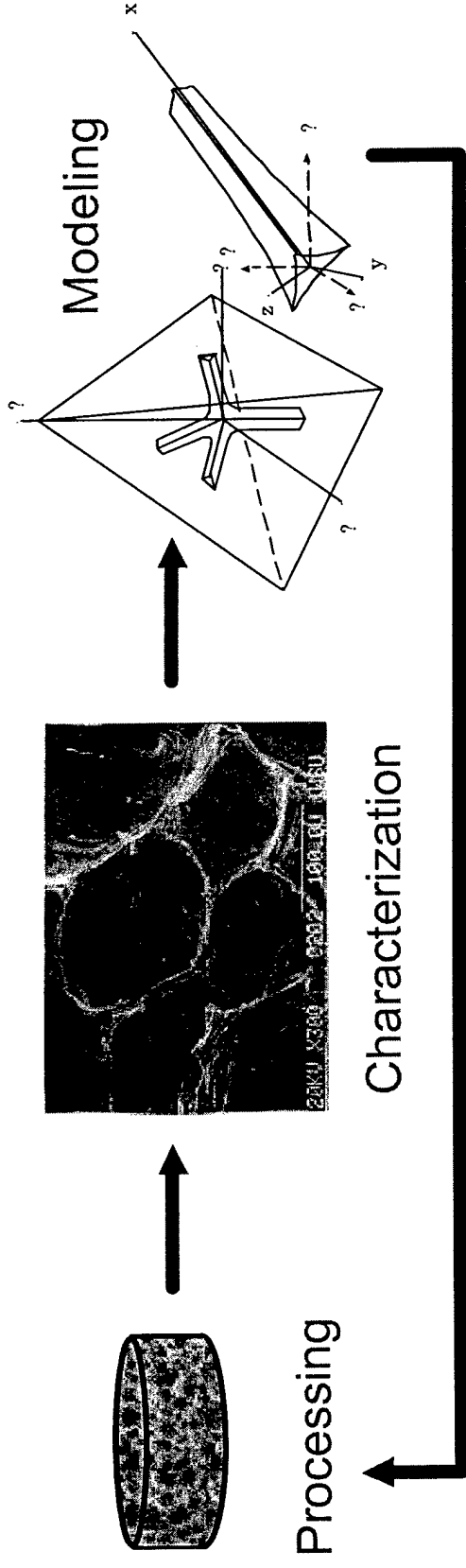
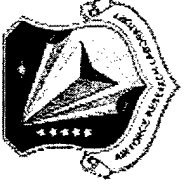
# Materials Development: Carbon Foam



- Extremely tailorable material - process dependant
  - General qualities
    - Isotropic properties
    - Moisture insensitive
    - Ultralightweight structure
      - 3-D preform (fill with various matrices)
      - Sandwich structure
  - Wide variety of densities (5 to 50 pounds/ft<sup>3</sup>)
- Low temperature processing:
  - Insulator
  - High temperature processing
    - Conductor, Stronger



# Carbon Foam Research Objective

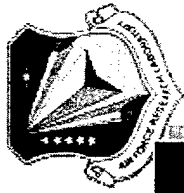


Foam ligament of about 120-150  $\mu$ m in length with changing cross-section and varying microstructure

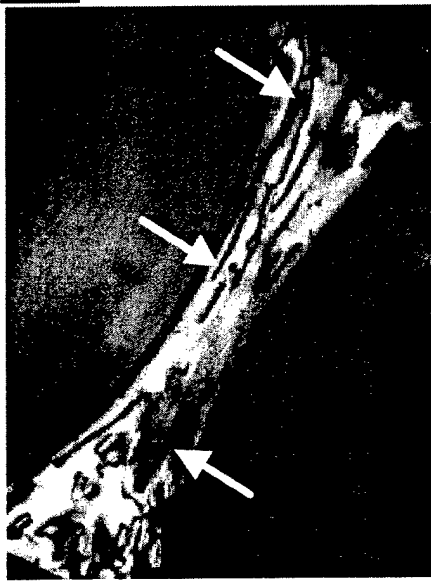
- Overall Objective
  - Integrated “Processing-Characterization-Modeling” approach to OPTIMIZE foam properties
  - To Model Foam Microstructure
  - To Characterize and Quantify Carbon Foam Ligament Microstructure



# Optical Microscopy of Stabilized Foam



Ligaments



With Disclinations

Free of Disclinations



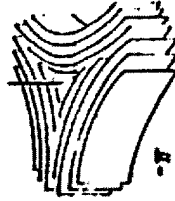
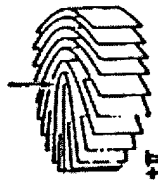
General View



Nodes with Wedge & Twist Disclinations



WEDGE DISCLINATIONS

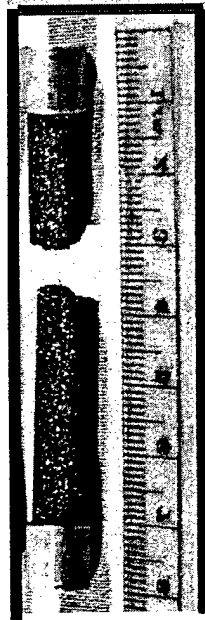
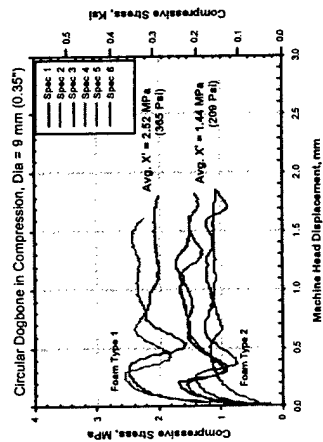
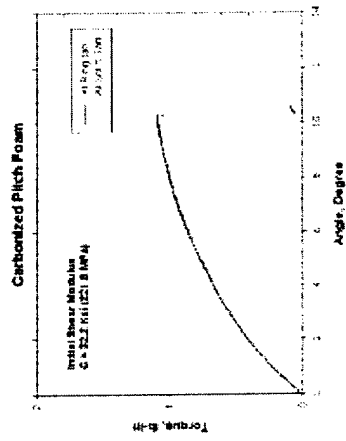
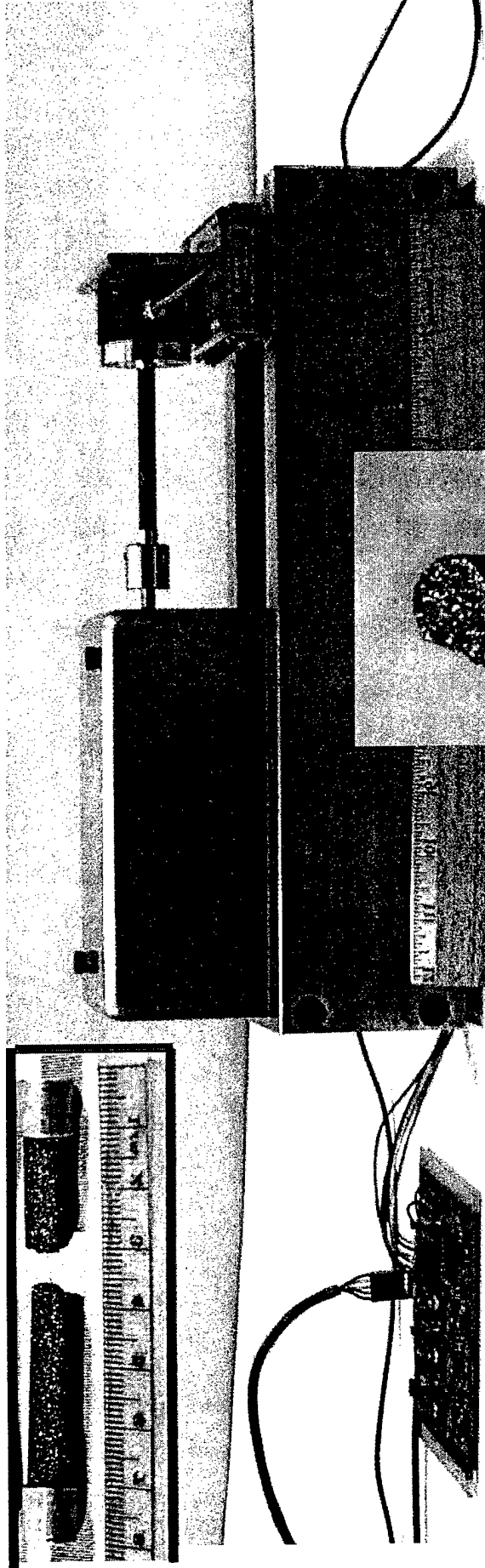
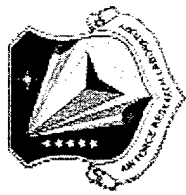


+2π

-2π

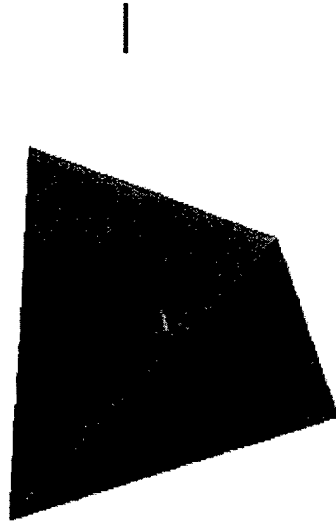


# Test Method Development (Mechanical, Thermal)

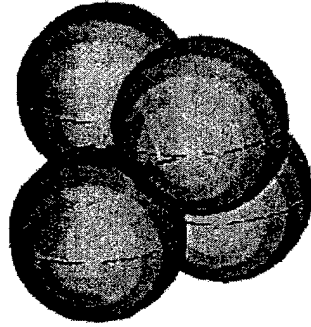




# Modeling to Predict Properties



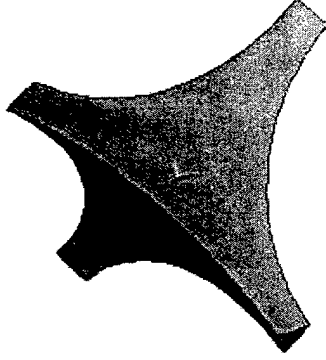
?? 10%



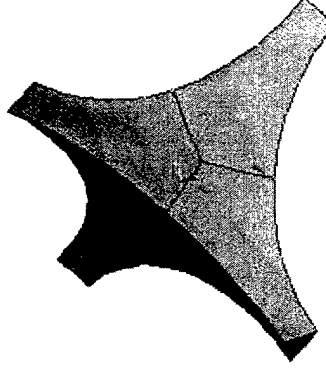
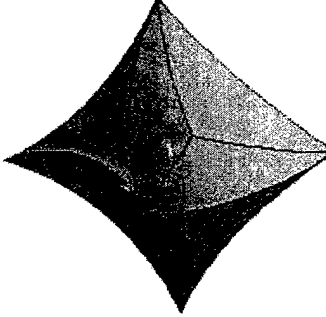
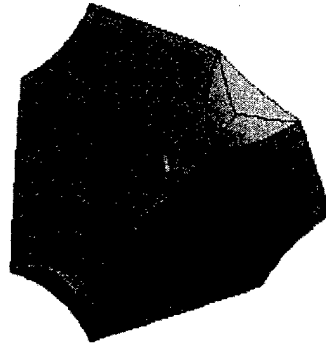
?? 78%

—

=



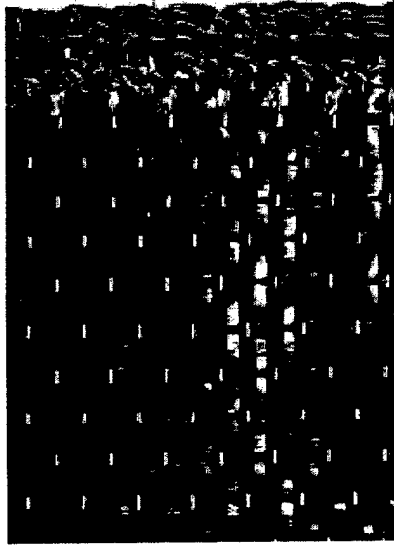
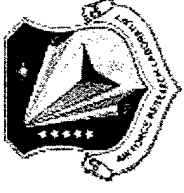
?? 98%



$$?? I? : \frac{V_{cell}}{V_{tetra}} \text{ : porosity}$$



# Materials Development: Preformed Composites



3D Weave (Z-reinforcement)

Enables

Low Cost Process



CMC (Z-reinforcement)



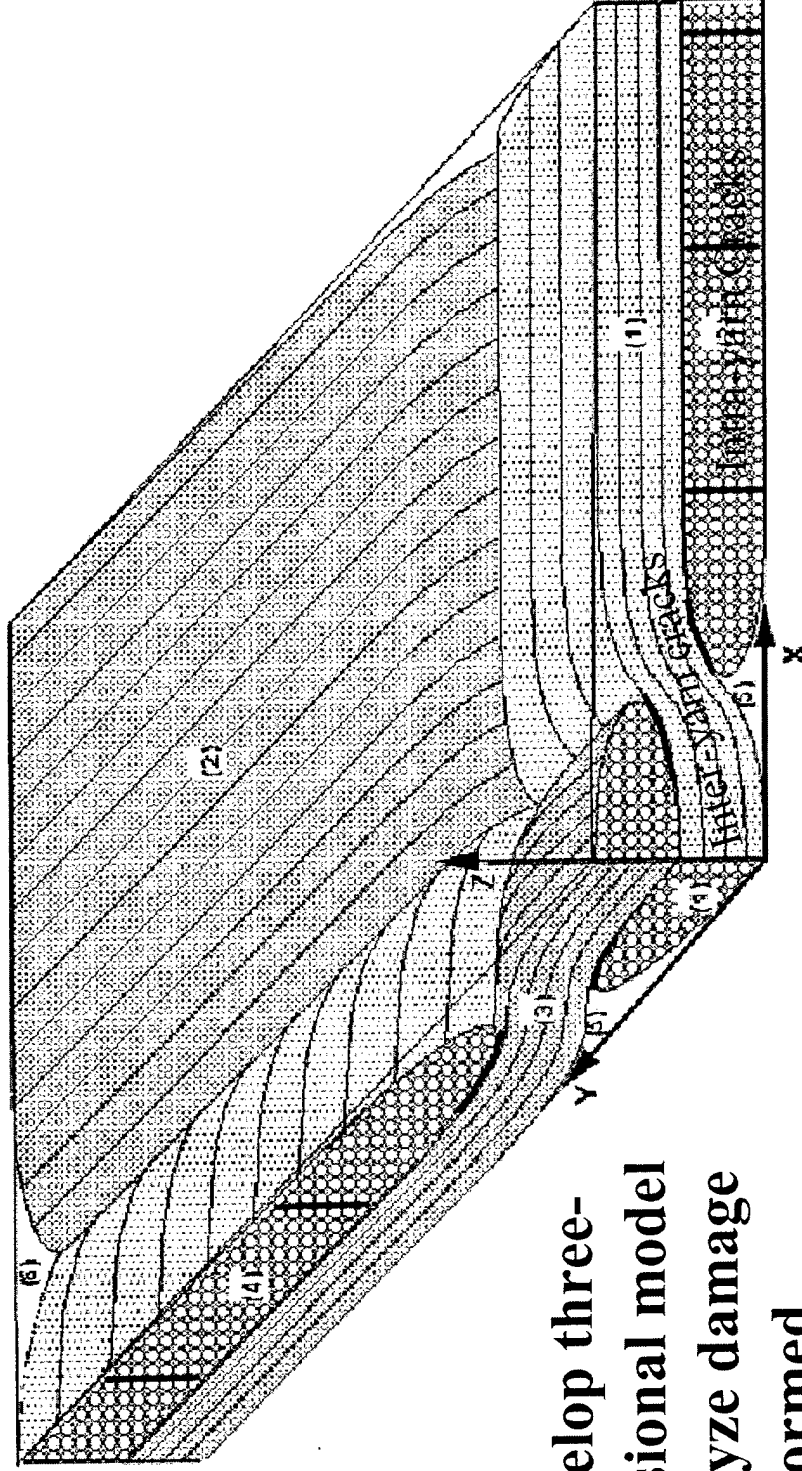
Processing Complex Shape



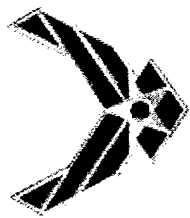
Angle Interlock - LO  
Dimensional Control



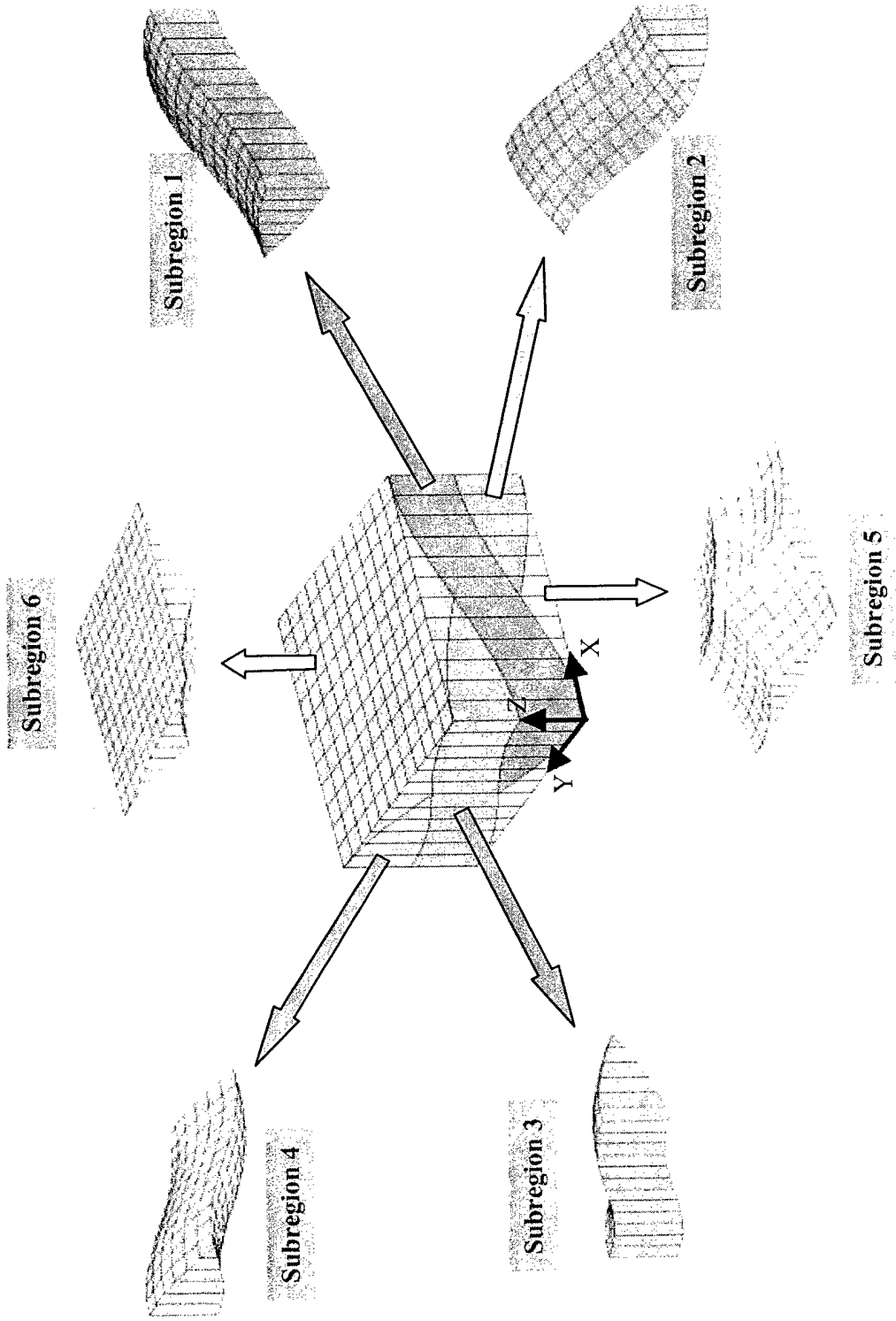
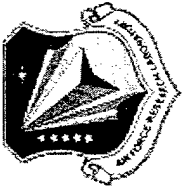
# Fracture Mechanics of Preformed Composites

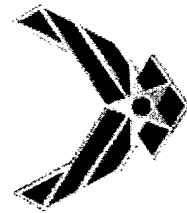


**Objective:**  
To develop three-dimensional model to analyze damage in preformed composite with fracture mechanics approach

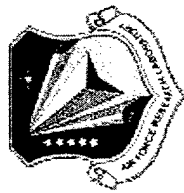


# Unit Cell of Plain-Woven Composites

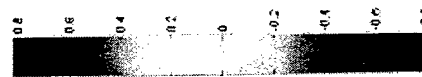
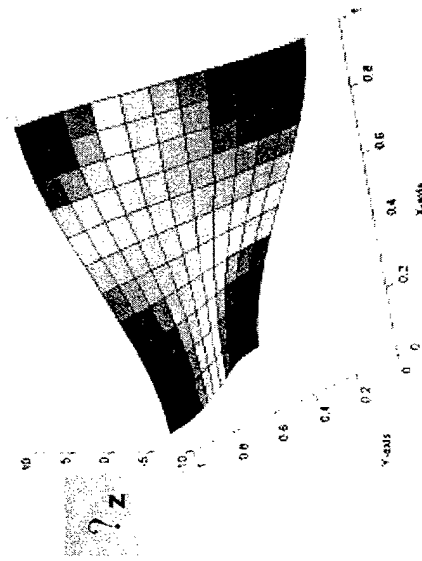
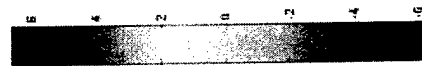
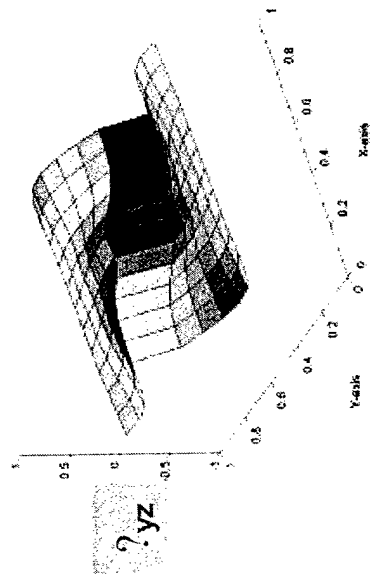
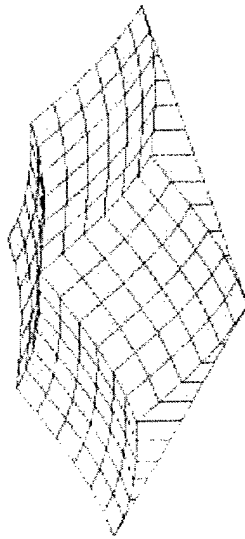


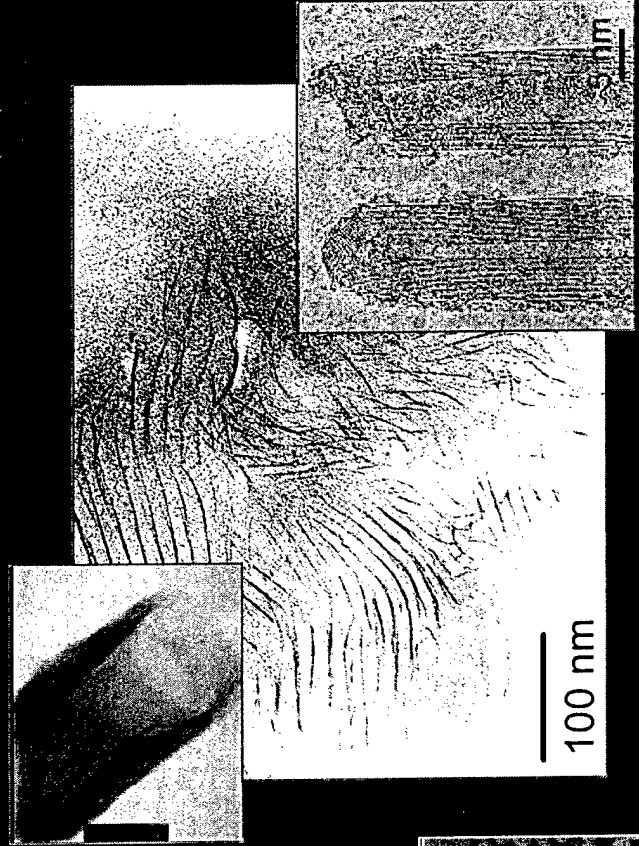
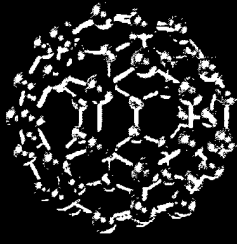


# Interfacial Stress Distribution

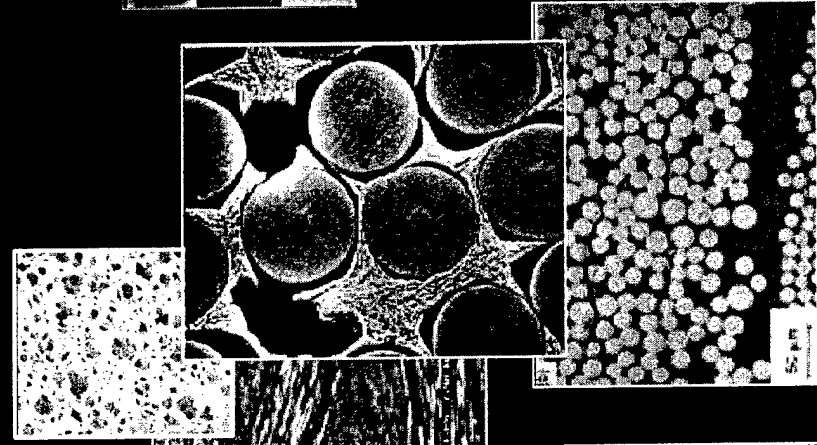


Subregion 5

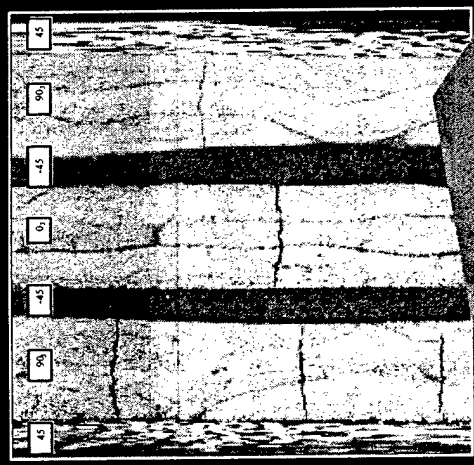
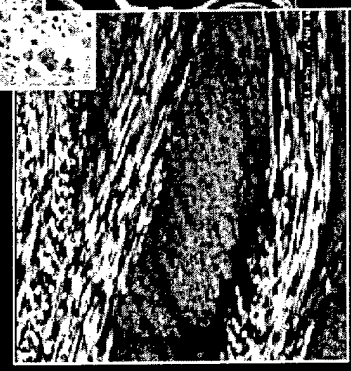




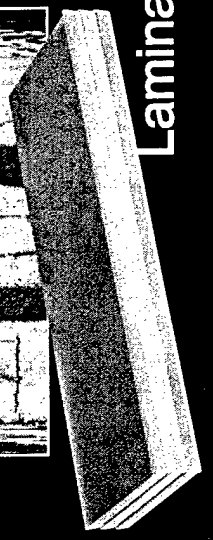
# Nanomechanics



# Micromechanics

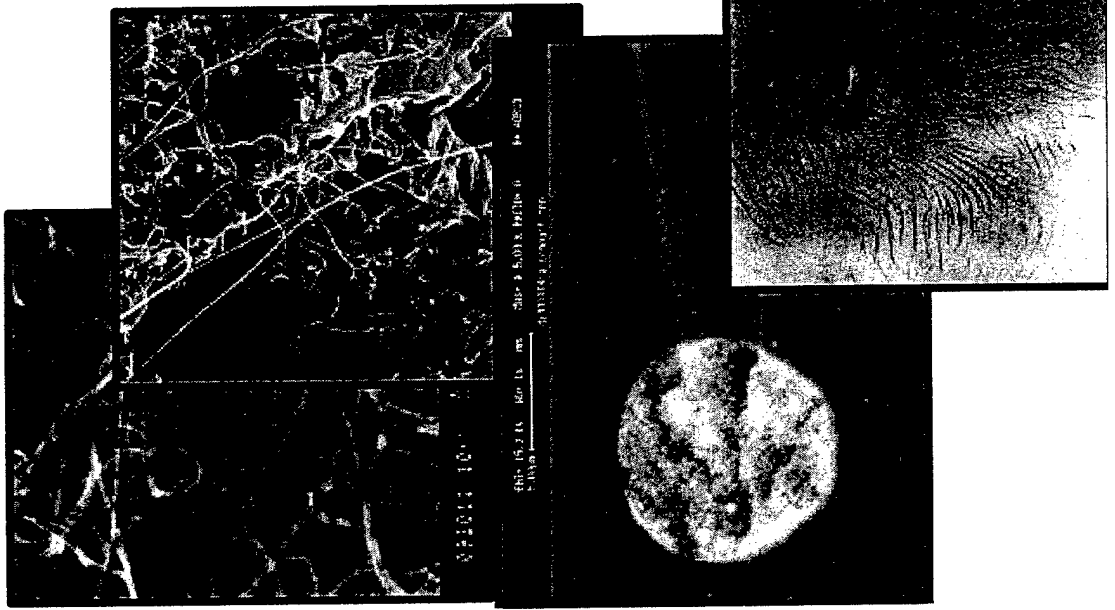
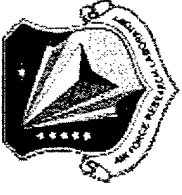


# Laminate Mechanics





# Material Forms... Challenges of Nanoscale

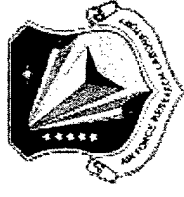


- Model Material Necessary
  - Well controlled morphology
  - Repeatability
- Resins (Suitable E, Tg, ...)
- Nanoconstituent
  - Processability
  - Availability
- Geometry/aspect ratio/1-2-3D
- Potential for property enhancement
- Interface
- Fabrication: May need to look into 'new' techniques (IC fab'n, ..) or out-of-the-box constituents

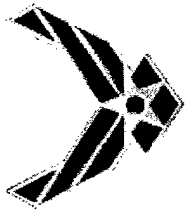


# Nano Composites Potential/Challenges

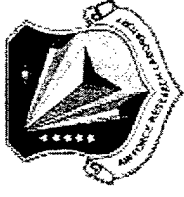
---



- Nanoconstituents offer an exciting new dimension of tailorability to composites
  - **Additional constituent for providing new behaviors to existing composites**
  - **Not just mechanical properties of interest – expect high interest in multifunctionality: CTE, electrical, thermal...**
- Fundamental understanding of the predictive processing-structure-property relationship must be addressed
  - **Necessary to enable manipulation and exploitation of nanomaterials**
  - **Key opportunity for mechanics community leadership**
  - **Focus required for advancement**
- Bring micromechanics/continuum, nanocomposites community and molecular modelers together to dialogue
- Advocate unified focus; harness mechanics community

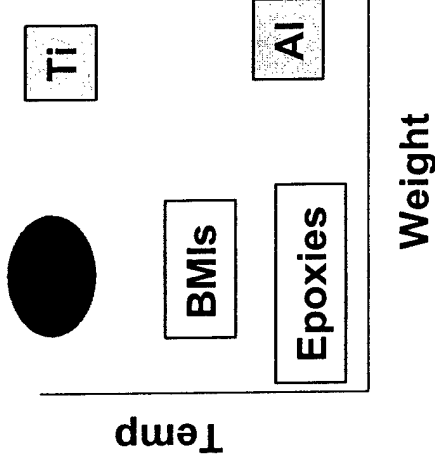


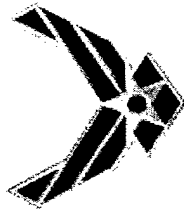
# Extreme Environment: High Temperature Composites



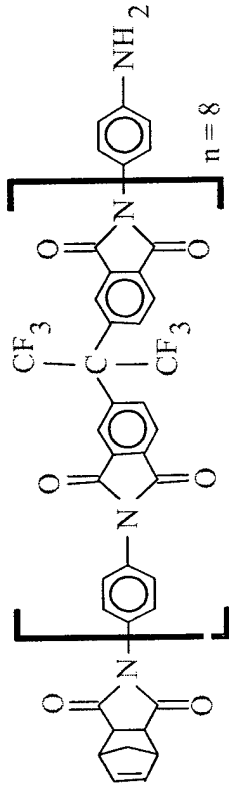
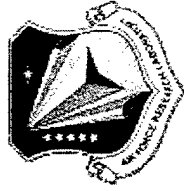
## Rationale

- Today: Military aerospace platforms require performance that is currently not met by nonmetallic systems
  - Ti primary material of choice
  - BMI qualified for use at 325°F
  - PMR-15, AFR-700B flying with issues
- Need: Reduced weight, reduced cost, special performance, fatigue...high payoff for many military applications
  - Airframes – high temperature primary and secondary structure
  - Engines
  - Exhaust washed structures
  - Launch vehicles
- Needs identified by multiple existing and future military platforms



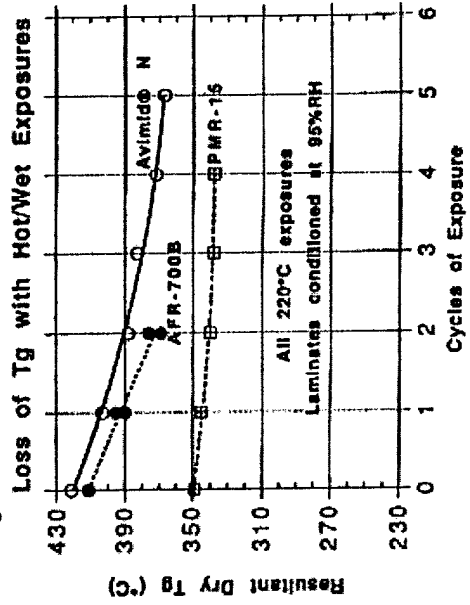
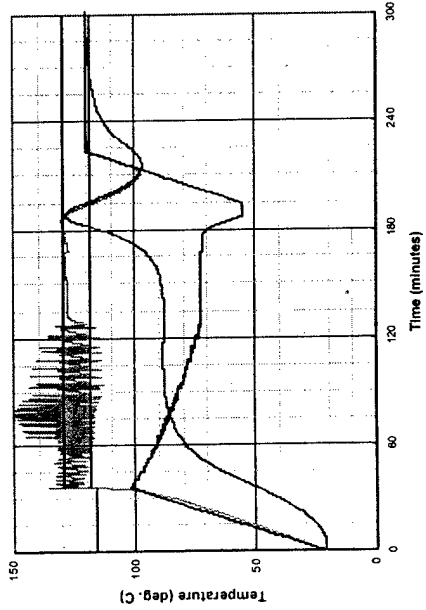
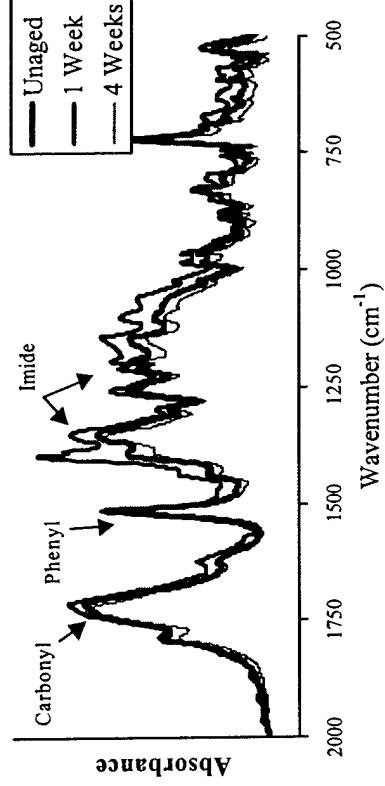


# High-Temp PMC Research



- System Support**
- SPOs
  - Primes
  - Other AFRL
  - Contract Programs

## Material

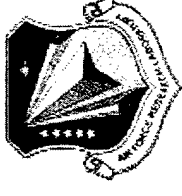


## Process Development

## Service Life Performance 26



# Extreme Environments: Cryo

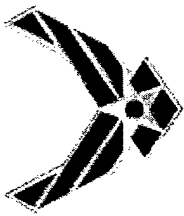


## Background

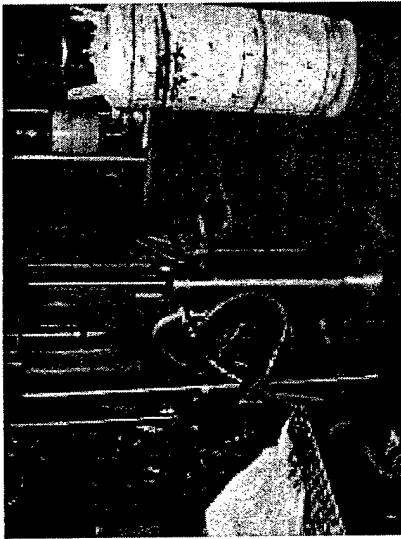
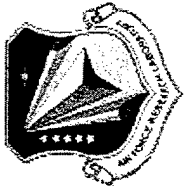
---

- Extensive use of PMCs is enabling for next generation civilian and military reusable launch vehicle concepts
- Use of PMCs proposed for structural cryotanks; limited number have been built
- Key is life and performance prediction including:
  - Microcracking and permeation
  - 1000s of thermal/mechanical cycles
  - Large temperature extremes: cryo (-253 °C for LH<sub>2</sub>) to re-entry temp.
- Extremely limited test protocol / knowledge base available

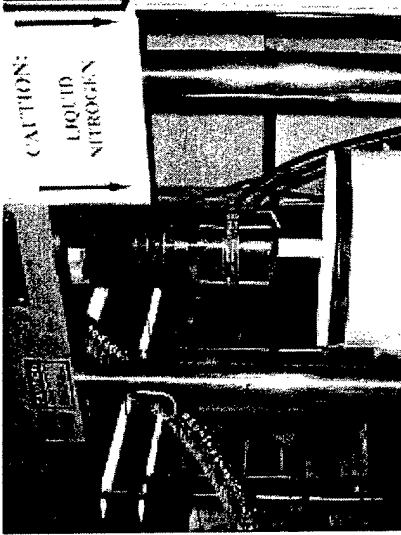




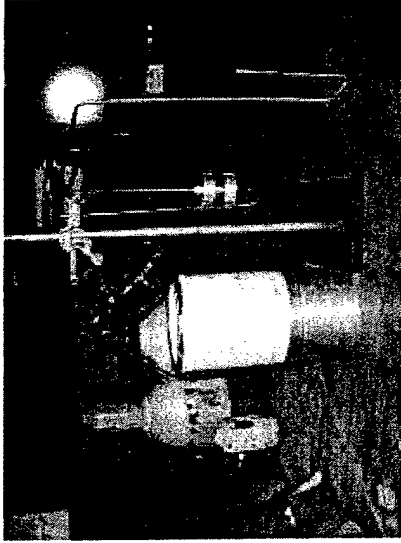
# Extreme Environments: Cryo MLBC Cryogenic Capabilities



LHe Cryostat  
+ mech load



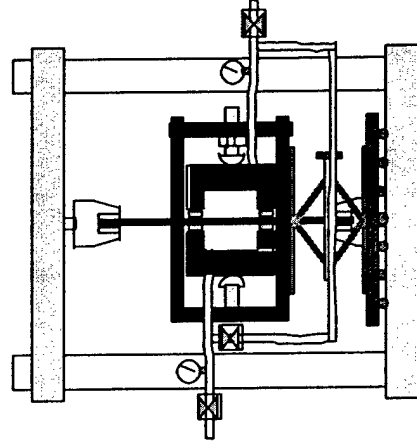
LN<sub>2</sub> Cryostat  
+ mech load, fatigue



LN<sub>2</sub> / GHe Permeability



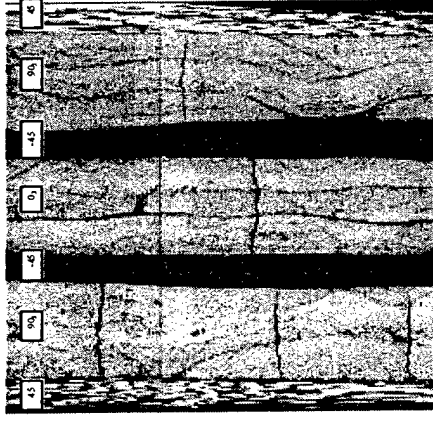
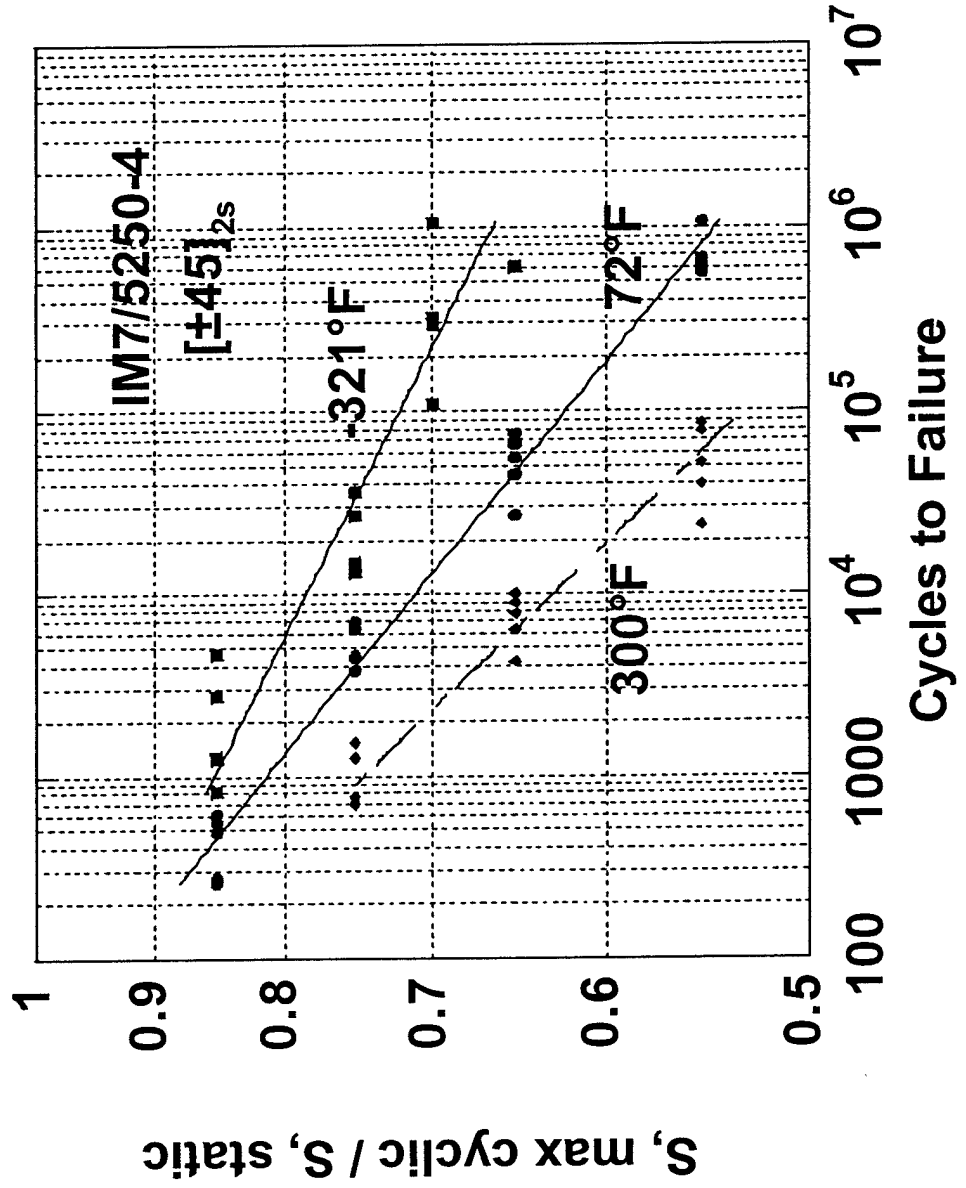
LN<sub>2</sub> Cryo/Thermal Cycler  
+ constant mech load

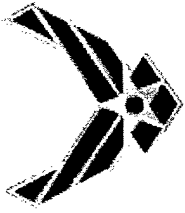


LN<sub>2</sub> Permeability  
+ mech load

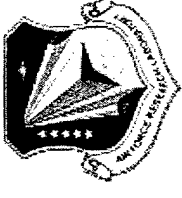


# Extreme Environments: Cryo Fatigue Data





# Improved Capabilities: Thermal Management (TM) Materials

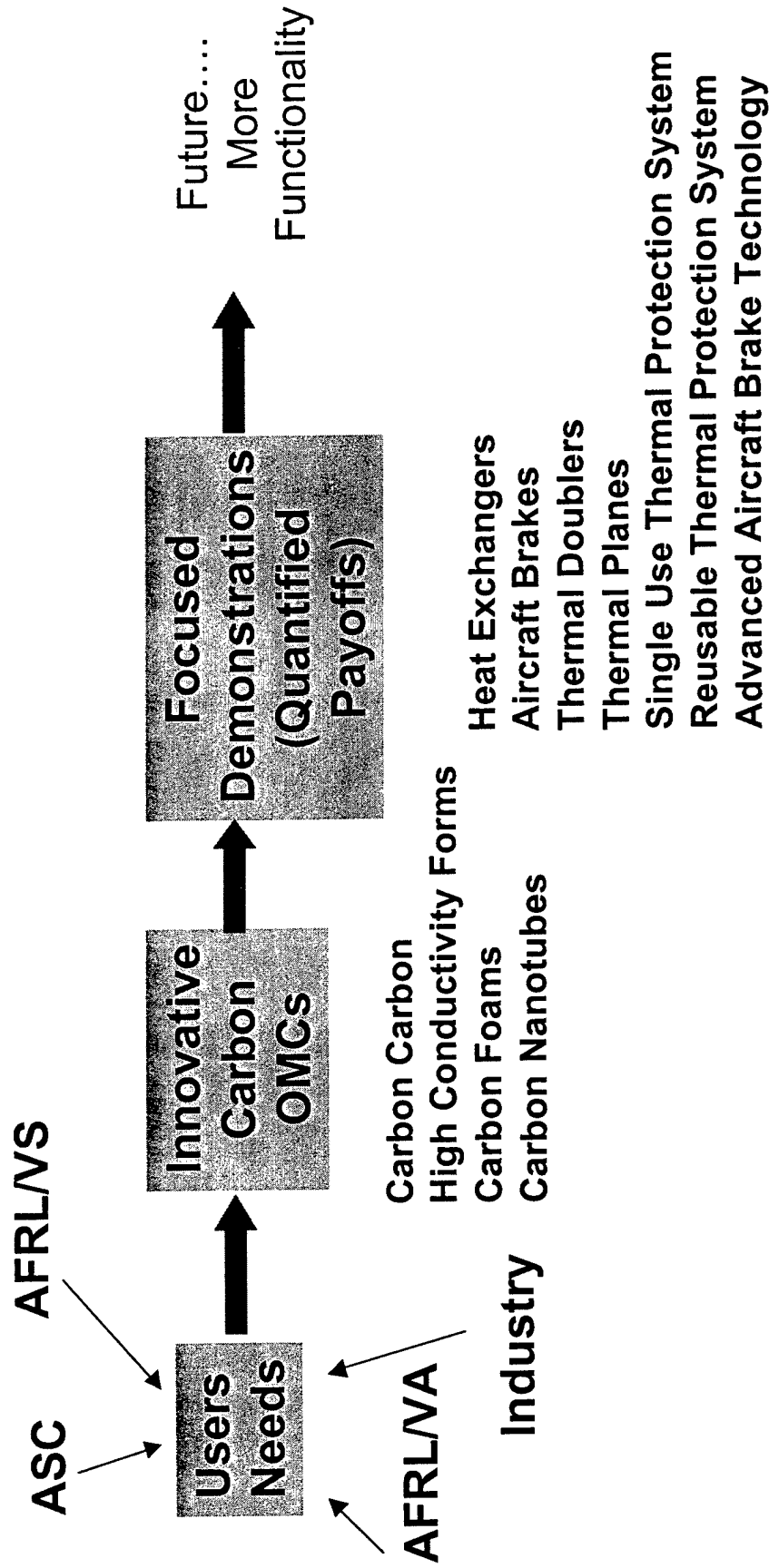
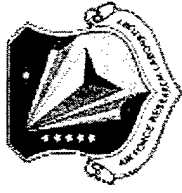


## Rationale

- **Challenge:** Systems are becoming increasingly sophisticated. Structures are required to do more than perform load bearing or volume encasing functions-multifunctionality
- Thermal loads that must be managed are increasing as capability grows
- Pervasive in aerospace
- Military applications:
  - Aircraft:
    - Environmental Control System for C-130, F-22, JSF, F-18 E/F
    - Electronics cooling: F-22, JSF
    - Thermal Management: UCAV, Sonic Engine Cooling, Airborne Laser, Brakes
  - Spacecraft:
    - Minisats, Space Based Laser, Launch Vehicles

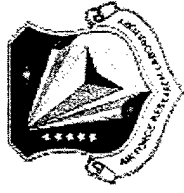


# Improved Capabilities: TM Materials Strategy

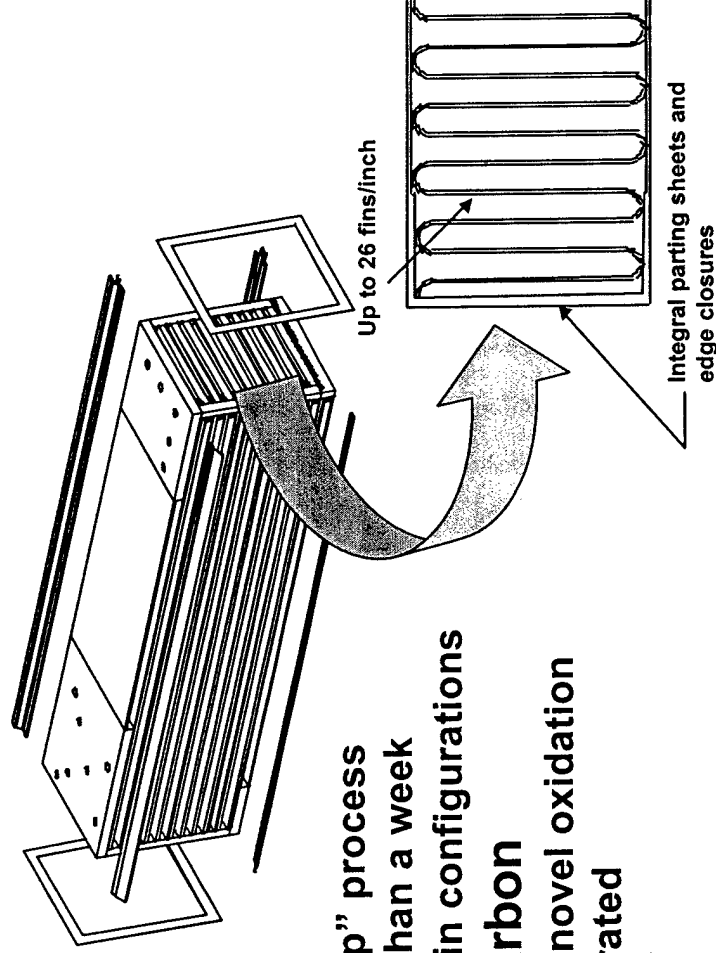
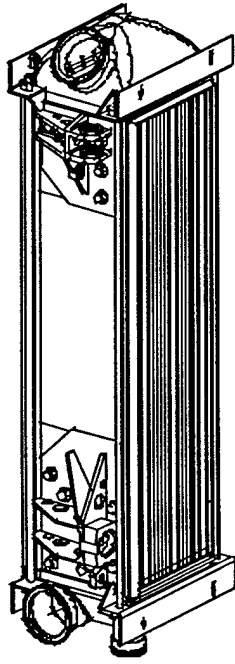




# TM - Air Applications Materials Technology Development



## Thermal Management for Heat Exchangers



### Low Cost Carbon-Carbon

- Multiple approaches to a "one-step" process
- Reduces processing time to less than a week
- Enables thin walled high density fin configurations

### Oxidation Resistant Carbon-Carbon

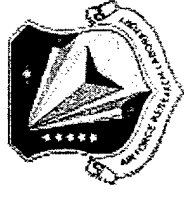
- 1200°F temperature goal requires novel oxidation schemes not previously demonstrated
- The use of inhibitors is necessary

**Extends time between failure by 2X**

**Extend range due to 40% weight reduction and increase heat exchanger efficiency by 10%**



# TM - Current Programs: Non-metallic Heat Pipes



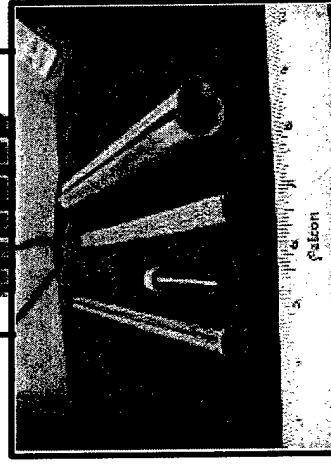
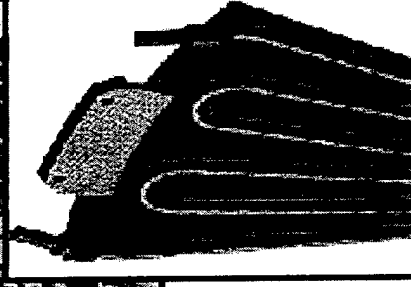
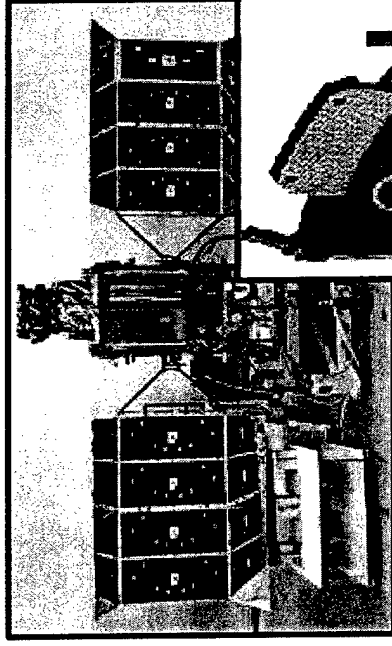
## OMC Heat Pipes

### Why OMCs?

- The trend towards OMC structures for weight, stiffness and dimensional stability has driven the need to have composite radiators
- Aluminum heat pipes cannot be readily embedded in composite panels due to CTE mismatch issues

### Technical challenges of OMC heat pipes:

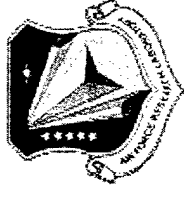
- Non permeable –  $2 \times 10^{-10}$  scc/sec He
- CTE match of hybrid OMC material and interface joint material – ? CTE – 0 to 1 ppm/K
- Integration of thermal efficient heat pipes with OMC skins and honeycomb core components
  - Fewer heat pipes per radiator possible
  - Less weight
  - Less complex design and fabrication processes



The use of OMC reduces component weight (i.e. up to 10-20%)



# PACT: Partnership for Advanced Composites Transition



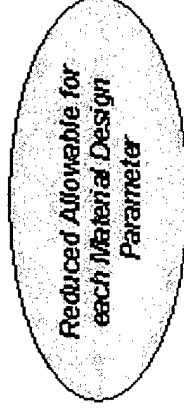
New and innovative composite systems can enable advancements in aircraft design and operational limits

## HOWEVER

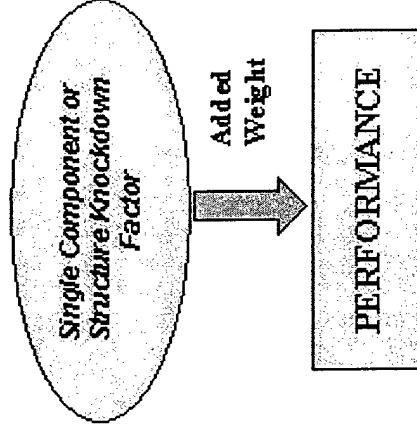
- Knockdown factors for environmental effects, effects of defects, etc. based on worst-case assumptions lead to unrealistic, excessively conservative designs.
- Knockdown factors (resulting in weight penalties) often remove composites from systems during EMD phase.

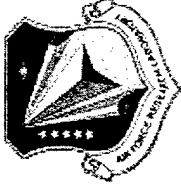
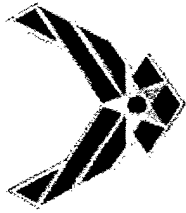
### Environmental 'Knockdown Factors'

Method 1



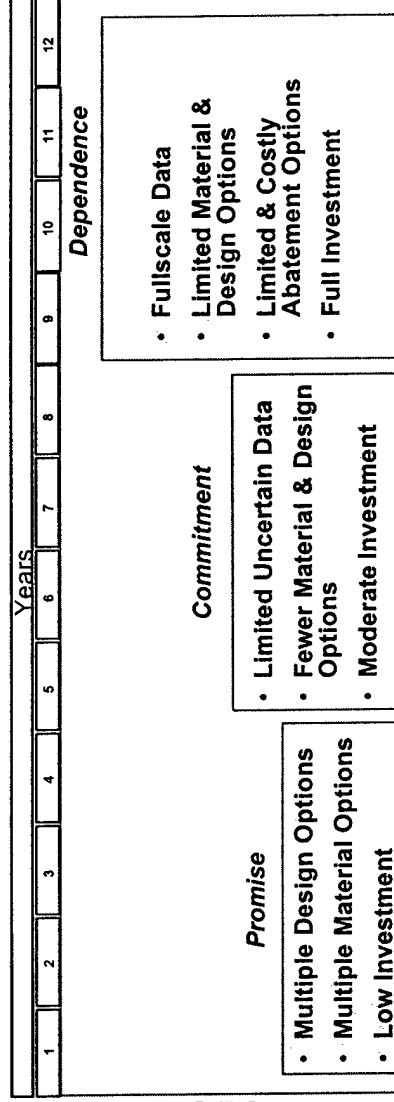
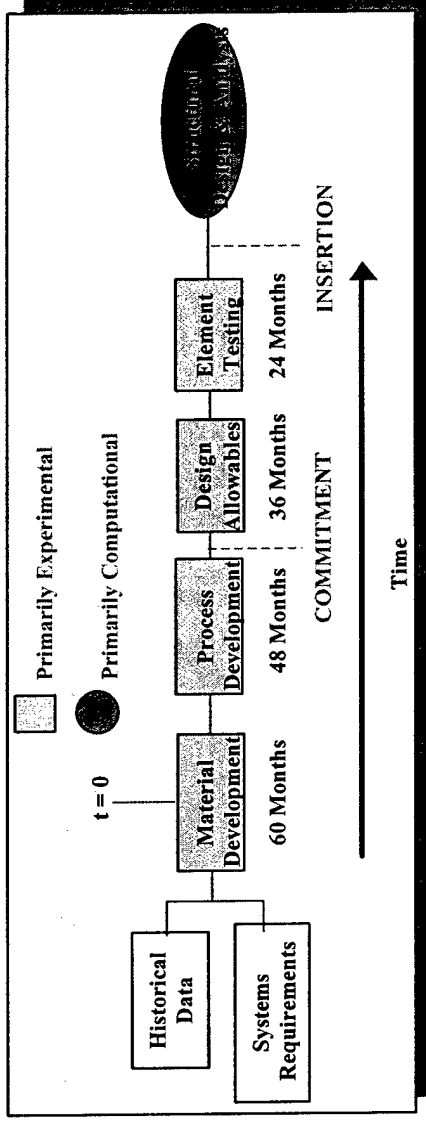
Method 2



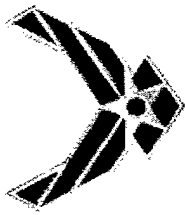


# Motivation for PACT

- Complex 12+ year cycle
- Most data generated after commitment
- Producibility and performance issues are identified at a time when:
  - design options are limited
  - abatement is costly
- Uncertainty creates risk for designers throughout the cycle



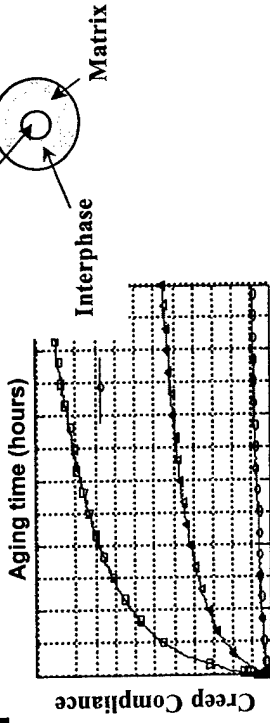
***Designers Need to Get Earlier Data with Less Uncertainty to Lower Insertion Risk***



# PACT: Grand Challenges

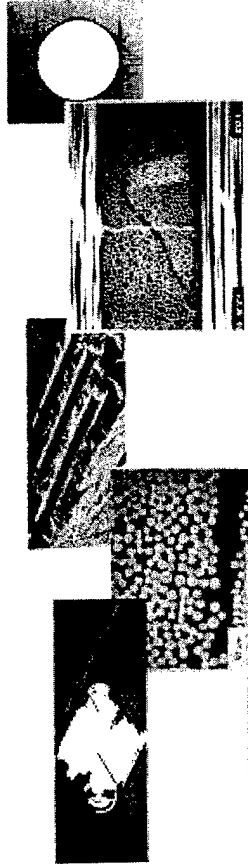


- Processing/property relationships

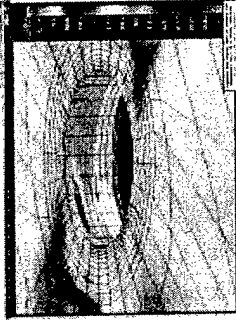


- Chemistry/mechanics linkage

- Lack of robust/validated failure criteria

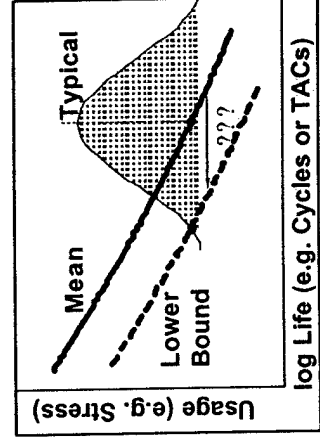


- Development of accurate deterministic engines



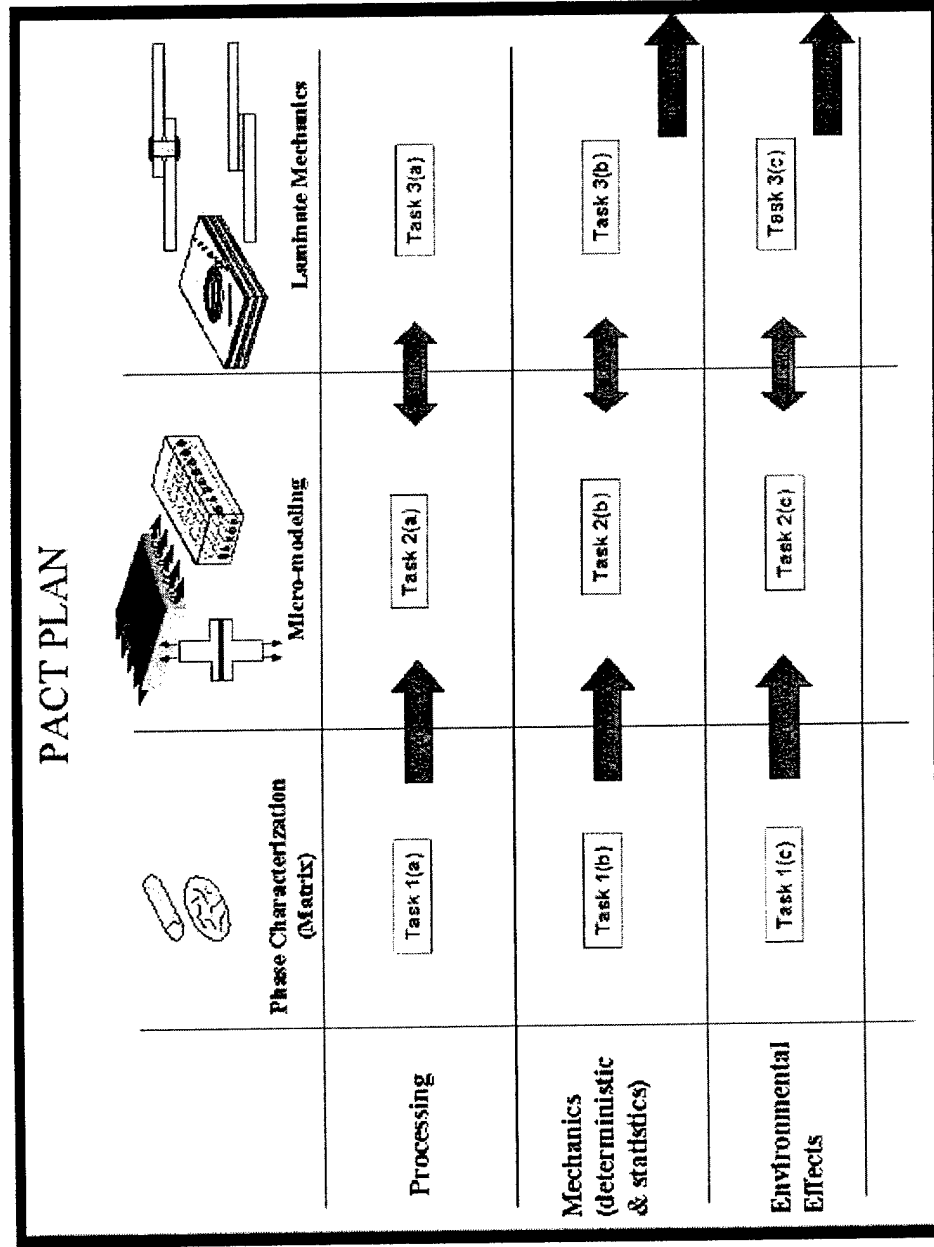
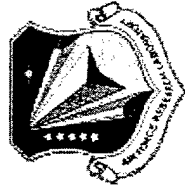
[-45/90/45/-45/45/0<sub>y</sub>? 45°]

- Statistical variability in materials, process, handling and loading

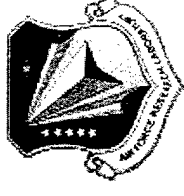
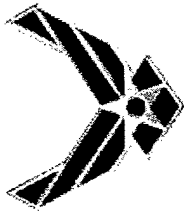




# PACT: Hierarchy of Models



- *Interdisciplinary task linkages are prime motivation*
- *Interdisciplinary programs are required*
- *Polymer Science and Mechanics expertise in MLBC*



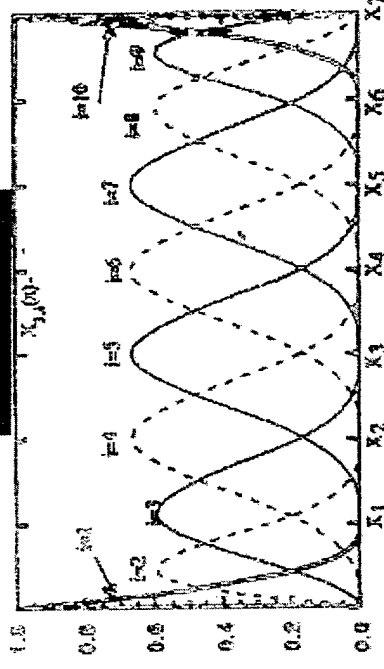
# B-Spline Analysis Method (BSAM)

- 3-D Geometries
- p-, h-, and b-spline approximations
- 21- constant thermo-elasticity
- fracture mechanics

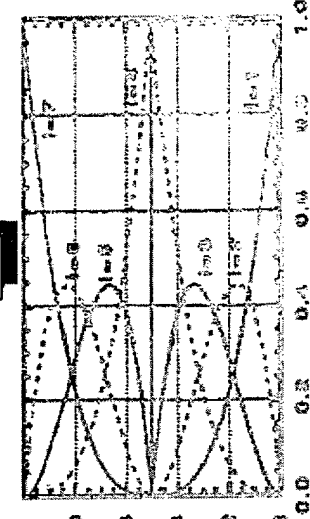
$$u(x, y, z) = \sum_i \sum_j \sum_k U_{ijk}(x) Y_j(y) Z_k(z)$$

$u$  ? continuous at all points  
 $\frac{\partial u}{\partial x}$  ? continuous at all points  
 $\frac{\partial u}{\partial y}$  ? continuous at all points  
 $\frac{\partial u}{\partial z}$  ? discontinuous at ply interfaces

$X_i$  and  $Y_j$



$Z_k$

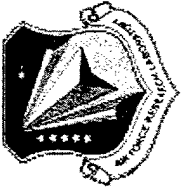


Ply Interfaces

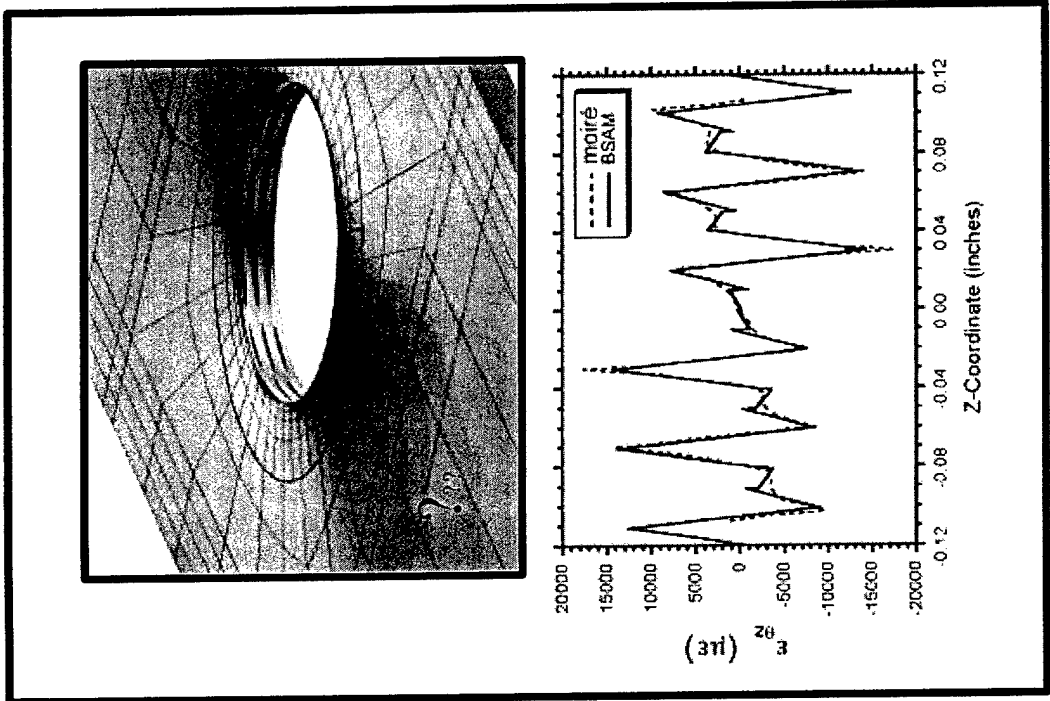
Similar to the old SVELT, but much more flexible!



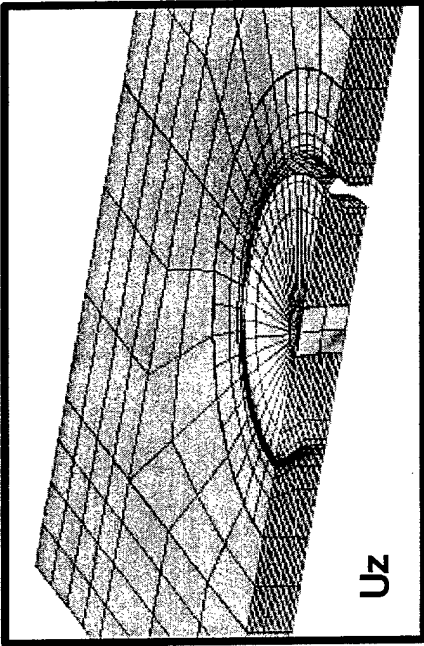
# Capabilities



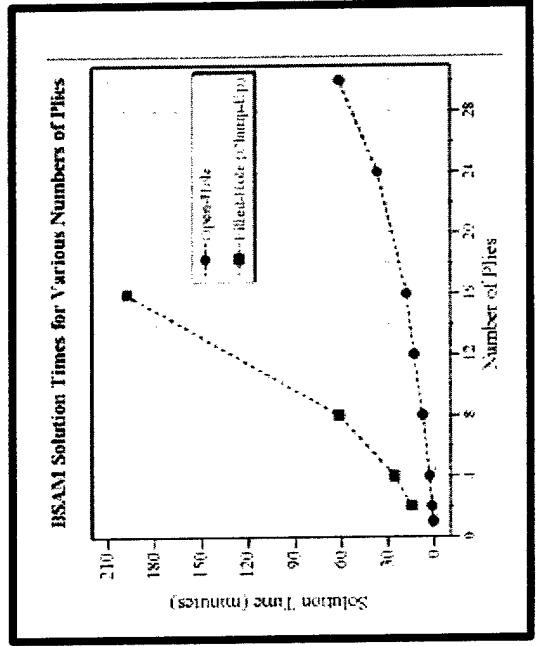
## Validated Open-Hole Solutions

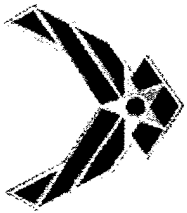


## Filled-Hole Analyses

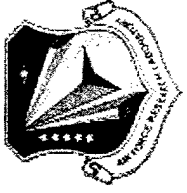


## Quick Solution Times





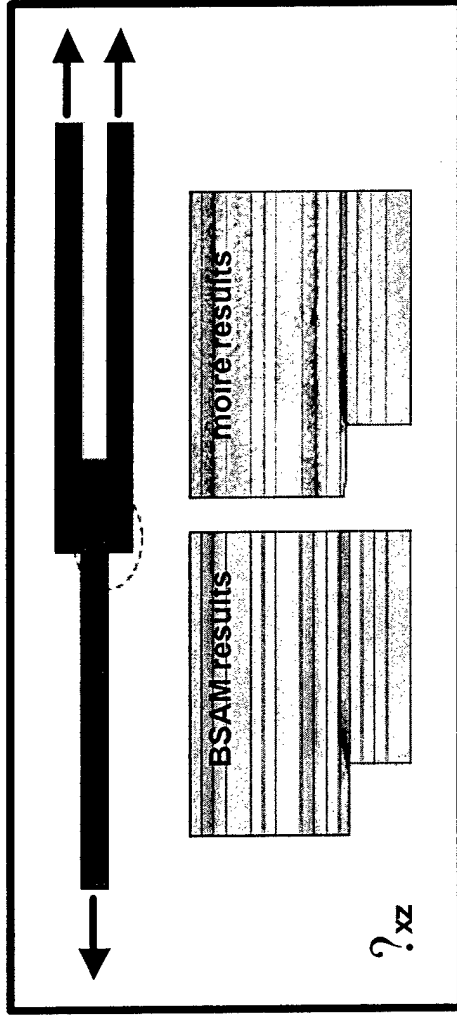
# Capabilities



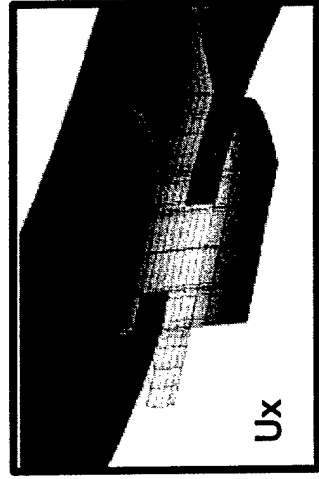
## Mesh-Independent Crack Modeling



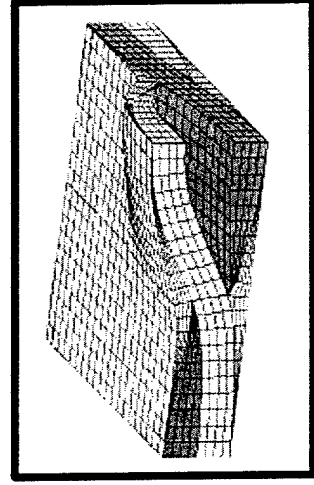
## Bonded Lap-Shear Joints (with residual stresses)



## Bolted Joints



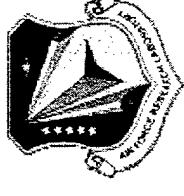
## Woven Architectures





# Summary

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- **Critical mass group: 26 government / 9 on-site professionals / 8 technicians**
- **History of innovation and transition of composites technology**
- **Enthusiasm, expertise, and ideas to keep the composites revolution alive**

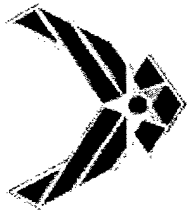
# Overview of Research Activities at AFRL Space Vehicles Directorate

23 Oct 02



**Jeffrey S. Welsh, Ph.D.**  
**Aerospace Engineer**  
**Space Vehicles Directorate**  
**Air Force Research Laboratory**

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# Spacecraft Component Technology (VSSV) Our Position Within AFRL/VS



6400 People  
US\$1.2 Billion

Air Force Research Laboratory

10

Directorates

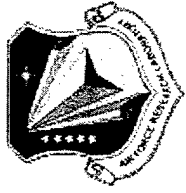
VS: Space Vehicles

VSS: Spacecraft Technology (VSS)

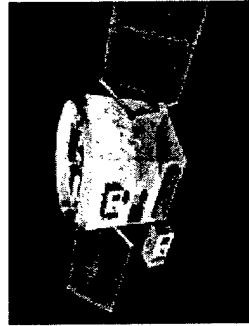
VSSV: Spacecraft Component Technology



# Goal: Enabling Technologies for Future Space Architectures



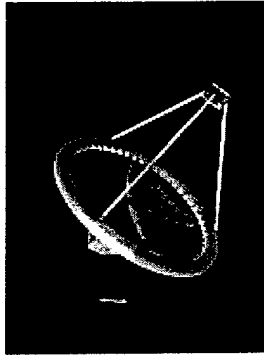
Distributed Spacecraft



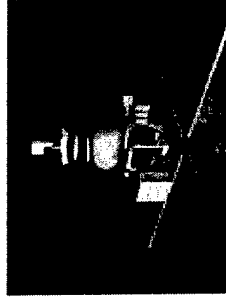
On-Orbit Servicing



Maneuvering Spacecraft



Super Apertures

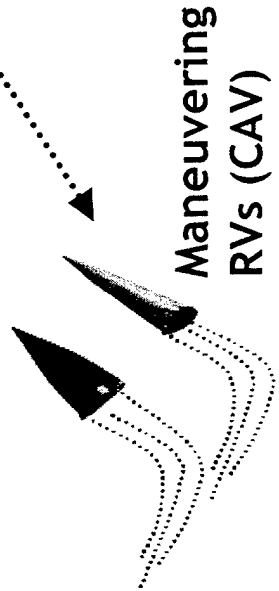
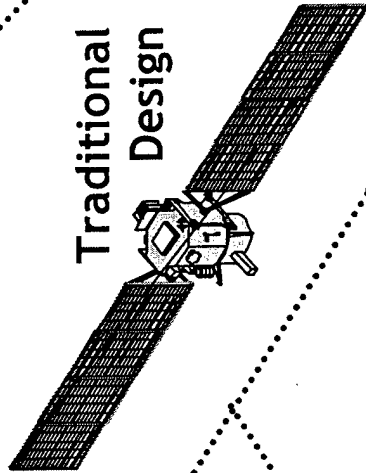


Aero-Braking Systems

Collaborating Constellations



Traditional Design



Maneuvering RVs (CAV)

Space-Based Directed Energy

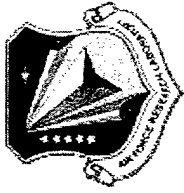


Containerized Payloads

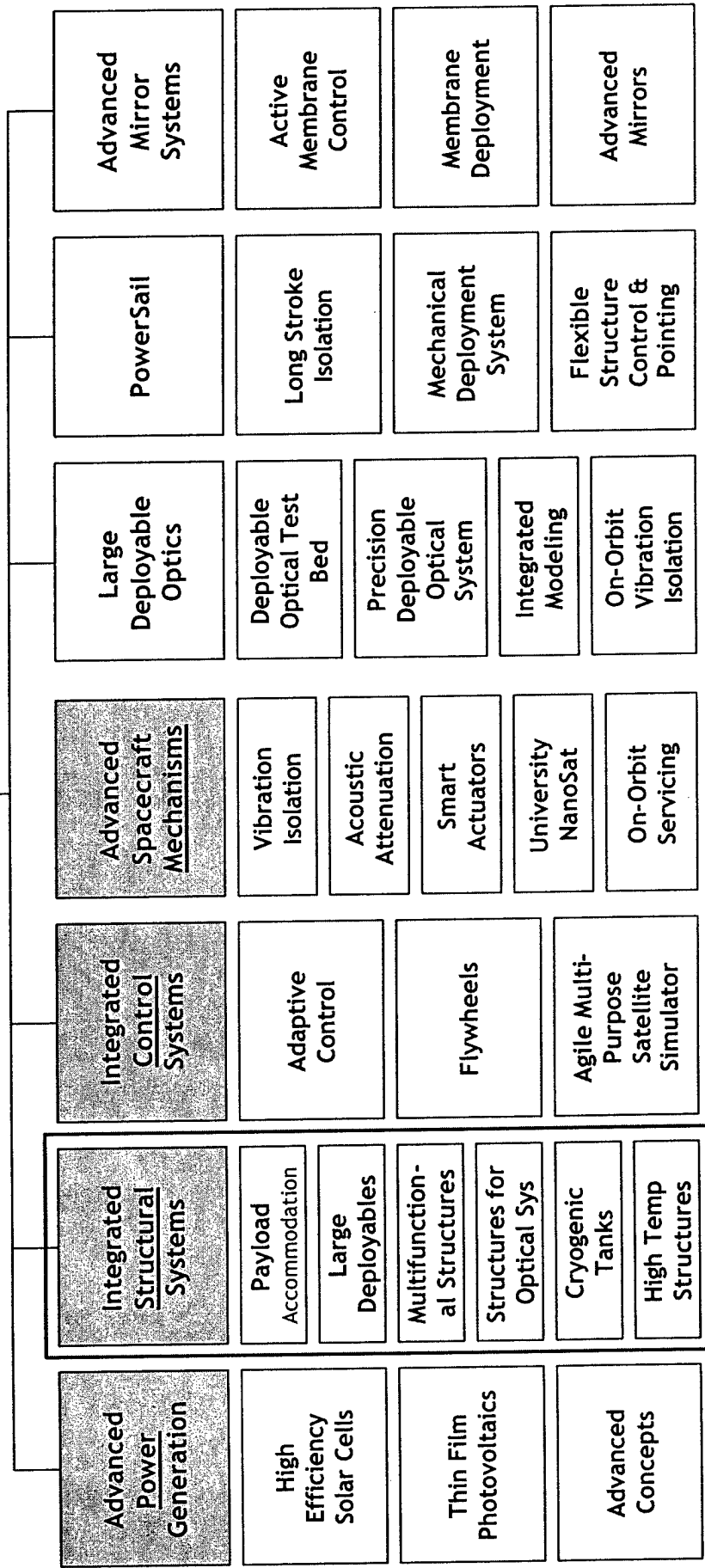




# Spacecraft Component Technology Research Thrusts

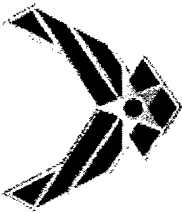


## Center for Spacecraft Component Technologies

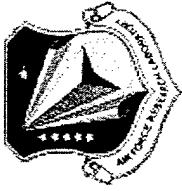


Technology Disciplines

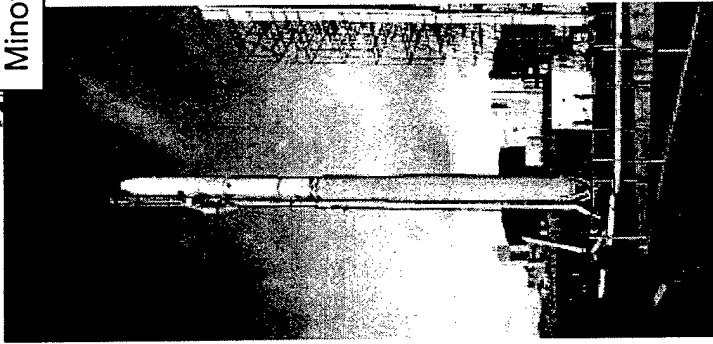
Multi-Discipline Grand "Challenges"



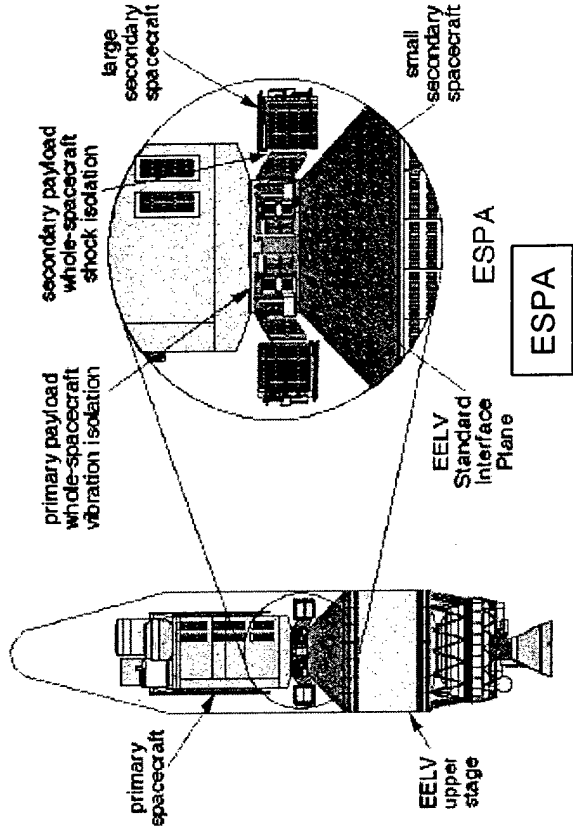
# Integrated Structural Systems Payload Accommodations



Minotaur Grid Stiffened Fairing



Minotaur Grid Stiffened Fairing



- Decrease cost of space access with innovative design and manufacturing
  - Fairings
  - Adapters
  - Payload containers for Reusable Launch Vehicles

- Enable launch of large space systems with large payload fairing development program



# Low-Cost Fabrication of Advanced Grid-Stiffened Structures Results

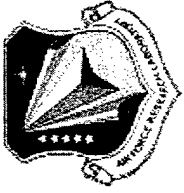
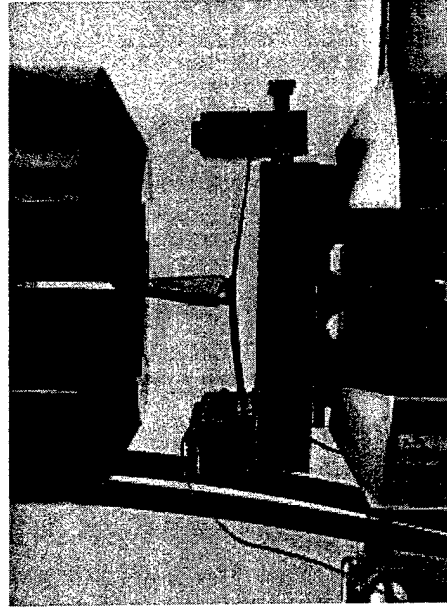


Table 1. Comparative Results

| Design                                   | Base-line | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|--|-----------|----------|----------|----------|----------|----------|
| Average failure load (lbs/inch of joint) | 76.8      | 173.7    | 200.7    | 121.1*   | 167.0    | 233.4    |
| Percent of Baseline                      | 100       | 226      | 261      | 158      | 217      | 304      |
| Testable Coupons                         | 2         | 1        | 1        | 1        | 3        | 3        |

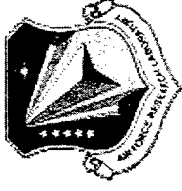
\* specimen failed in rib above the staples, not at the joint



Typical coupon test approaching failure load

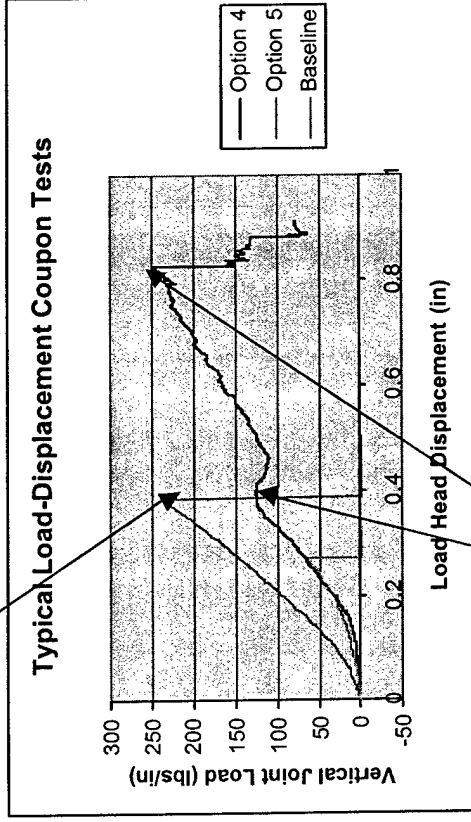


# Low-Cost Fabrication of Advanced Grid-Stiffened Structures Results



- All options improved joint performance
- Options reducing peeling stress worked better compared to direct reinforcement techniques
- Direct reinforcement ultimate strength was high but initial failure strength must be used for design

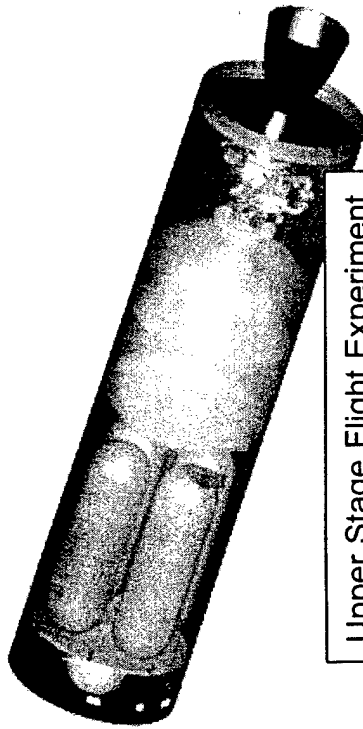
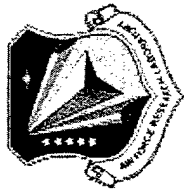
Low peel stress option  
(initial and ultimate failure  
coincident)



Direct reinforcement option  
(initial failure much lower  
than ultimate)



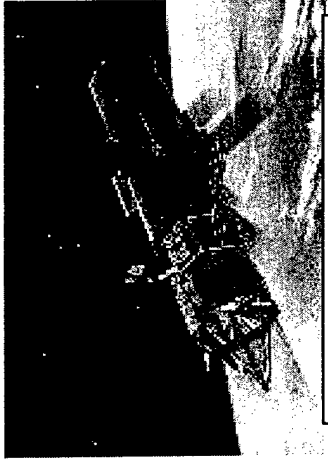
# Integrated Structural Systems Cryogenic Tanks



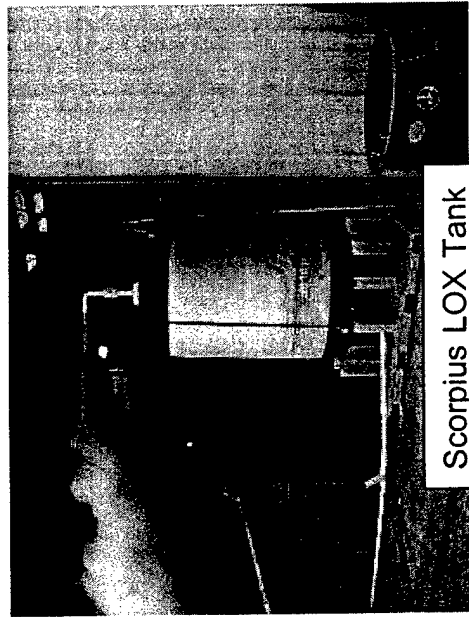
Upper Stage Flight Experiment



InterWeave Winding

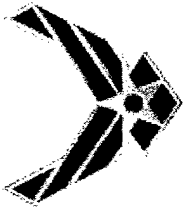


Long Term Cryo Storage



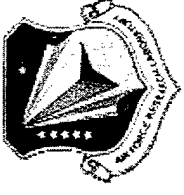
Scorpius LOX Tank

- Enable Single Stage to Orbit (SSTO) with composite cryogenic storage tanks
- Provide lighter, less costly tanks for long term on-orbit storage of cryogens
- Reduce cost of space access thru low cost cryo tanks for expendable rockets

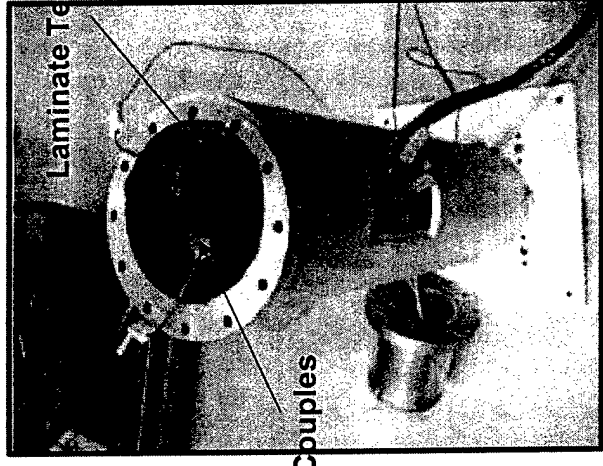
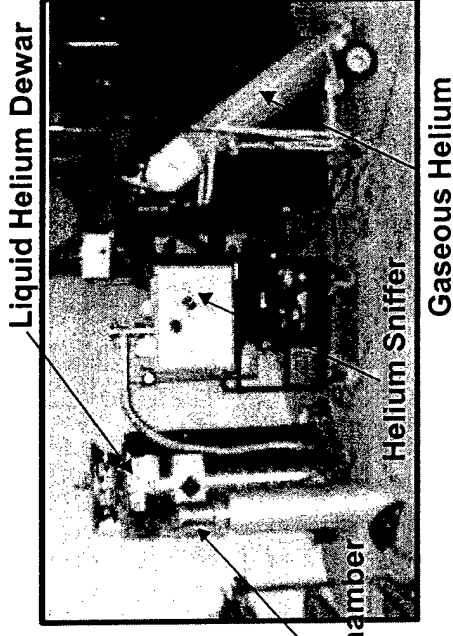


# Composite Laminate Microcrack Mitigation

## Introduction/Background

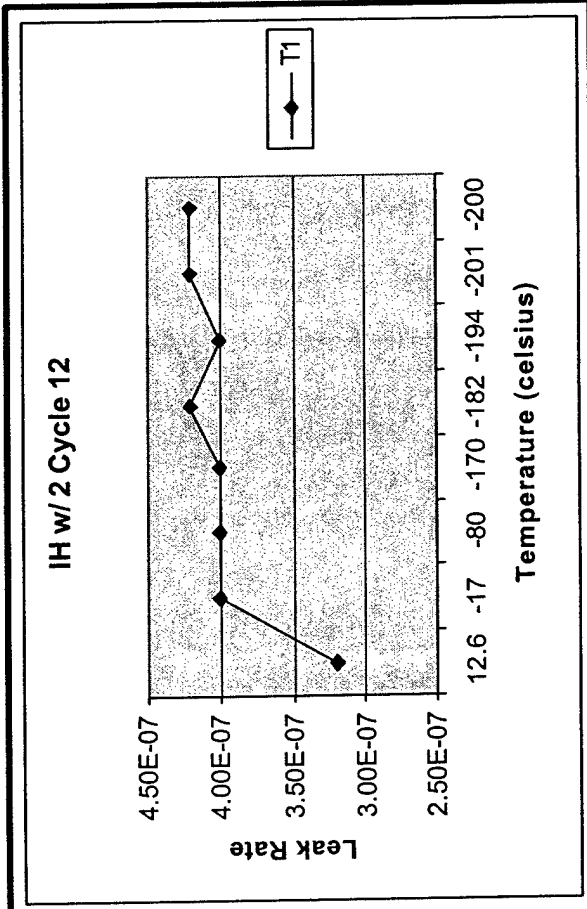
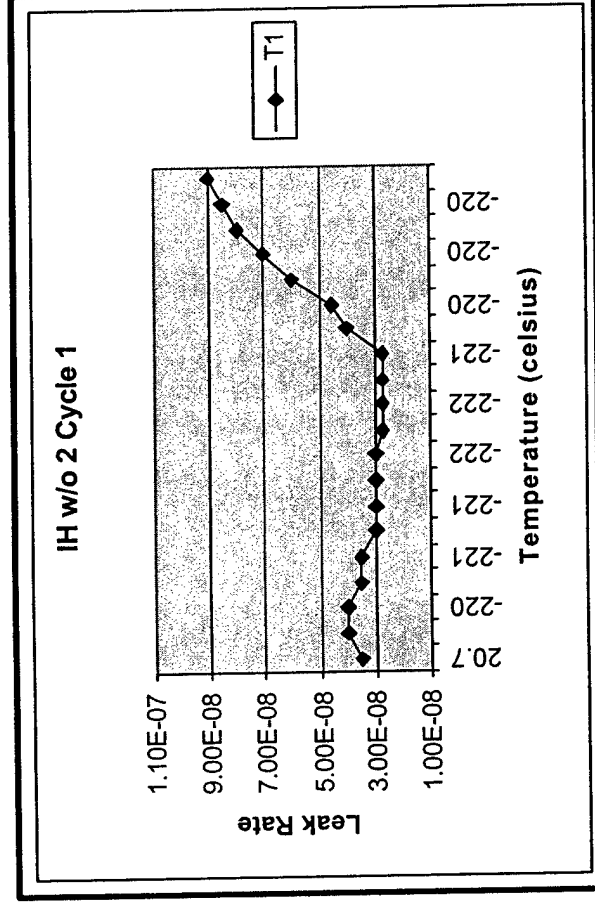


- Objective: Develop Manufacturing Processes, & Novel Material Concepts to Delay, Reverse, Prevent, or Stop Composite Laminate Microcracking under Extreme Thermo Cycling.
- Background: Space Community unsuccessful thus far developing cryogenic composite tankage, forced to use Metallic Tankage (Payload margin not optimized).
- Current Focus: Self Healing Laminate, & Laminate Surface Texture Research
- Operational Benefits
  - 50% Less Mass than Metallic Tanks
  - Enabling for SSTO, Reusable Vehicles
  - Reduced Tank Fabrication Costs





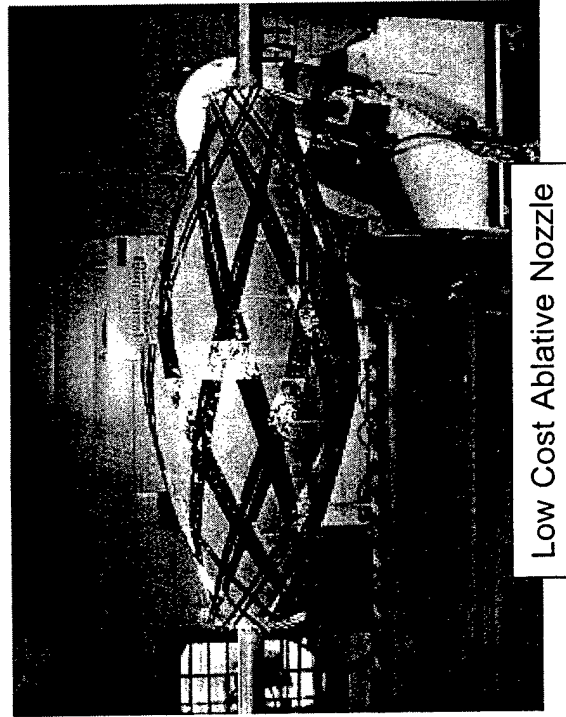
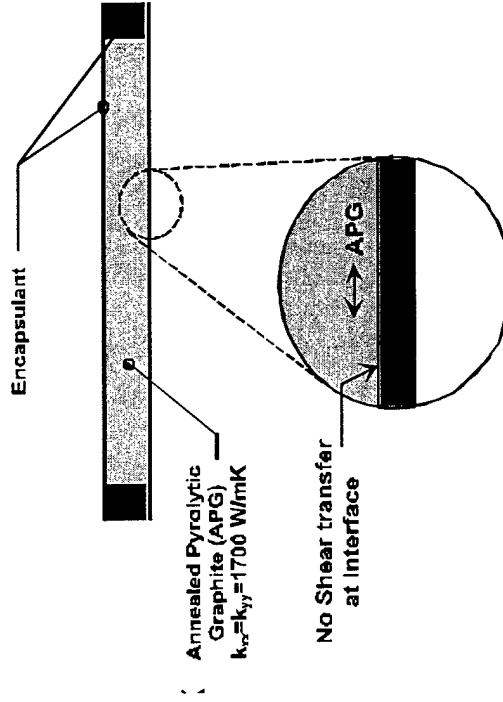
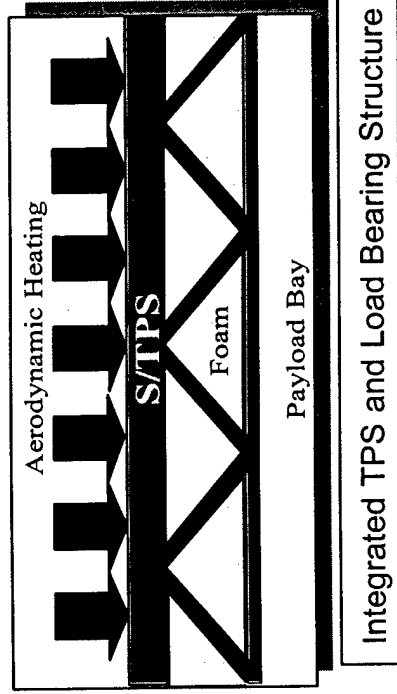
# Composite Laminate Microcrack Mitigation Results



- Data Summary - Results as Expected
  - Leakage Increases as Temperature Decreases
  - Slight Leak Rate Decrease during “Heatup” to Ambient
  - Fiber/Resin CTE Difference Primary Cause of Microcrack
  - Need additional data on Omni-Directional Fabric



# Integrated Structural Systems High Temperature Structures

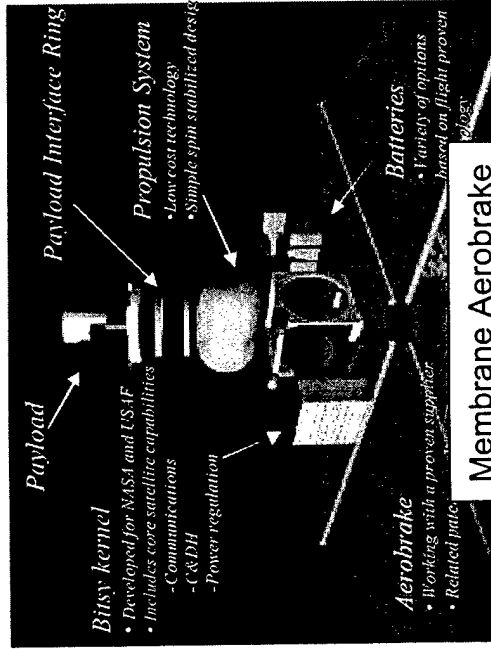


- **Enable Single Stage to Orbit (SSTO) Reusable Launch Vehicles**

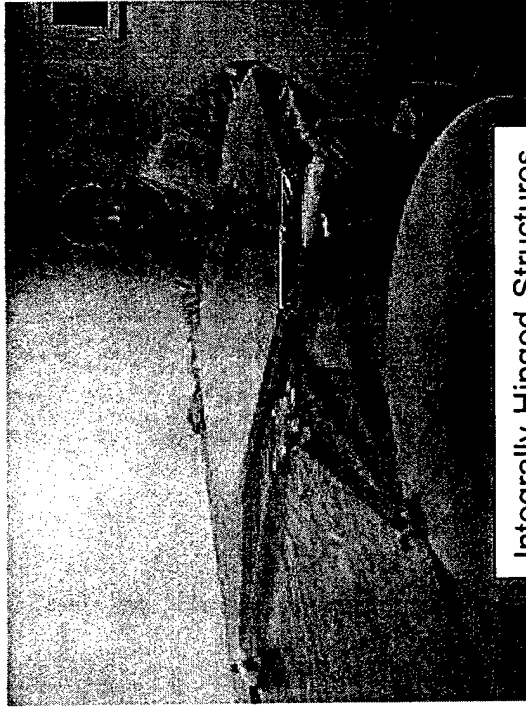
- Integrate TPS and Structure into hybrid system
- Low maintenance between sorties
- Low cost
- Light weight



# Integrated Structural Systems Large Deployable Structures



Membrane Aerobrake

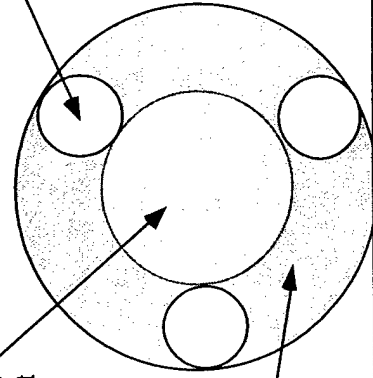


Integrally Hinged Structures

A Few Pre-Pultruded S-Glass Epoxy Rods Made Using "Leadtrusion" Lock Graphite Rod to Precise Center

Graphite/Epoxy Pre-Pultruded Core Element

S-Glass Epoxy Wet-Out Tows Fill Interstitial Sites During Pultrusion Process



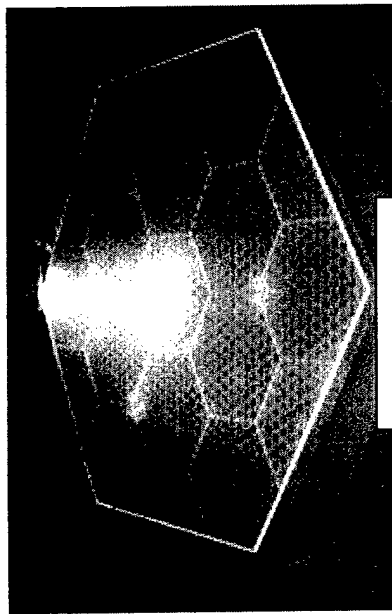
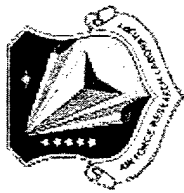
Pultrusion for Space Structures

• Enable new ultra-large space system architectures

- Membrane structures
- Elastic Memory Composites (EMCs)
- Pultruded booms
- Stiffness critical structures



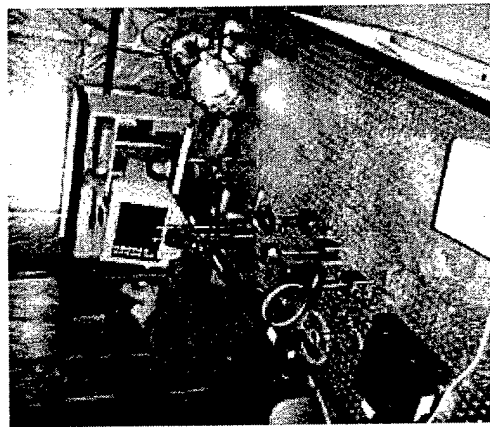
# Integrated Structural Systems Structures for Optical Systems



AMSD Mirror



Elastic Memory Composite

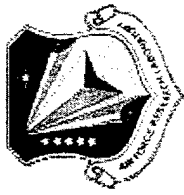


Active Membrane Structures

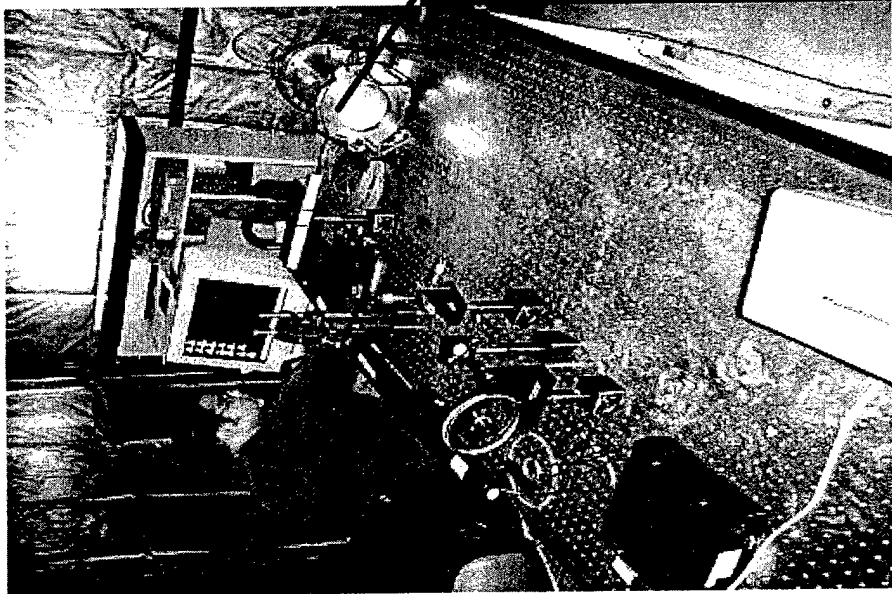
- Enabling technologies for space-based optical systems
  - Lightweight mirror structures
  - Active membrane optics
  - Stiffness critical joining
  - Rapid mirror fabrication



# Electroactive Polymer for Membrane Optics Experimental Measurement of Surface Change

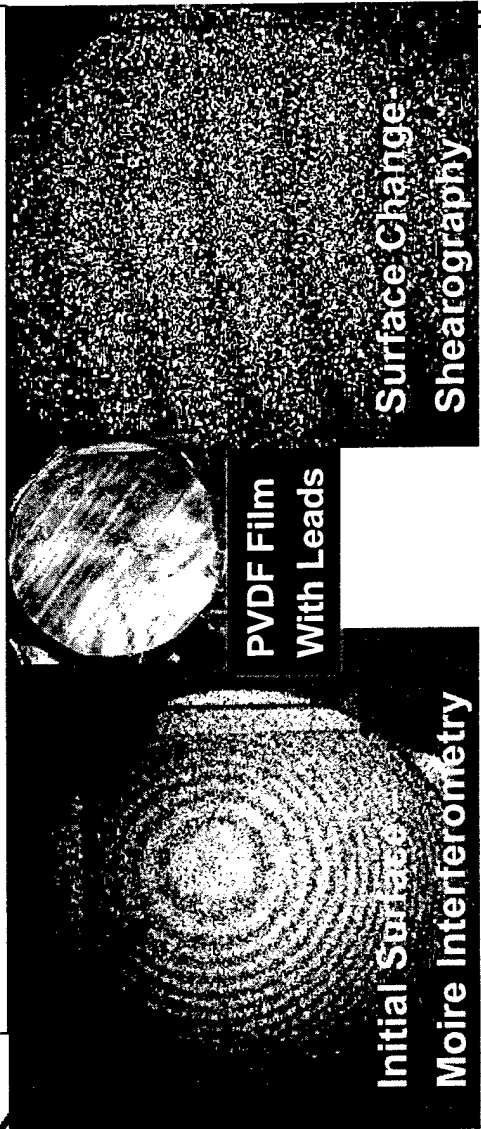


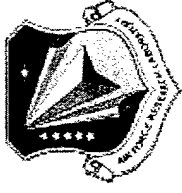
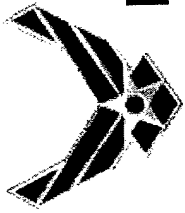
LabView Based Interferometry  
Software Development  
6" Diameter Vacuum Chamber



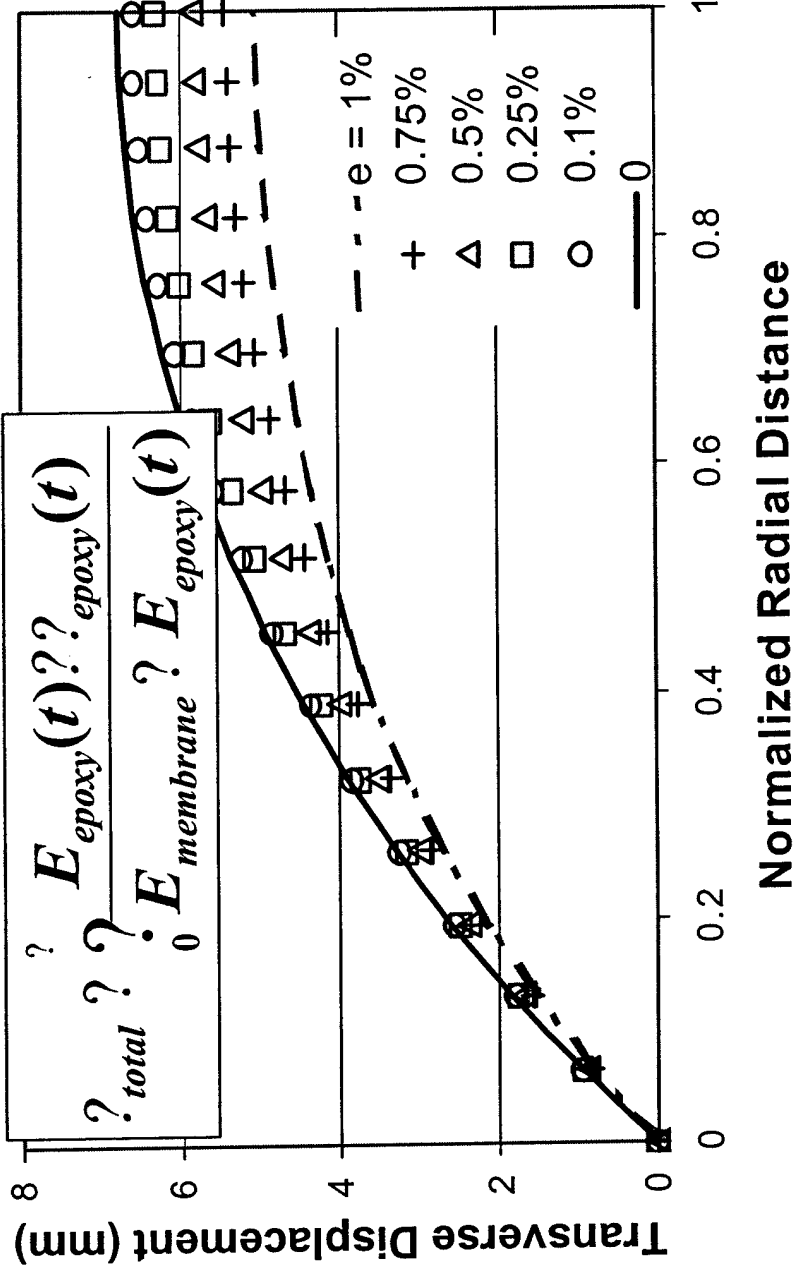
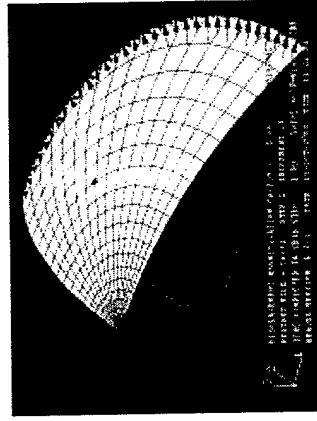
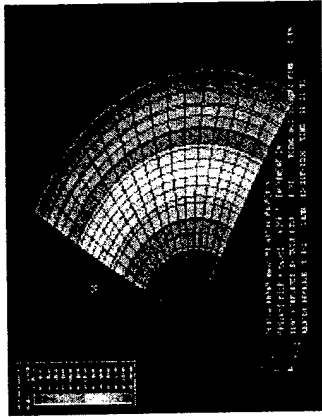
\* Apply epoxy to membrane and monitor surface shape change over 30 minutes to 4 hours.  
Observed movement <0.2mm  
Analytically prediction supports observations  
Vacuum loss interferes with test sensitivity

\* Actuate PVDF (Electroactive) polymer  
Micron (?10?) level movement monitored  
Larger (mm level) movement not possible

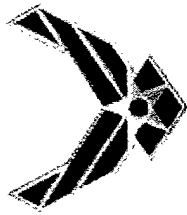




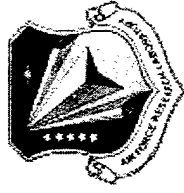
# Electroactive Polymer for Membrane Optics Finite Element (ABAQUS) Analyses of Actuation



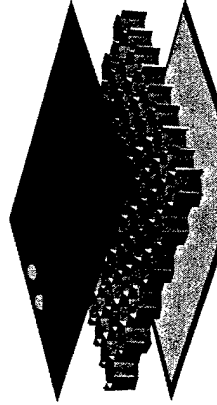
**Conclusion:**  
 Based on Analytical (FEM) results and available test data,  
 Possible shape correction is much less than the surface error!



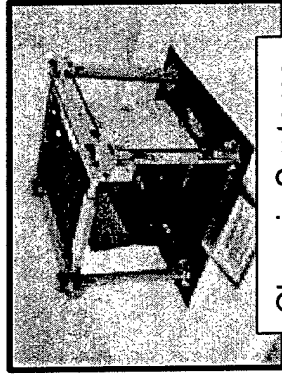
# Integrated Structural Systems Multifunctional Structures



LightWeight Flexible Solar Arrays



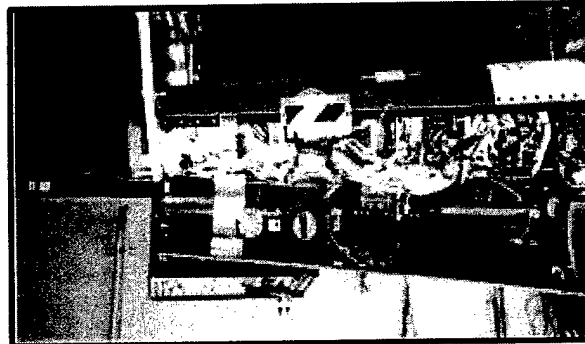
Integral Power Storage



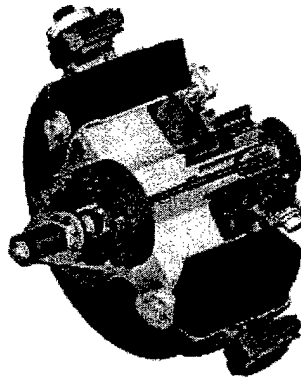
Chassis Systems



Magnetostictive Materials



Launch Vehicle Systems



High-speed Rotors

- Revolutionary improvements in performance through multifunctional structures

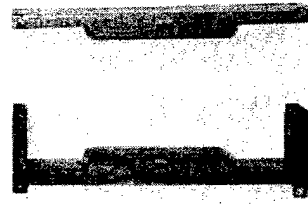
- Lightweight flex cabling
- Miniaturized electronics
- Flywheel rotors for energy storage and attitude control
- Materials with high passive damping
- Energy storage materials/structures



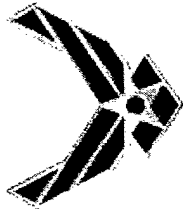
# Self Consuming Satellite Objectives/Background



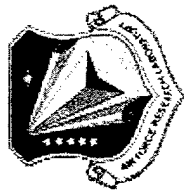
- ✧ Investigate the material properties of Tefzel (fuel for PPT) with Kevlar whiskers reinforcement
- ✧ Variables to be investigated:
  - ✧ Fabrication techniques
  - ✧ Number of layers in lamination construction
  - ✧ Fiber contents
  - ✧ Fiber forms



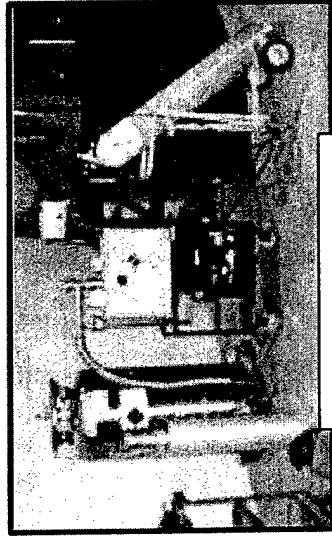
Tensile specimen mold



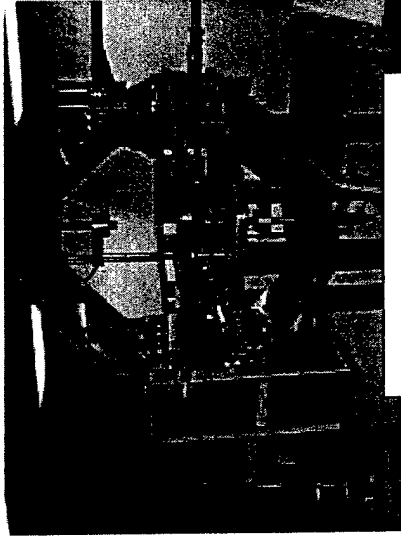
# Integrated Structural Systems Innovative Concepts



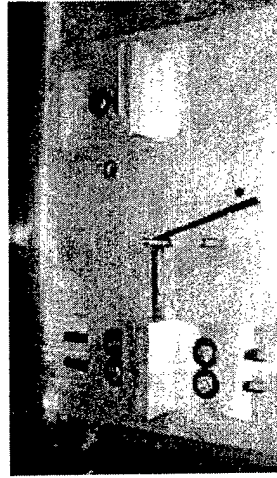
Electrically Disbonding  
Adhesive



Cryo Test Facility



Biaxial Test Facility

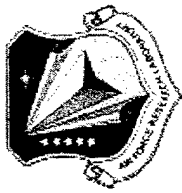


Deployment of Elastic  
Memory Composite

- Basic research provides the seeds to enable generation + 2 systems
  - Electrically disbonding adhesives
  - Elastic memory composites
  - Multiaxial testing of composites
  - Self healing composite materials

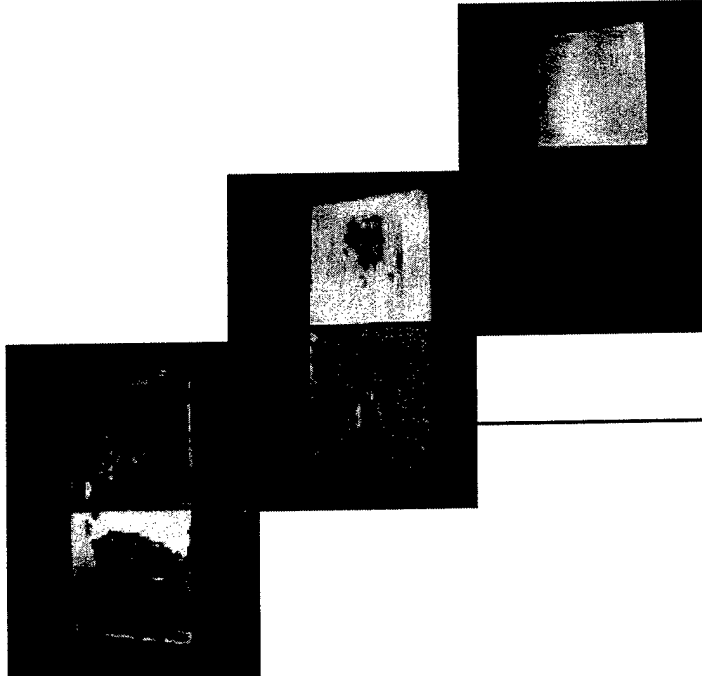
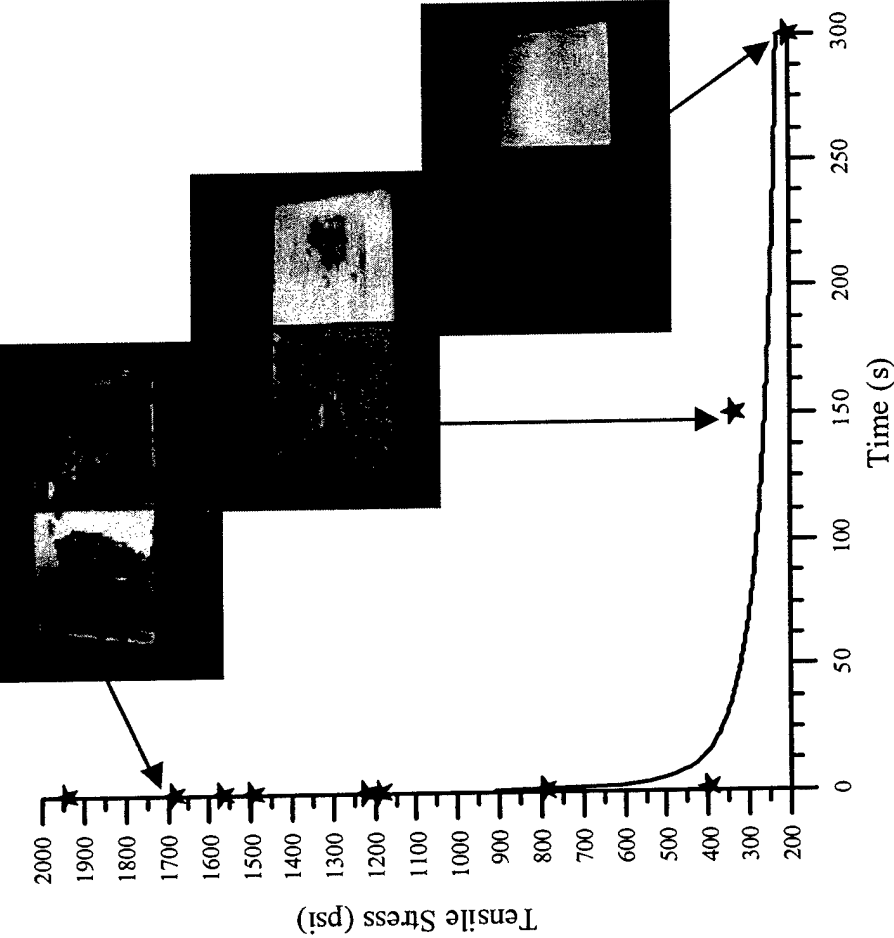
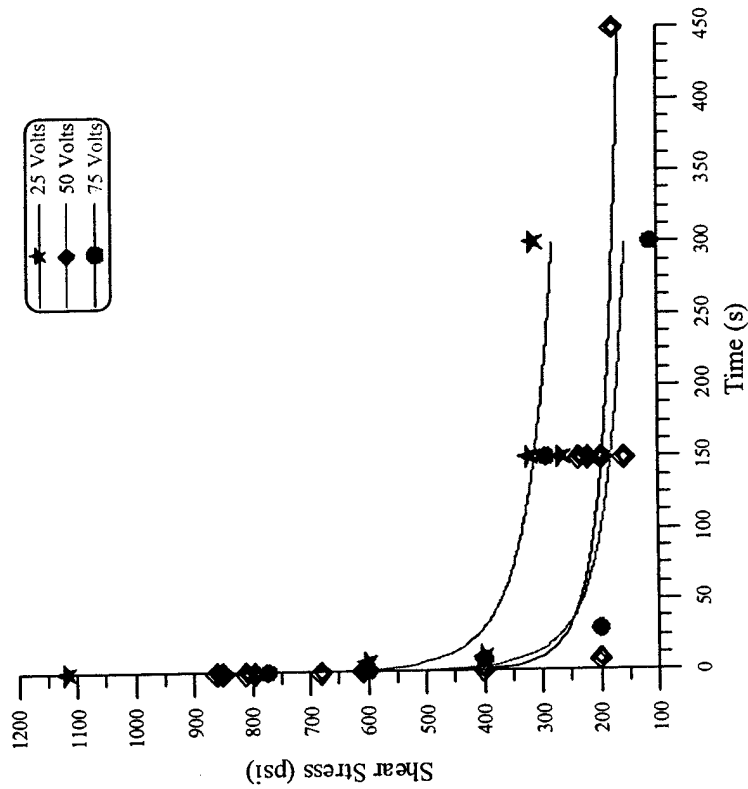


# Electrically Dis-Bonding Epoxy Results



ElectRelease Lap Shear Stress:  
6061-T6 Aluminum Substrate

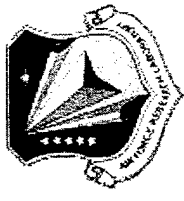
ElectRelease Tensile Stress:  
6061-T6 Aluminum Substrate @ 75V



**Dis-bond time affects failure mode of adhesive**

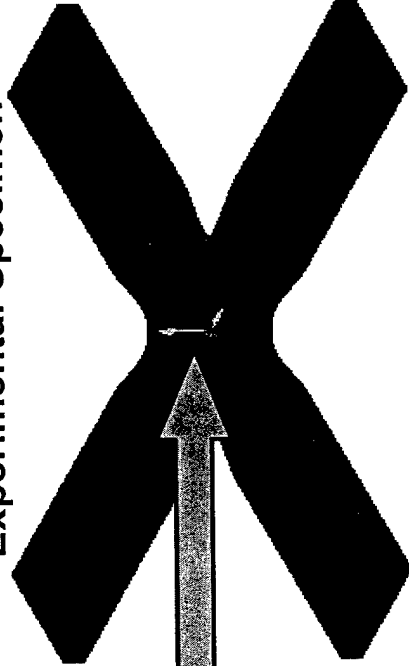


# Biaxial Testing of Composite Laminates

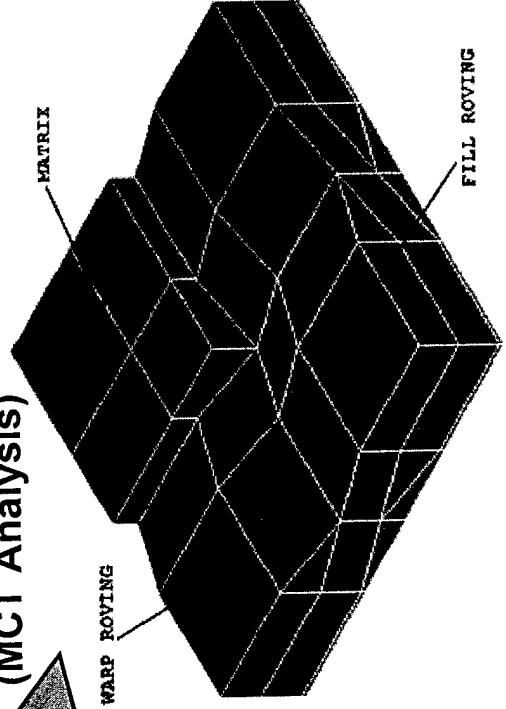


## Results

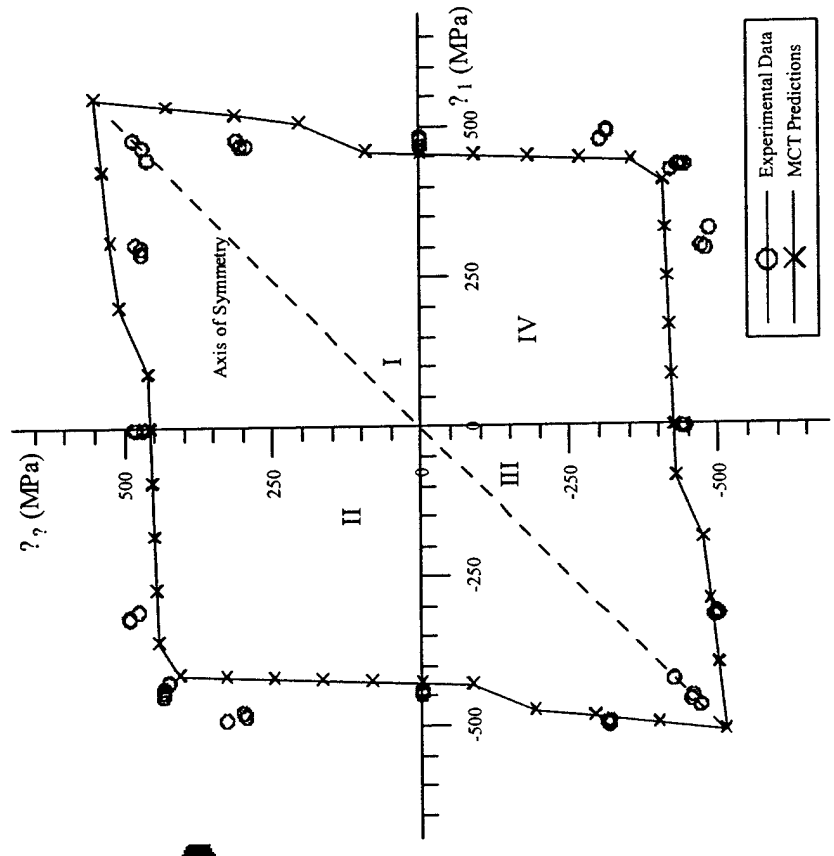
Experimental Specimen



Unit cell model only  
(MCT Analysis)



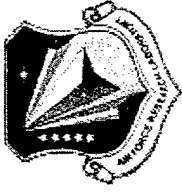
18-oz Biased (5 warp/4 fill rovings)  
Plain Weave E-Glass/Vinyl Ester  
Cross-ply Laminate



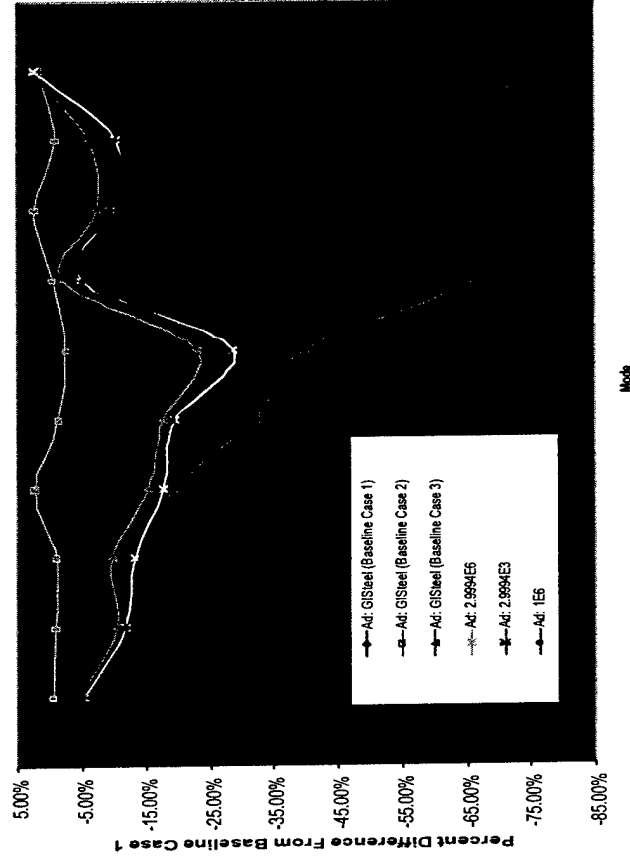
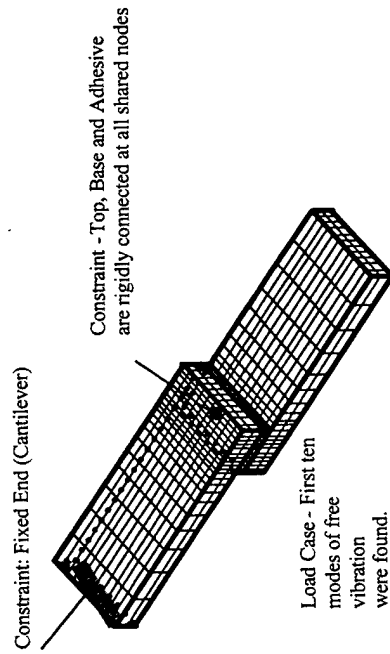
Close agreement between numerical predictions and experimental data!



# Stiffness Critical Composite Joining Results



- Step 1 – Predict static stiffness of lap-shear joint
  - Compare numerical model to experiment

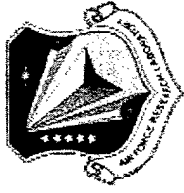


- Results

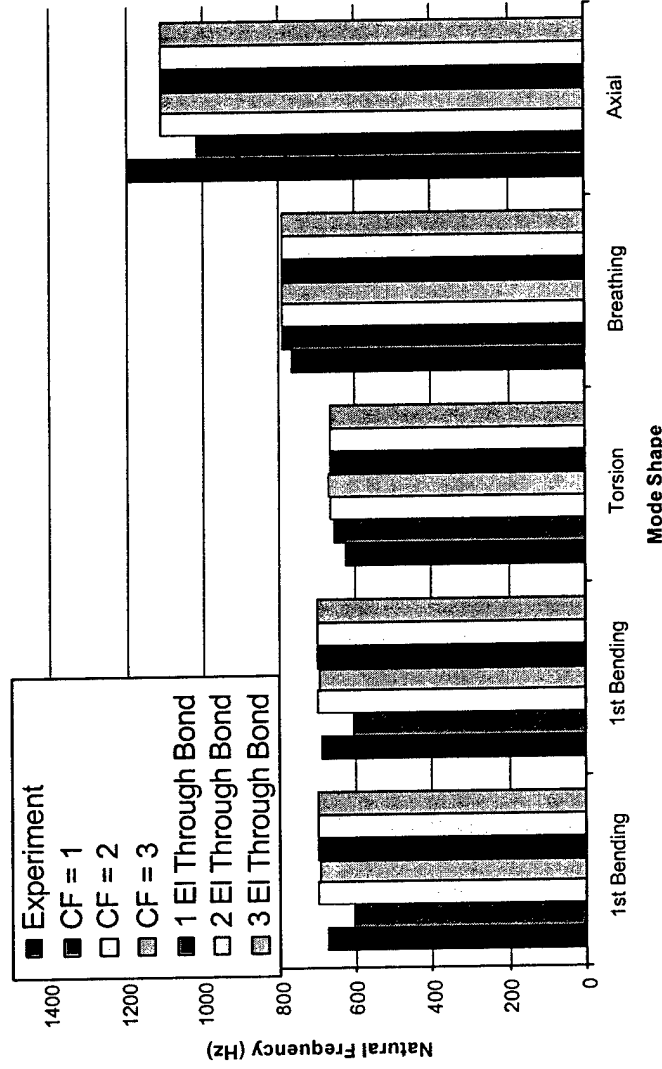
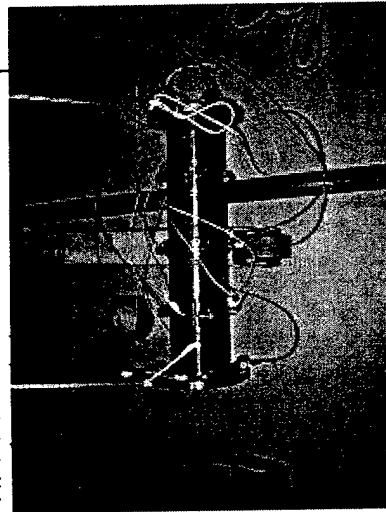
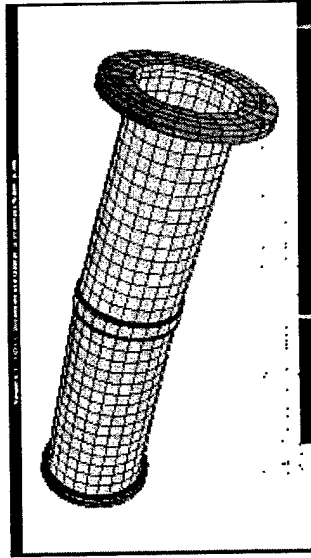
- Neglecting the adhesive bond results in errors > 25%
- One element through the thickness captures the dynamic behavior (3D brick element with nonlinear material properties)<sup>21</sup>



# Stiffness Critical Composite Joining Results



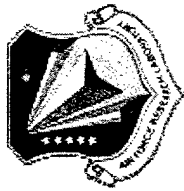
- Step 2 – Predict behavior of dynamic test article
- Compare numerical model to experiment



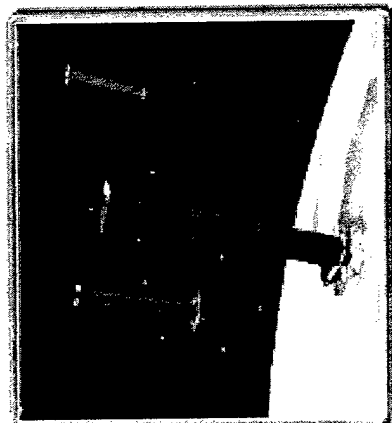
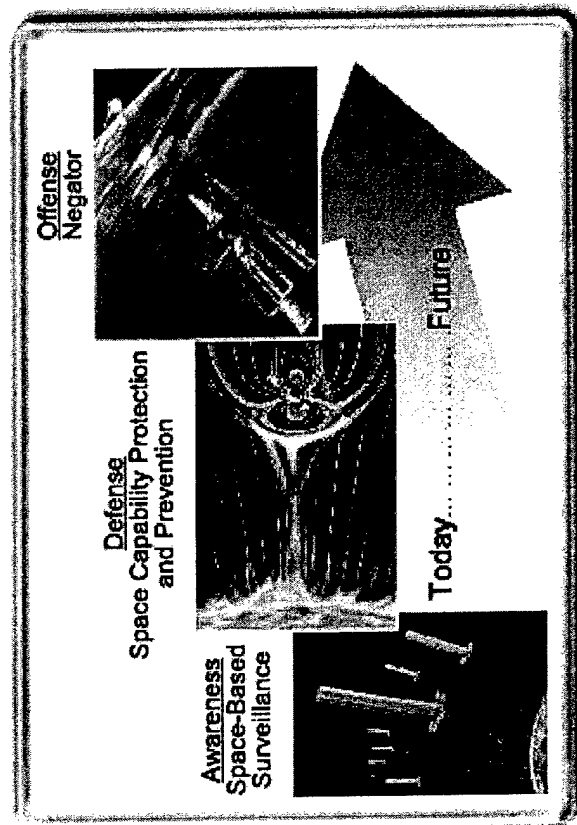
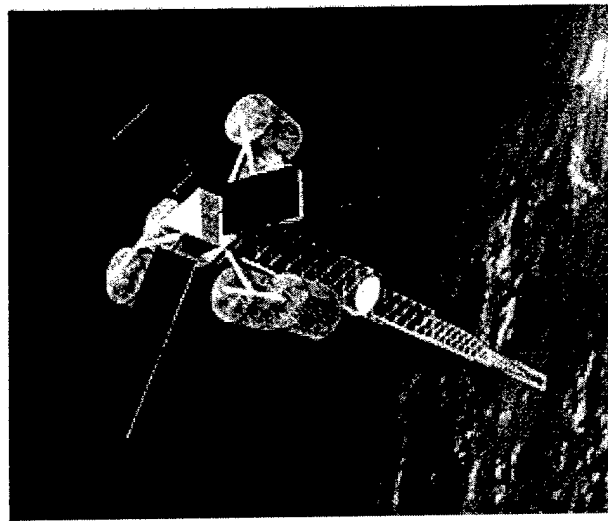
- Results
  - FE model can predict performance for first 6 modes
  - Higher modes not measured due to experimental setup



# Conclusions



- AFOSR support is vital to AFRL/VSSV programs.

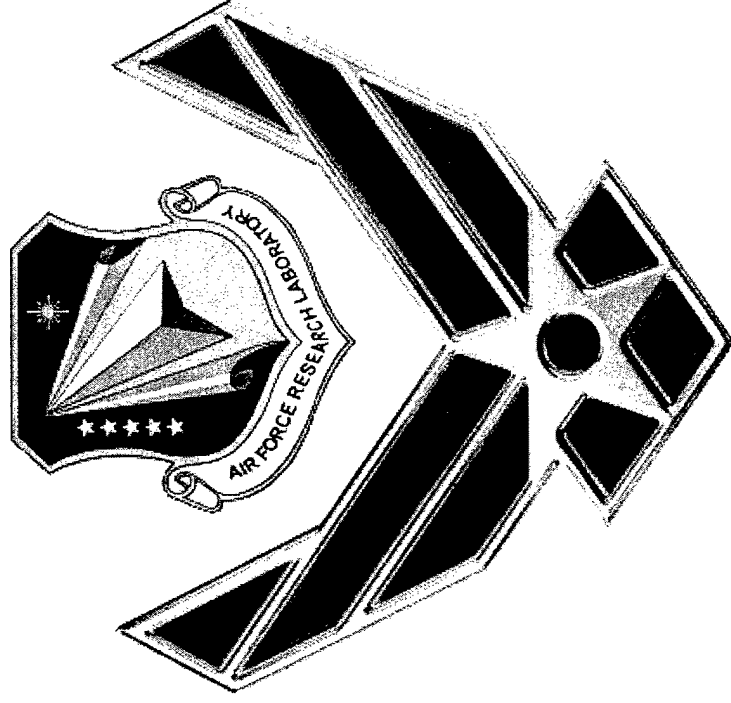


# **1st Multifunctional Aerospace Materials Workshop**

**Purdue University**

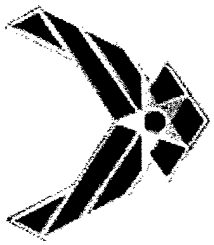
**23-24 October 2002**

## **Conformal Load-Bearing Antenna Structures (CLAS)**

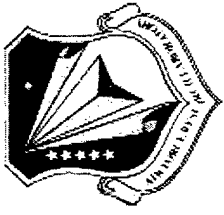


**William G. Baron**  
AFRL/VAS

**Joe Tenbarge**  
AFRL/SNR

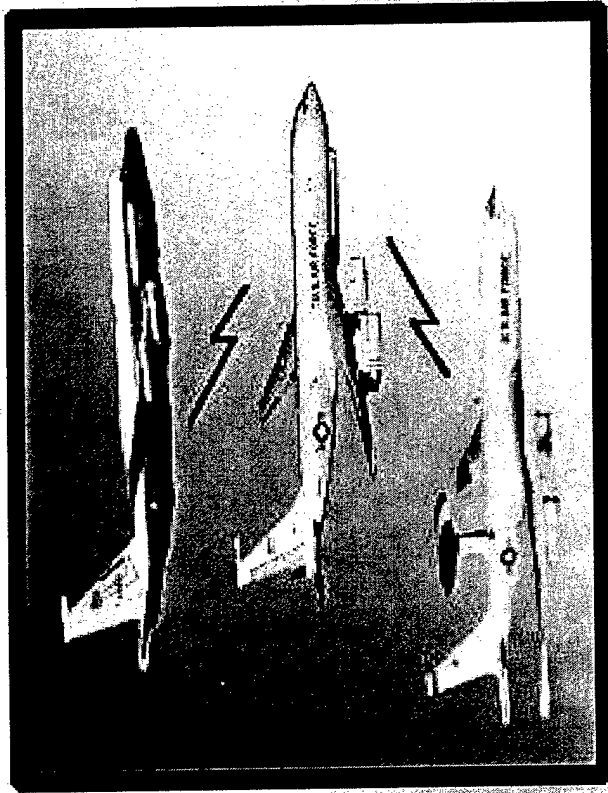


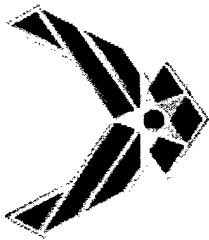
# Critical ISR Needs Not Met with Today's Systems



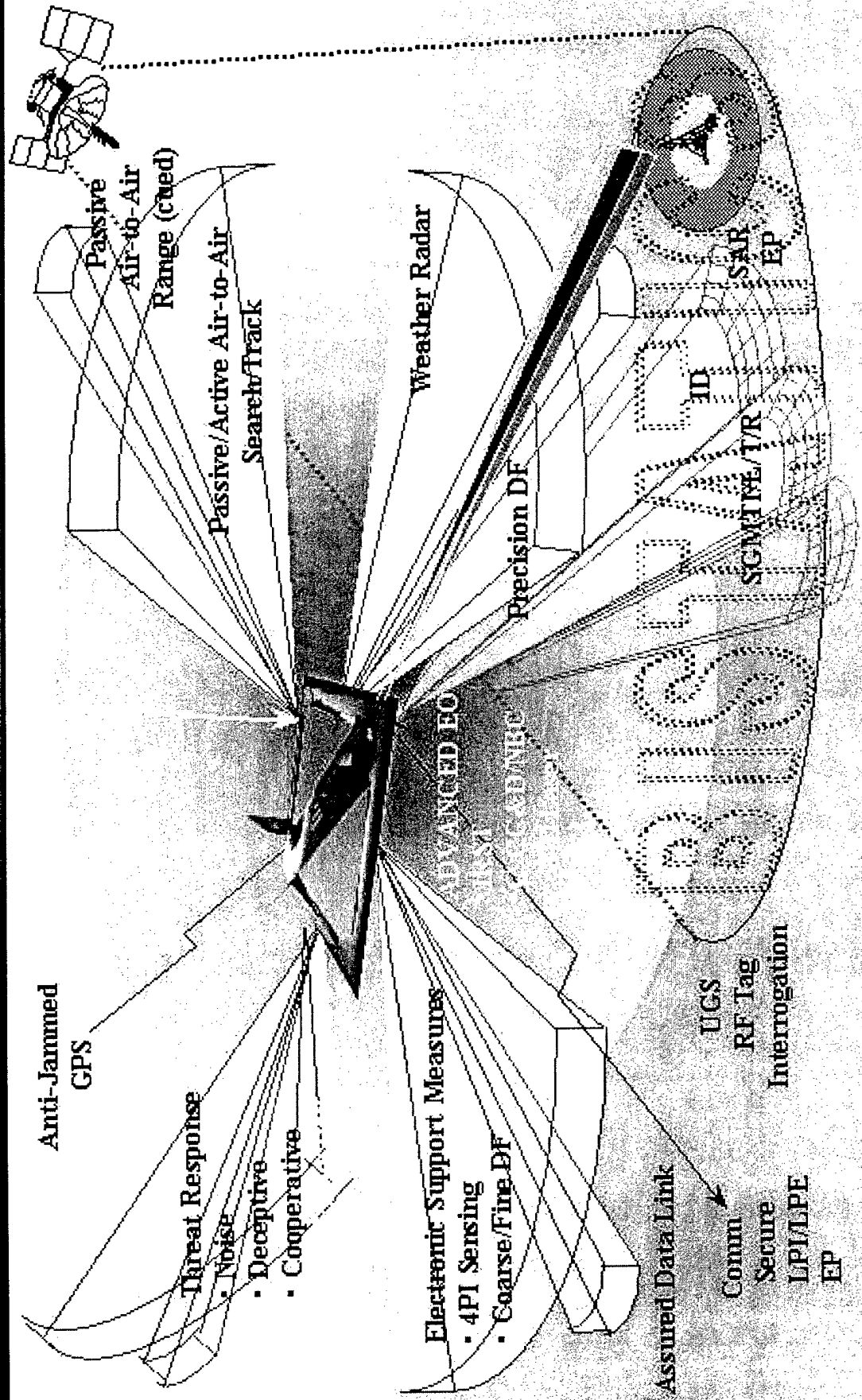
**Long Range Positive Detection, Identification, Tracking and Targeting**

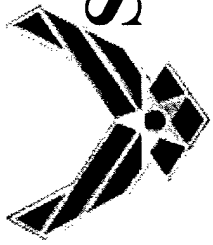
**Critical Manpower Shortages, Aging Systems, and Significant Infrastructure Costs Associated with ISR**



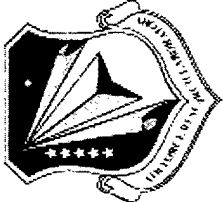


# Sensorcraft Functionality & Space Interdependence





# Sensorcraft Cost and Weight Challenges



## X-Band aperture (20 ft x 1.5 ft):

### Current technology

• cost

\$300K/ft<sup>2</sup> x 30 ft<sup>2</sup> = \$9M/array

\$9M x 4 arrays = \$36M

• weight

35lbs/ft<sup>2</sup> x 30 ft<sup>2</sup> =

1050lbs/array

1050lbs x 4 arrays = 4200lbs

## Low-Band (>40 ft - freq. dependent):

### Current technology (UHF)

• Size - significant volume required  
array elements (>18 inches deep)

• weight

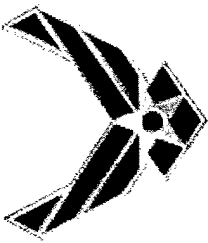
800lbs/array (antenna only)

800lbs/array x 4 arrays = 3200lbs

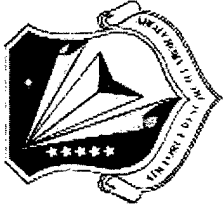
# Significant cost, volume and weight savings required

RF-on-Flex

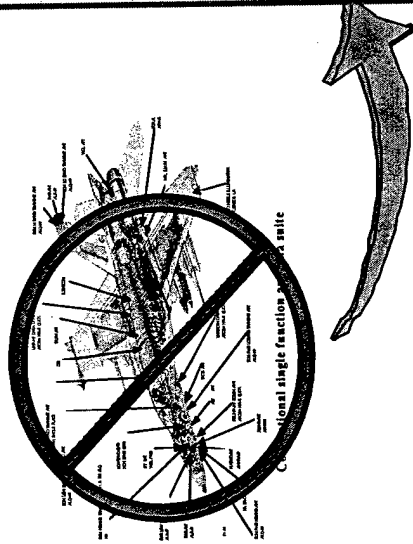
Conformal Load Bearing Arrays



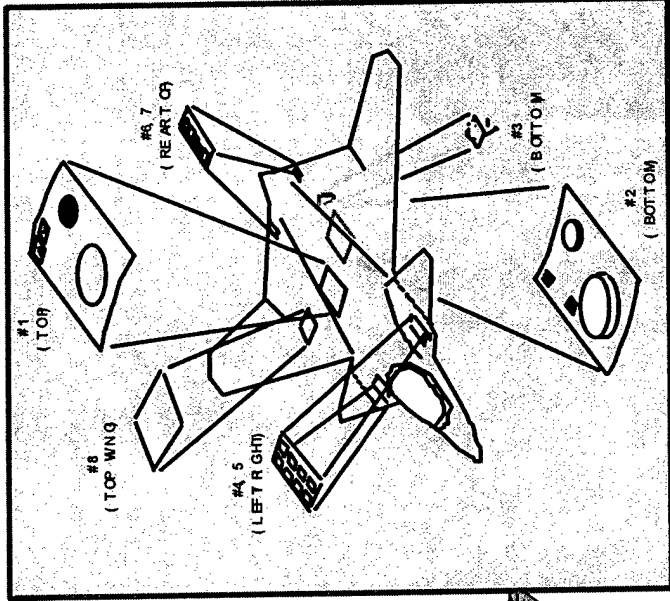
# Conformal Load Bearing Antenna Structure (CLAS)



Non load bearing cavity installations require support structure adding weight & cost



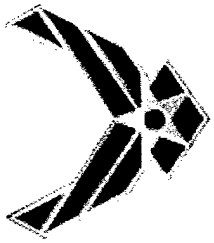
## SOLUTION



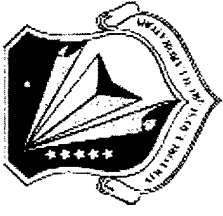
- Integrate antenna function into the structure
- Antenna structure is load bearing
- LO enabling
- Reduced maintenance vulnerability

## PAYOFFS

- Enhanced Antenna Performance by Exploiting Skin Acreeage
- Improved Aerodynamics and Structural Efficiency

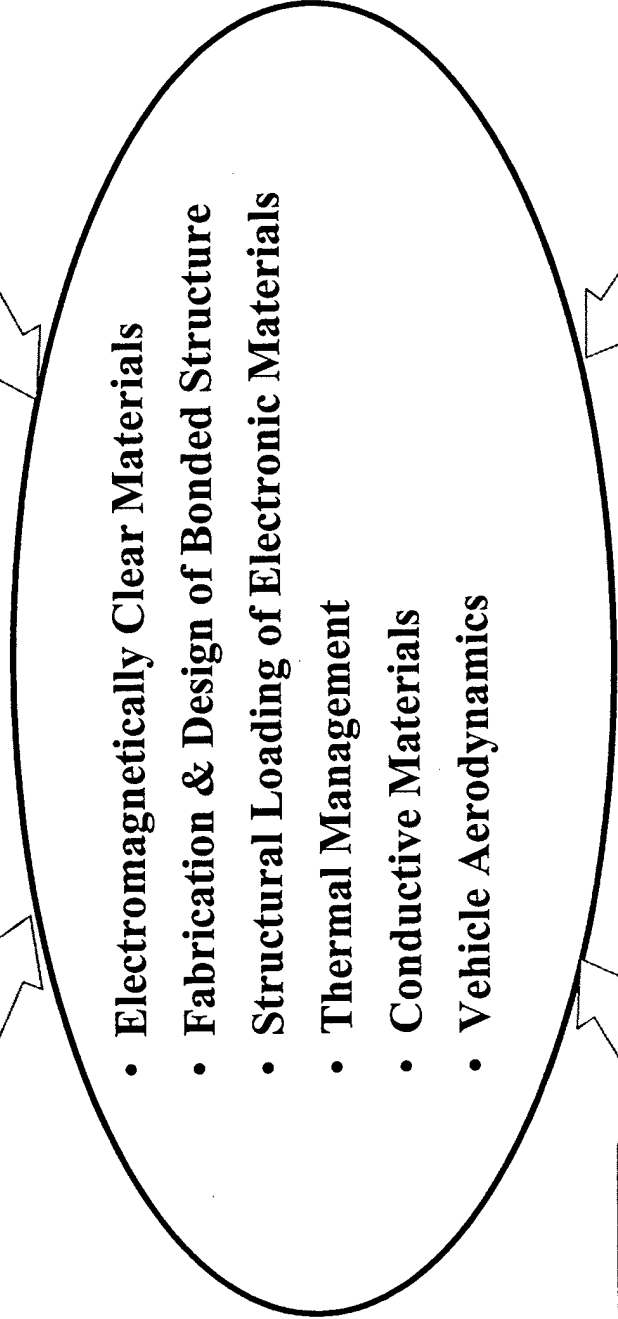


# Multidisciplinary Antenna Integration Challenges



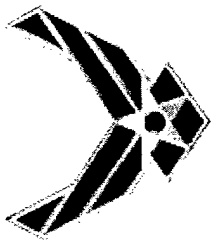
**AIR VEHICLES**

**MANUFACTURE**



**MATERIALS**

**SENSORS**



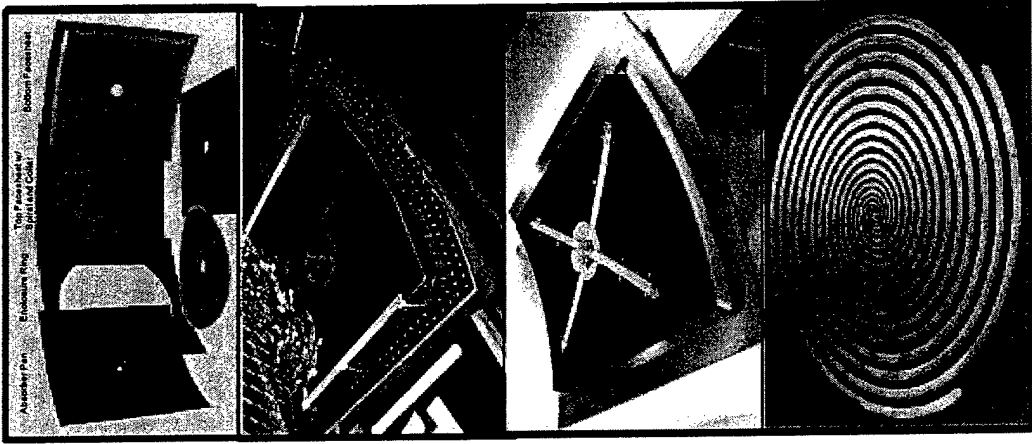
# Wide Band Spiral Antenna Comm/Nav

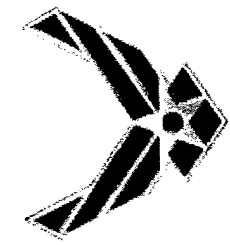


## *Fuselage Panel*

Designed, Developed & Tested a  
Conformal, Load-Bearing, Multifunction  
(0.15 - 2.0 GHz) Antenna

- The First and Largest Multifunction, Conformal, Load-Bearing, Spiral Antenna Built for Airborne Application
- Eliminates up to 10 Comm/Nav Elements
- Spiral Element Developed by SN
- Combined-Load Fatigue Testing
- Spinning Linear Mode Testing



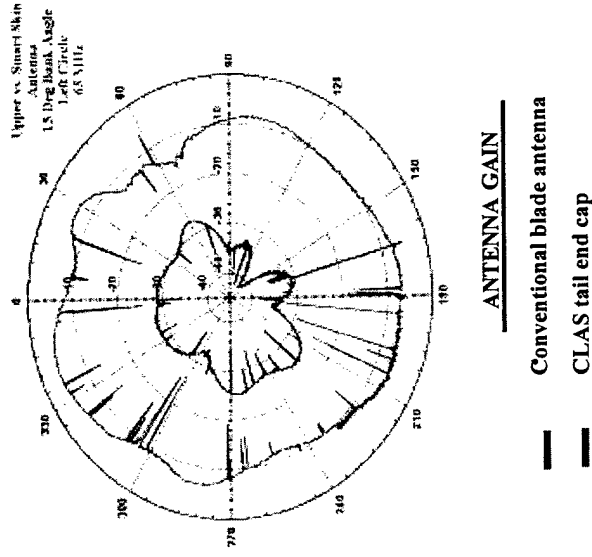
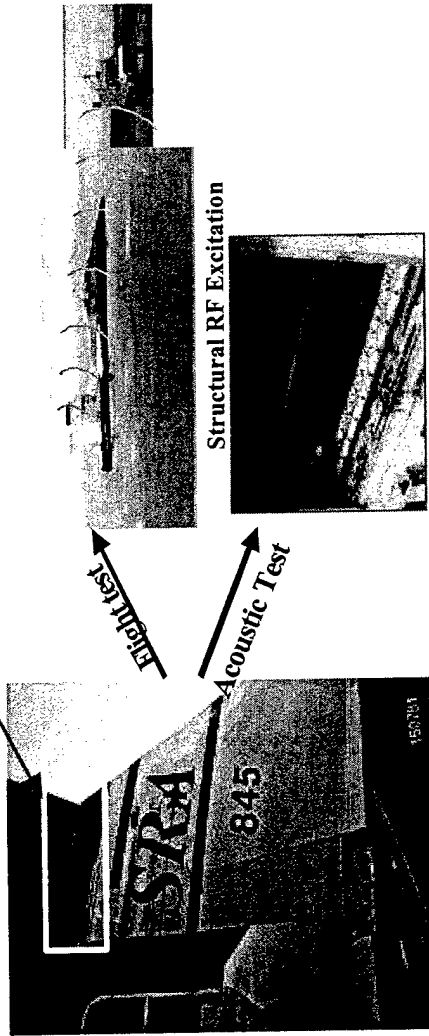


# Communication Element Development

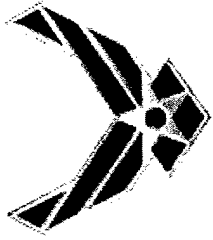


Goal: Replace Conventional Blade Antennas with End Cap with no Degradation in Performance

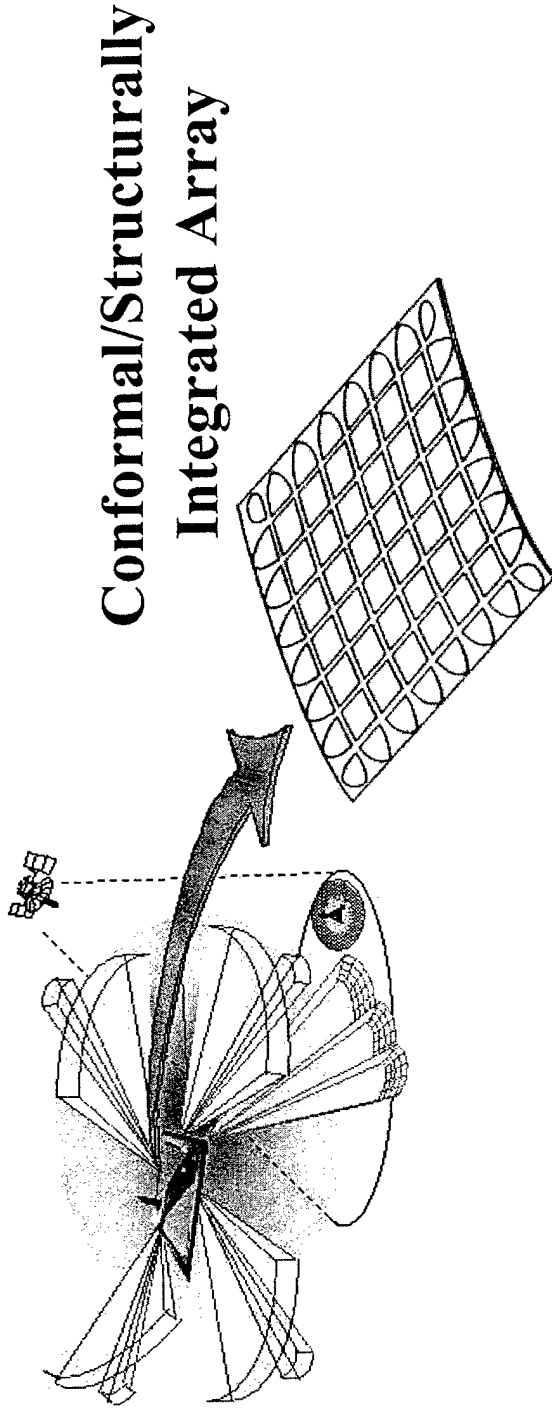
CLAS UHF/VHF Tail End Cap Concept



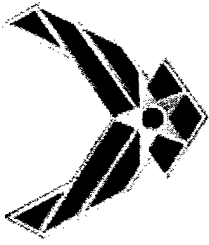
- Blade Antennas not suitable for LO and subject to damage
- The CLAS end cap was flight tested with dramatic gain improvement results, as shown in the gain vs azimuth plot
- The CLAS end cap increased VHF voice communication range 17 fold



# Structurally Integrated Phased Arrays Development Focus



- Low & High Frequency Array Development
- Deformation Sensing for Beam-Forming
- Low Cost Flexible Electronics
- Design for Repair/Graceful Degradation
- Bonded Structure



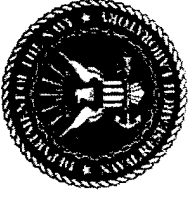
# Multifunctional Material Research Needs



- **Deformation sensing**
  - Sensor integ & development, ingress/egress, algorithm development
- **Conductor development**
  - Nano based conductive polymers
  - Conductive fiber
  - Electroless reel to reel plating
- **Integrated thermal management**
  - High thermal conductivity tailored material
  - Heat exchanger/heat pipe solutions for integrated electronics
- **Electrical distribution – data/power**
  - Direct write, thin films, co-cured conduits & conductors
  - Self healing electrical conductors
  - Bonding of conductors
- **Dielectric material development**
  - Voltage breakdown strength
  - Nano particle dispersion for high dielectric constant polymers
  - High strength/stiffness dielectric polymers
  - Tunable dielectrics for broadband performance



*1st Air Force Workshop on  
Multifunctional Aerospace Materials*



## Design Issues for Multifunctional Materials and Structures

J. P. Thomas, M. A. Qidwai, and P. Matic  
Multifunctional Materials Branch, Code 6350  
Naval Research Laboratory  
Washington, DC

**Acknowledgements:** Support for this work from Defense Advanced Research Projects Agency and Naval Research Laboratory Core Research Program is gratefully acknowledged.

*Purdue University, West Lafayette, IN  
October 23, 2002*



# Multifunctional Structure-Power Materials



**DARPA PROGRAM GOALS:** Develop design strategies, analysis methods, performance indices, and UAV component prototypes for three multifunctional structure-power concepts.

- Concept #1: Multifunctional structure-battery** -- Telcordia's Plastic-Lithium-Ion battery as UAV structure.
- Concept #2: Autophagous structure-fuel** – UAV structural elements that transform into propulsion fuel.
- Concept #3: Variform structure-power** -- pressurized fuel structural elements for morphing UAV's.

## Industry Partners

**M. Keennon and J. Asplund**  
**AeroVironment, Inc.**  
**Design Development Center**  
**Simi Valley, CA**

**A. DuPasquier**  
**Telcordia Technologies, Inc.**  
**Energy Storage Research**  
**Red Bank, NJ**





# What's Possible with Structure-Power ??



## Empirical Aircraft Weight Data

| Micro                       | Total        | Weights   |         |        | Propulsion | Payload | Str. Wgt. Total Wgt. | Fuel Wgt. Total Wgt. |
|-----------------------------|--------------|-----------|---------|--------|------------|---------|----------------------|----------------------|
|                             |              | Structure | Fuel    |        |            |         |                      |                      |
| Black Widow (AeroVironment) | 81 gms.      | 9         | 41.1    | 17.5   | 13.4       | 0.111   | 0.507                |                      |
| Microstar (Lockheed-Martin) | 85 gms.      | 7         | 44.5    | 13.5   | 20         | 0.082   | 0.524                |                      |
| <b>Unmanned</b>             |              |           |         |        |            |         |                      |                      |
| Dragon Eye (NRL)            | 4 lbs.       | 0.5       | 1.5     | 1      | 1          | 0.125   | 0.375                |                      |
| Pointer (AeroVironment)*    | 9.2 lbs.     | 4         | 2.2     | 1      | 2          | 0.435   | 0.239                |                      |
| Sender (NRL)                | 10 lbs.      | 4         | 3       | 1      | 2          | 0.400   | 0.300                |                      |
| LOCAAS (Lockheed-Martin)    | 85 lbs.      | 51        | 10      | 7      | 17         | 0.600   | 0.118                |                      |
| Shadow 200 (AAI)            | 328 lbs.     | 179       | 63      | 26     | 60         | 0.546   | 0.192                |                      |
| Predator (General Atomics)  | 2250 lbs.    | 1,013     | 650     | 137    | 450        | 0.450   | 0.289                |                      |
| Darkstar (L-M/Boeing)       | 8,600 lbs.   | 4,107     | 2960    | 452    | 1081       | 0.478   | 0.344                |                      |
| <b>Conventional</b>         |              |           |         |        |            |         |                      |                      |
| F/A-18 (Boeing)             | 56,000 lbs.  | 19,268    | 15,000  | 4,564  | 17,168     | 0.344   | 0.268                |                      |
| F-16C (Lockheed-Martin)     | 42,300 lbs.  | 14,977    | 14,234  | 3,940  | 9,149      | 0.354   | 0.337                |                      |
| F-14D (Grumman)             | 74,349 lbs.  | 34,730    | 19,557  | 7,050  | 13,012     | 0.467   | 0.263                |                      |
| 777-200 (Boeing)            | 545,000 lbs. | 195,072   | 207,700 | 33,328 | 108,900    | 0.358   | 0.381                |                      |
| 767-300ER (Boeing)          | 380,000 lbs. | 103,262   | 162,340 | 18,998 | 95,400     | 0.272   | 0.427                |                      |
| 747-200B (Boeing)           | 785,000 lbs. | 233,260   | 364,400 | 35,540 | 151,800    | 0.297   | 0.464                |                      |
| 737-900A (Boeing)           | 164,000 lbs. | 62,805    | 46,063  | 10,512 | 44,620     | 0.383   | 0.281                |                      |
| MD-11 (Boeing)              | 602,555 lbs. | 202,302   | 258,721 | 28,497 | 113,035    | 0.336   | 0.429                |                      |
| A320-200 (Airbus)           | 162,040 lbs. | 57,054    | 52,495  | 10,826 | 41,665     | 0.352   | 0.324                |                      |
| A340-600 (Airbus)           | 804,675 lbs. | 299,103   | 344,936 | 21,976 | 138,660    | 0.372   | 0.429                |                      |

References: James "All the World's Aircraft"; "Unmanned Aerial Vehicles..."; "Aero-Engines"; and unpublished data.

**Average= 0.369**  
**Std.Dev.= 0.129**

Battery-Powered

Liquid-Fuel Powered



**Variform Structure-Fuel Morphing Aircraft with Liquid Fuel as Structure !!**



# System Optimization

## UAV Flight Endurance Time



### Structure-Power Multifunctionality

$$E_E (time) = \frac{\text{Available Battery Energy}}{\text{Total Weight}^{3/2}} \times \left[ \frac{\rho S C_L^3}{2 C_D^2} \right]^{1/2} \times \eta_P$$

Aerodynamics, Geometry
Propeller Efficiency

$$\frac{\Delta E_E}{E_E} = \frac{\Delta (E_B \eta_B)}{E_B \eta_B} = \frac{3 (\Delta W_S + \Delta W_B + \Delta W_{SB})}{2 W_{total}}$$

**Complication:**

$\eta_B = \eta_B (E_B, W_{total})$   
 $\eta_P = \eta_P (W_{total})$

→ System-Level Multidisciplinary Design Optimization Required !!!



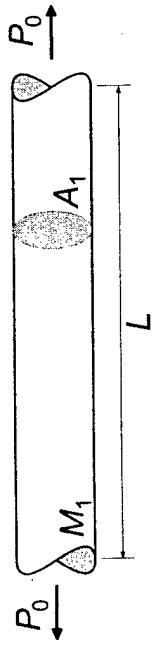
# Unifunctional Materials Performance



Design Objective: minimize the system weight

## I. Unifunctional Design: Structure and Power Functions

### Structure: Axial Tie



$$m_1 = \rho_1 A_1 L$$

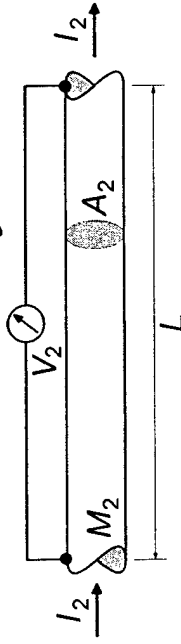
: component weights:

$$m_2 = \rho_2 A_2 L$$

M1 constraint: stress  $\leq$  strength

$$\sigma_1 = \frac{P_0}{A_1} \leq (\sigma_Y)_1 \Rightarrow m_1 \geq P_0 L \left\{ \frac{\rho_1}{(\sigma_Y)_1} \right\}$$

### Power: Battery cell



M2 constraint: total stored energy  $\geq$  constant,  $E_0$

$$E_2 = m_2 \times \underbrace{(e_B)_2}_{\text{specific energy}} \geq E_0 \Rightarrow m_2 = E_0 \left\{ \frac{1}{(e_B)_2} \right\}$$

total unifunctional system weight,  $(m_T)_u = m_1 + m_2$

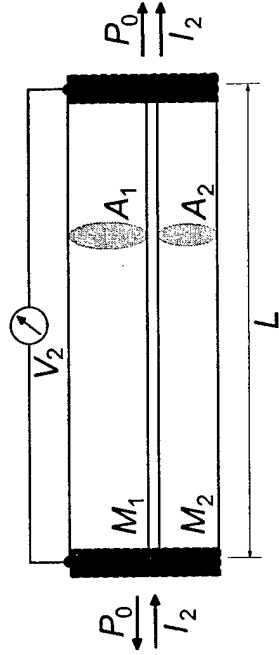
$$(m_T)_u = P_0 L \left\{ \frac{\rho_1}{(\sigma_Y)_1} \right\} + E_0 \left\{ \frac{1}{(e_B)_2} \right\}$$



# Multifunctional Materials Performance



## II. Multifunctional Design: Structure-Battery Function



System constraints:

$$\delta_1 = \delta_2 = \delta_T = \frac{P_1 L}{A_1 E_1} = \frac{P_2 L}{A_2 E_2}$$

$$P_0 = P_1 + P_2$$

Total multifunctional system weight,  $(m_T)_m$

$$(m_T)_m = m_1 + m_2 = (\rho_1 A_1 + \rho_2 A_2) L$$

**Case 1:**  $\frac{(\sigma_Y)_2 \geq (\sigma_Y)_1}{\rho_2 \geq \rho_1} \Rightarrow$  Eliminate  $M_1$ , replace with  $M_2$  structure-battery!!

**1a:**

$$(m_T)_m = E_0 \left\{ \frac{1}{(e_B)_2} \right\} \ll (m_T)_u$$

$$E_2 = m_2 \times (e_B)_2 = E_0 \quad \text{and} \quad \sigma_2 = \frac{P_2}{A_2} \leq (\sigma_Y)_2$$

**1b:**

$$(m_T)_m = P_0 L \left\{ \frac{\rho_2}{(\sigma_Y)_2} \right\} \ll (m_T)_u$$

$$\sigma_2 = \frac{P_2}{A_2} = (\sigma_Y)_2 \quad \text{and} \quad E_2 = m_2 \times (e_B)_2 \geq E_0$$



# Multifunctional Materials Performance

**Case 2:**  $\frac{(\sigma_Y)_1}{\rho_1} > \frac{(\sigma_Y)_2}{\rho_2} \Rightarrow M_1 \text{ structure plus } M_2 \text{ structure-battery!!}$

$$\left( m_T \right)_m = \left( m_T \right)_u - E_0 \left\{ \frac{1}{(e_B)_2} \right\} \times \left\{ \frac{E_2/\rho_2}{E_1/\rho_1} \right\} < \left( m_T \right)_u$$

*unifunctional system weight*

$$\sigma_1 = \frac{P_1}{A_1} = (\sigma_Y)_1, \quad E_2 = m_2 \times (e_B)_2 = E_0, \quad \text{and} \quad \sigma_2 = \frac{P_2}{A_2} \leq (\sigma_Y)_2$$

**2a:**

$$\left( m_T \right)_m = \left( m_T \right)_u - E_0 \left\{ \frac{1}{(e_B)_2} \right\} \times \left\{ \frac{E_2/\rho_2}{E_1/\rho_1} \right\} + \rho_1 \left\{ \frac{(\sigma_Y)_1 - (\sigma_Y)_2}{(\sigma_Y)_1 (\sigma_Y)_1} \right\} P_0 l < \left( m_T \right)_u$$

*unifunctional system weight*

$$\sigma_2 = \frac{P_2}{A_2} = (\sigma_Y)_2, \quad E_2 = m_2 \times (e_B)_2 = E_0, \quad \text{and} \quad \sigma_1 = \frac{P_1}{A_1} \leq (\sigma_Y)_1$$

**2b:**

**Important Conclusions:**

1. System weight **always less** using multifunctional material design!
2. System optimization generally occurs with "non-optimal" subsystem designs.
3. Multifunctional performance ranking: **1a** or **1b**, **2a**, then **2b**.



# Mechanical Performance Indices



Minimal Axial Displacement and Weight  $\rightarrow$  Maximize Specific Axial Stiffness

**Axial Displacement:**  $\delta = \frac{PL}{E_R A^*}$

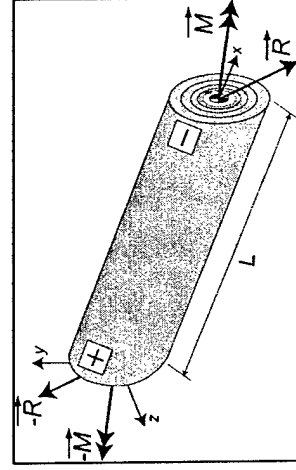
$$A^* := \sum_{i=1}^n \frac{E_i}{E_R} A_i$$

**Axial Stiffness:**  $k_a := \frac{E_R A^*}{L}$

Composite Property

**Mass Density:**  $\rho := \sum_{i=1}^n \rho_i A_i$

Composite Property



**Specific Axial Stiffness:**  $\rho_a := \frac{k_a \times L}{\rho} = \frac{\sum_{i=1}^n E_i A_i}{\sum_{i=1}^n \rho_i A_i} = \frac{E}{\rho}$

**Unifunctional** (top)      **Multifunctional** (bottom)

Multifunctional Composite Performance Indices generally depend on the constituent material properties, shapes, and location within the cross-section.

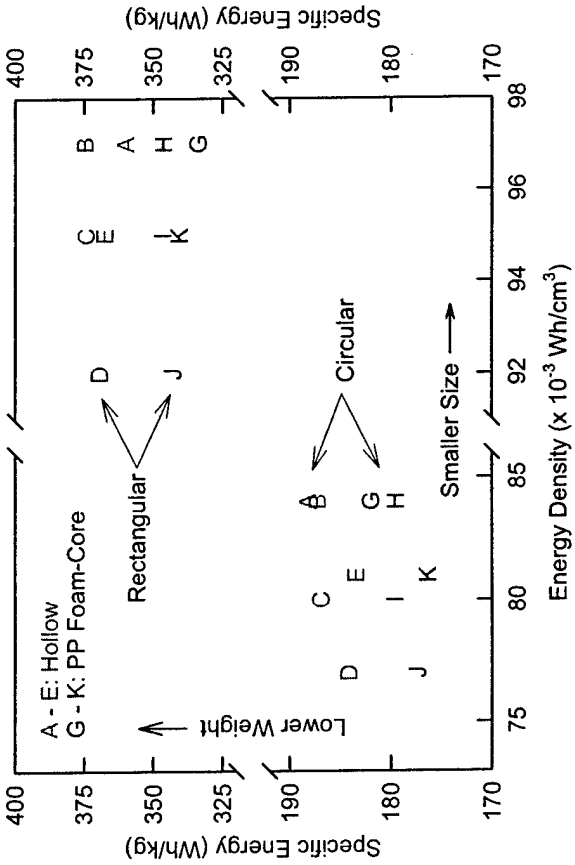
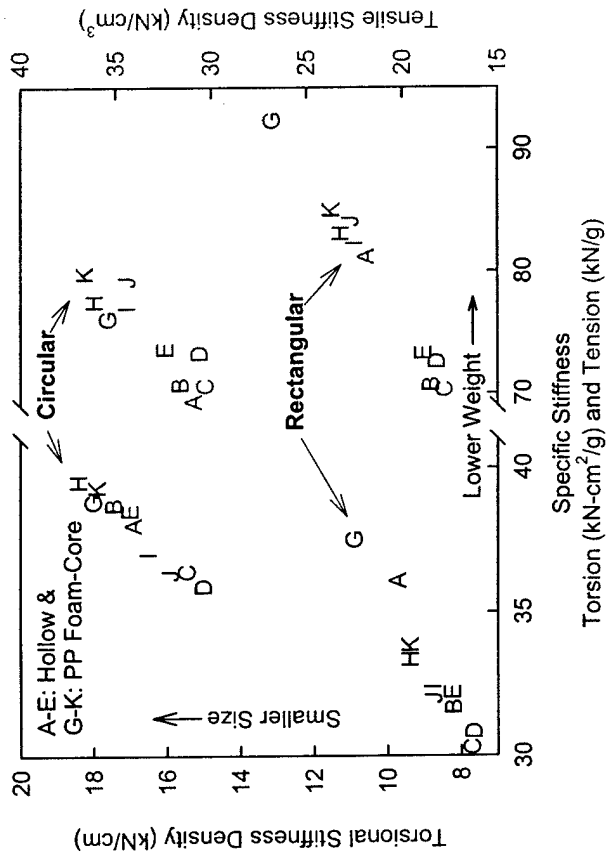
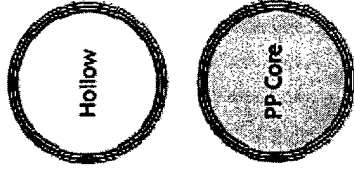
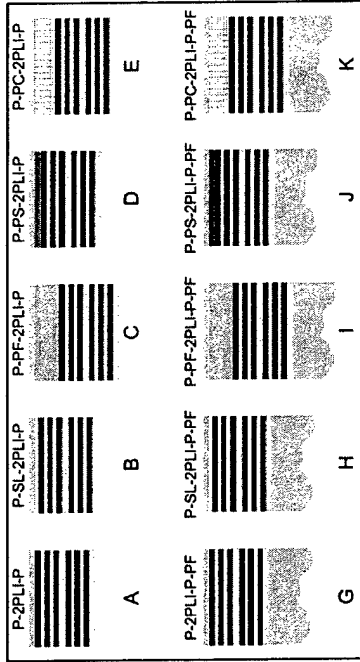




# SBDT Study: Structure-PLI Struts



| Material Legend                 |                            |
|---------------------------------|----------------------------|
| P: Packaging                    | SL: $\mu$ -porous PP/PE/PP |
| PLI: Plastic-lithium-ion bicell | PF: PP foam                |
| PVDF Tie-layer                  | PS: Porous PP sheet        |
| PF: PP foam                     | PC: Woven PP cloth         |

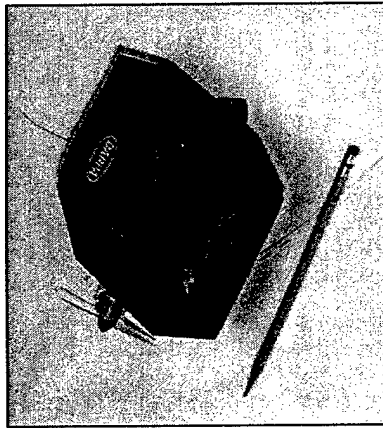


**Useful Design Ranking Information!**



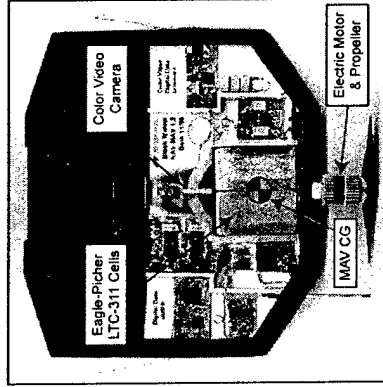
# Structure-Battery for UAV's

## Black-Widow Micro-Air-Vehicle

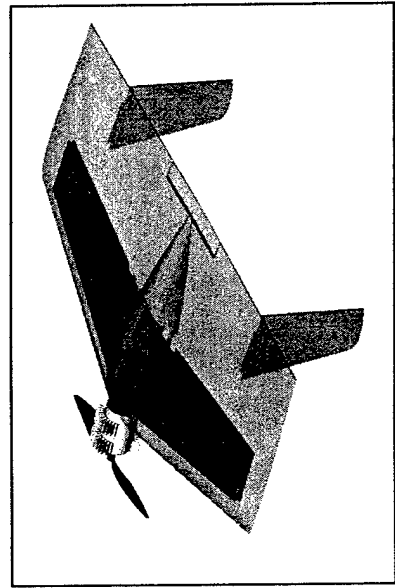


### Capabilities

- 6" wing span
- 81 g weight
- 30 min. endurance

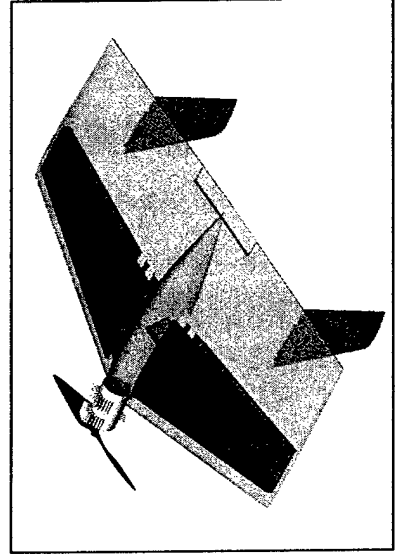


## New Multifunctional Unmanned-Air-Vehicle



### Design Goals

- 12" wing span
- 170 g weight
- 70+ min. endurance





# Structure-Battery Design for UAV's



## Desirable Features

- High energy density and specific energy
  - Arbitrary shaping capability
- Durability in flight, field, and storage
  - Reliability
  - Safe-failure modes

## Multiple-Mission UAV's

- Rechargeability of the structure-battery → secondary cells or easily removed primary cells

## Single-Mission UAV's

- Low Cost

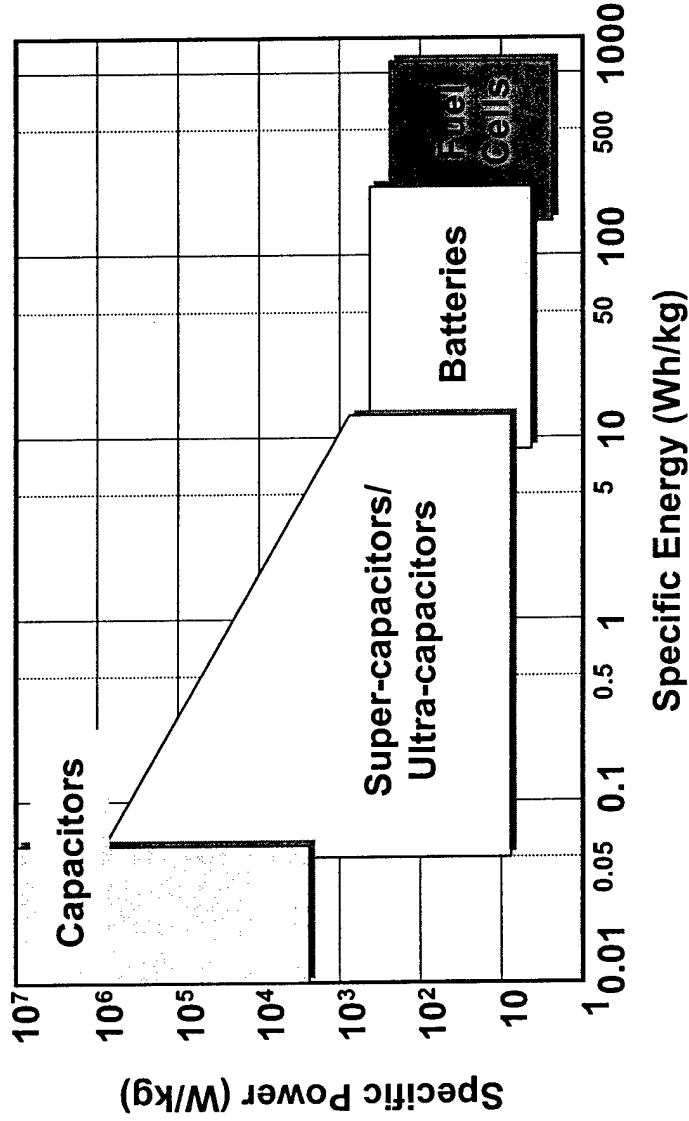
**Multifunctional Design Rule:** add functionality to the material with the more complex existing function.



# Electrical Performance Indices



Ragone Plot for Electrical Energy Storage Devices



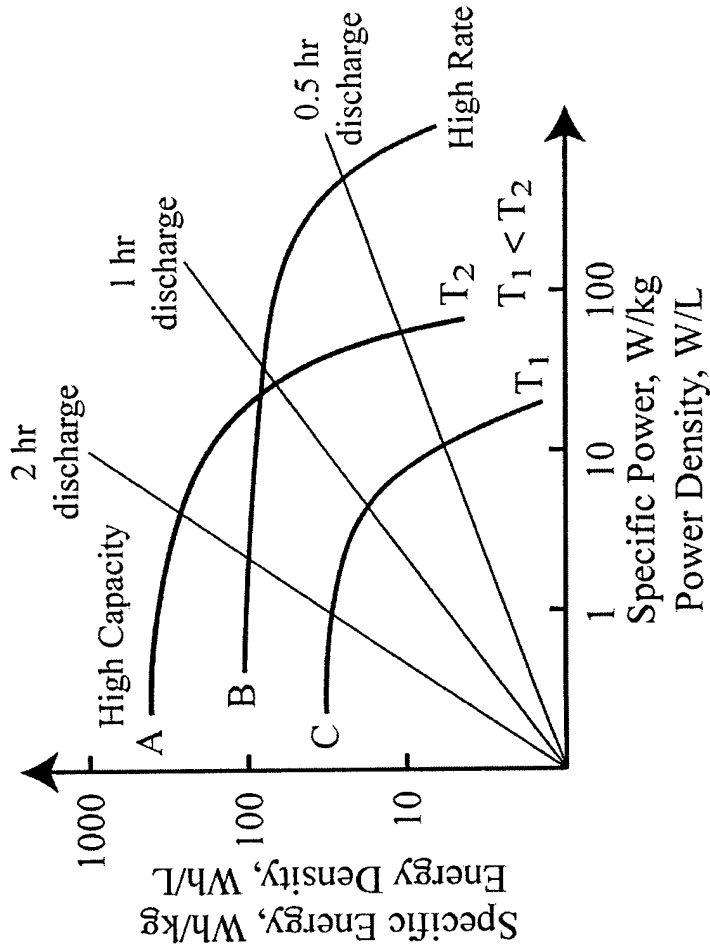
Wide range of Ragone performance due to intrinsic energy storage physics: **stretching** versus **breaking** of molecular bonds.



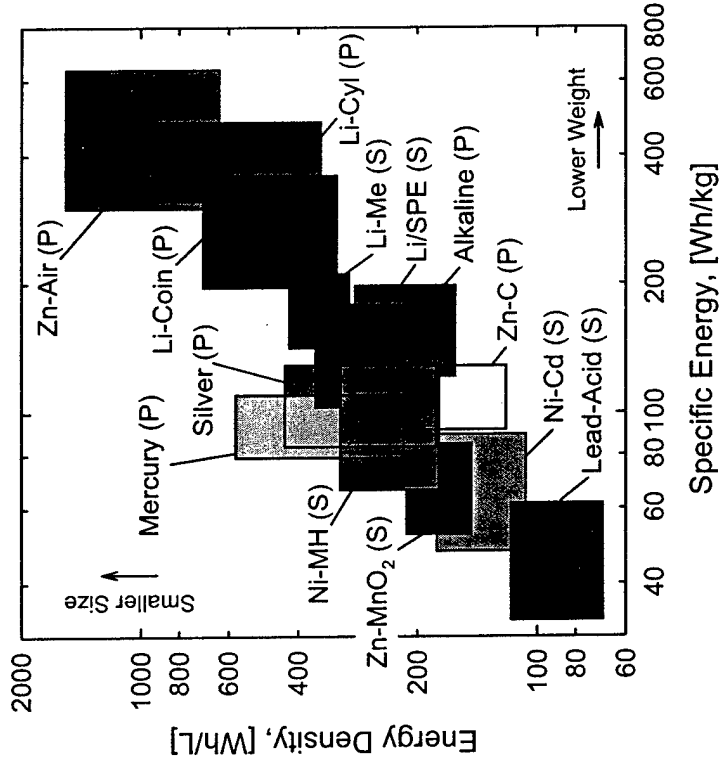
# Electrical Performance Indices



Ragone Plot



Energy Density -vs- Specific Energy



- **Li-Me (S)** and **Li/SPE (S)** cells show best rechargeable performance!!

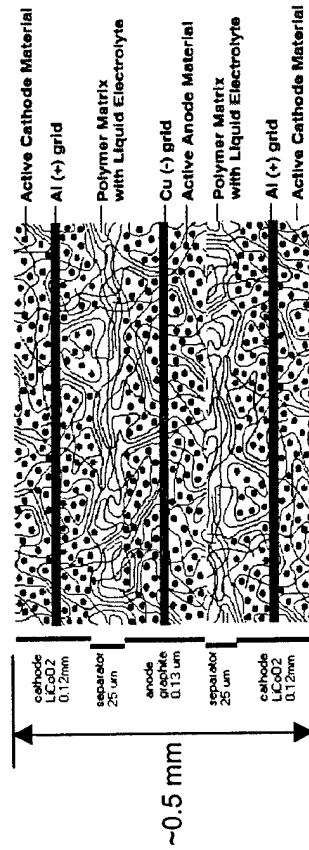


# Multifunctional Structure-PLI



**Structure-PLI = Plastic Li-Ion Bicell(s) + Barrier-Layer Packaging + Structural Additives**

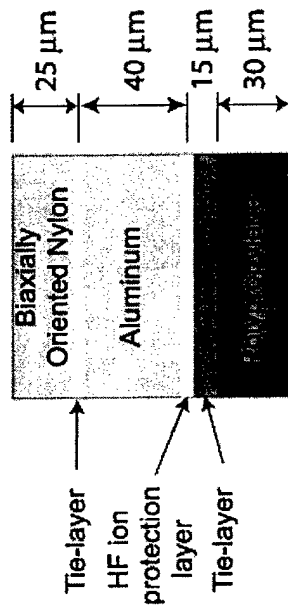
## Telcordia's Plastic Lithium-Ion (PLI) Bicell



### Nominal Properties

- 3.8 V & 7.2 mAh/cm<sup>2</sup>
- $\rho = 0.14 \text{ g/cm}^2$
- $E = 1020 \text{ MPa}$
- $\sigma_0 = 3.9 \text{ MPa}$

## Dai-Nippon EL-40 Packaging



### Nominal Properties

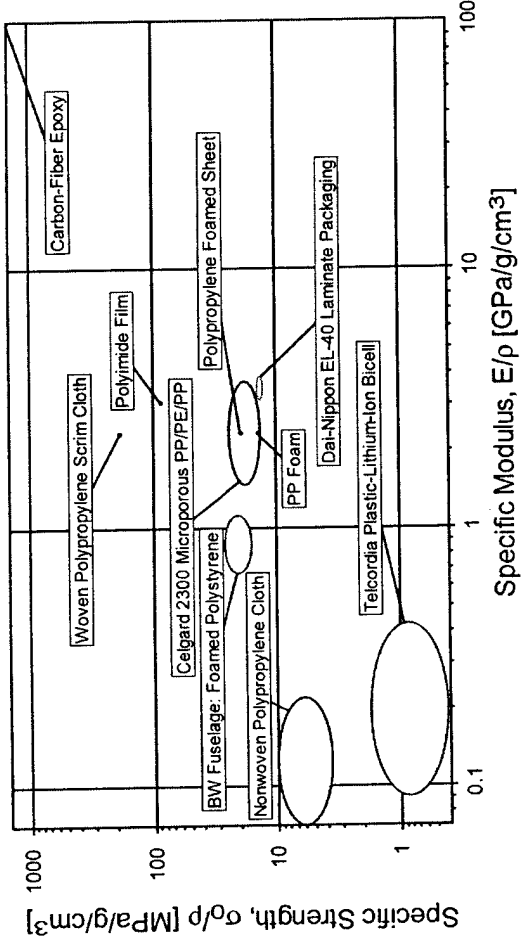
- $E = 4400 \text{ MPa}$
- $\sigma_0 = 16.8 \text{ MPa}$



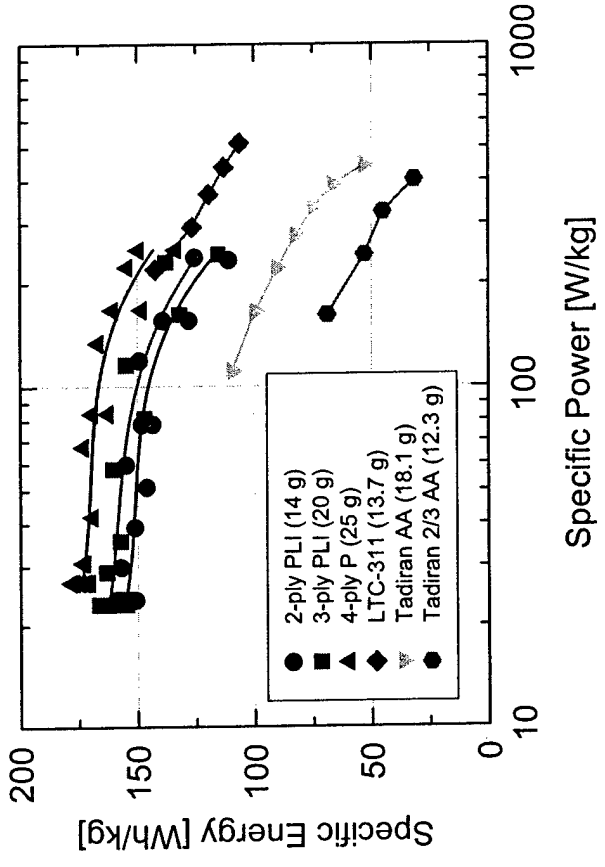
# Structure-PLI Performance



Specific Strength –vs- Specific Modulus



Ragone Data for Li Cells



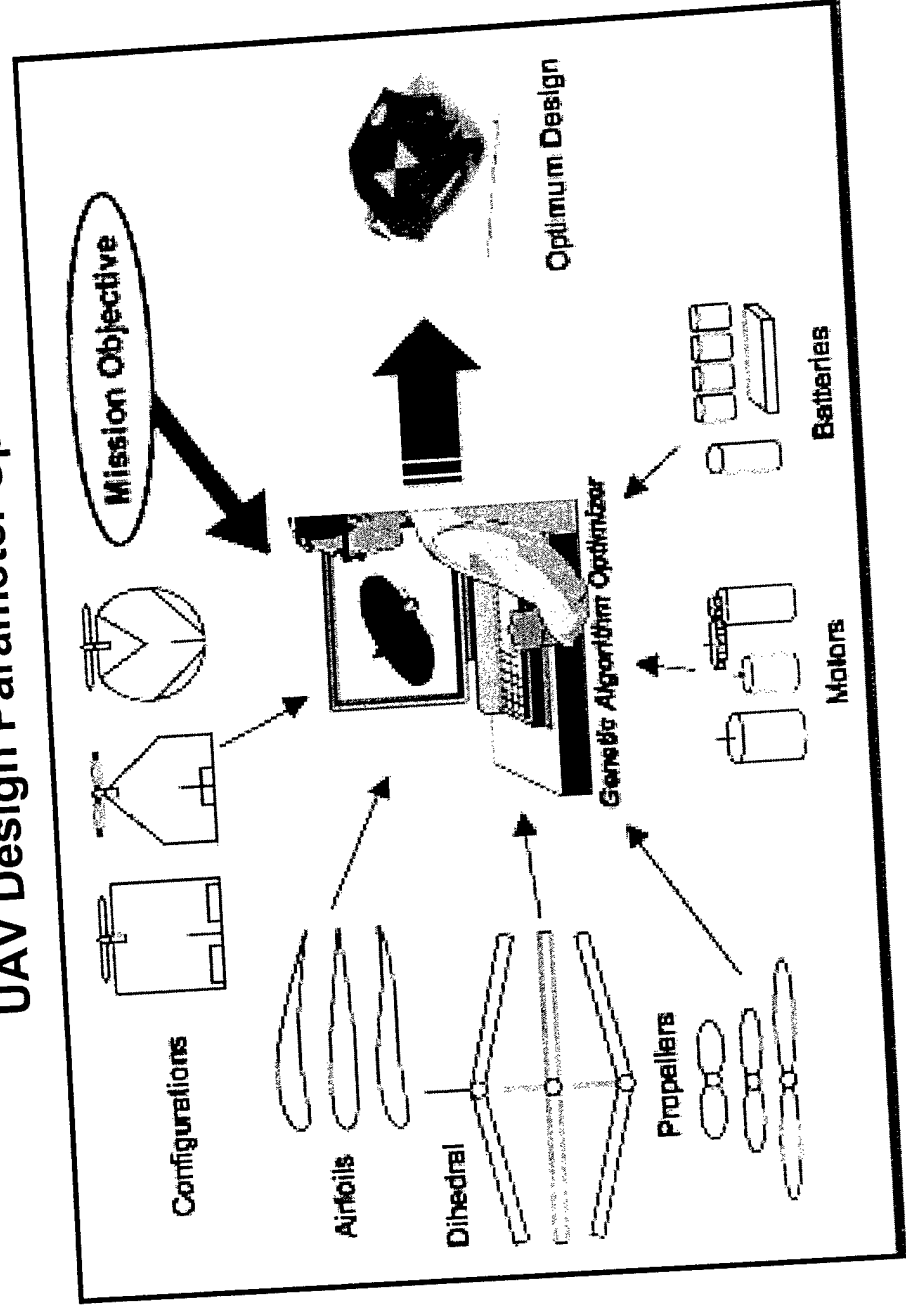
- Significant nonlinear, anisotropic behavior.
- Components with wide range of mechanical performance



# Multidisciplinary Design Optimization of UAV's



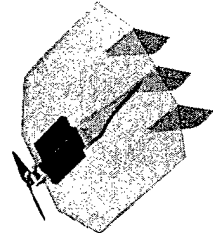
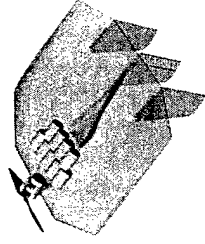
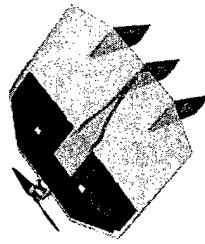
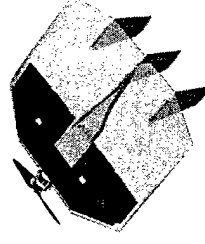
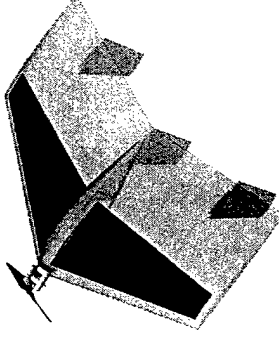
## UAV Design Parameter Space





# MDO Performance Analysis



| Black Widow Design   |  |  |  |  | Notional Design |
|--|--|--|--|--|-----------------|
| 1  | 2  | 3  | 4  | 5  |                 |
|  <p><b>Current Design</b></p> <ul style="list-style-type: none"> <li>• Eagle-Picher cells</li> <li>• Primary</li> <li>• 15 cm span</li> <li>• 81 gram mass</li> <li>• <b>30 min endurance</b></li> <li>• Flight tested</li> </ul> |  <ul style="list-style-type: none"> <li>• NiMH batteries</li> <li>• Rechargeable</li> <li>• 15 cm span</li> <li>• 71 gram mass</li> <li>• 5 min endurance</li> <li>• Flight tested</li> </ul> |  <ul style="list-style-type: none"> <li>• 2-ply PLIION cells</li> <li>• Rechargeable</li> <li>• 15 cm span</li> <li>• 82 gram mass</li> <li>• 29 min endurance</li> <li>• Wind tunnel test</li> <li>• Structural mockup</li> </ul> |  <ul style="list-style-type: none"> <li>• 3-ply PLI cells</li> <li>• Rechargeable</li> <li>• 15 cm span</li> <li>• 101 gram mass</li> <li>• <b>34 min endurance</b></li> <li>• Wind tunnel test</li> <li>• Structural mockup</li> </ul> |  <ul style="list-style-type: none"> <li>• 4-ply PLI cells</li> <li>• Rechargeable</li> <li>• 28 cm span</li> <li>• 121 gram mass</li> <li>• <b>70 min endurance!</b></li> </ul> |                 |



# WASP Multifunctional UAV



## ***One hour and 47 minutes flight endurance time!***

- 13 inch wingspan; 170 g total weight; 120 g structure-battery weight.
- Structure-PLI (silver) integrated into top and bottom of the wing.



- Aircraft detail design, fabrication, and test flying by **AeroVironment, Inc.**
- Structure-battery conceptual design and fabrication of the plastic-lithium-ion cells by **Telcordia Technologies**
- Structure-battery conceptual design and prototype development coordination by **Naval Research Laboratory**

**Benefits of multifunctionality clearly demonstrated by flight endurance of WASP UAV with fully integrated structure-battery!!!**



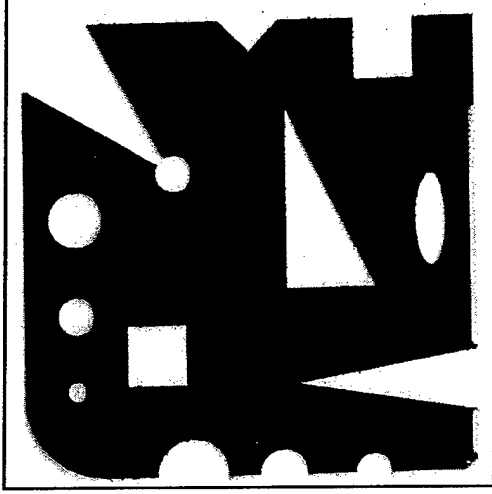
# Fabrication Procedures and Challenges



## Fabrication Steps

- Cutting laminated PLI bicell to shape
- Pre-assembly and lead attachments
- Electrolyte imbement
  - (<0.3% humidity)
- Lamina bonding and molding
- Packaging and sealing
- Electrical charging and testing

## Cutting Test Geometry



Automated Ultrasonic  
Blade Cutting

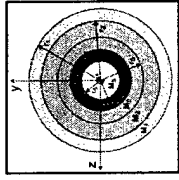
Include ~0.5 mm  
edge borders to avoid  
electrical shorting



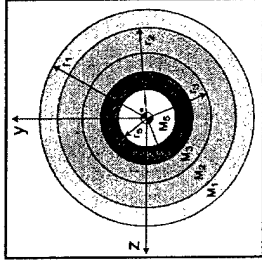


# Shape Factor: Size Does Not Matter!

2 x size  
↑



3 x size  
↑



Shape Factor is  
invariant WRT  
c-section size.

Unifunctional

$$\theta_t = \frac{TL}{GK}$$

Angle of twist:

Shape Factor  
for torsional  
deformation

$$\phi_t^e := \frac{\theta_{circle}}{\theta} = \frac{2\pi K}{A^2}$$

Multifunctional

$$\theta_t^* = \frac{TL}{G_R K^*}$$

$$\phi_t^{e*} := \frac{2\pi K^*}{A^{*2}} = 2\pi \left( \frac{E_R^2}{G_R} \right) \frac{\sum_{i=1}^n G_i K_i}{\left( \sum_{i=1}^n E_i A_i \right)^2}$$

Multifunctional Composite Shape Factors generally depend on the constituent material properties, shapes, and location within the cross-section.



# Health Management System Needs – Space Transportation Perspective

1<sup>st</sup> Air Force Workshop on  
“Multifunctional Aerospace Materials”

October 23-24, 2002

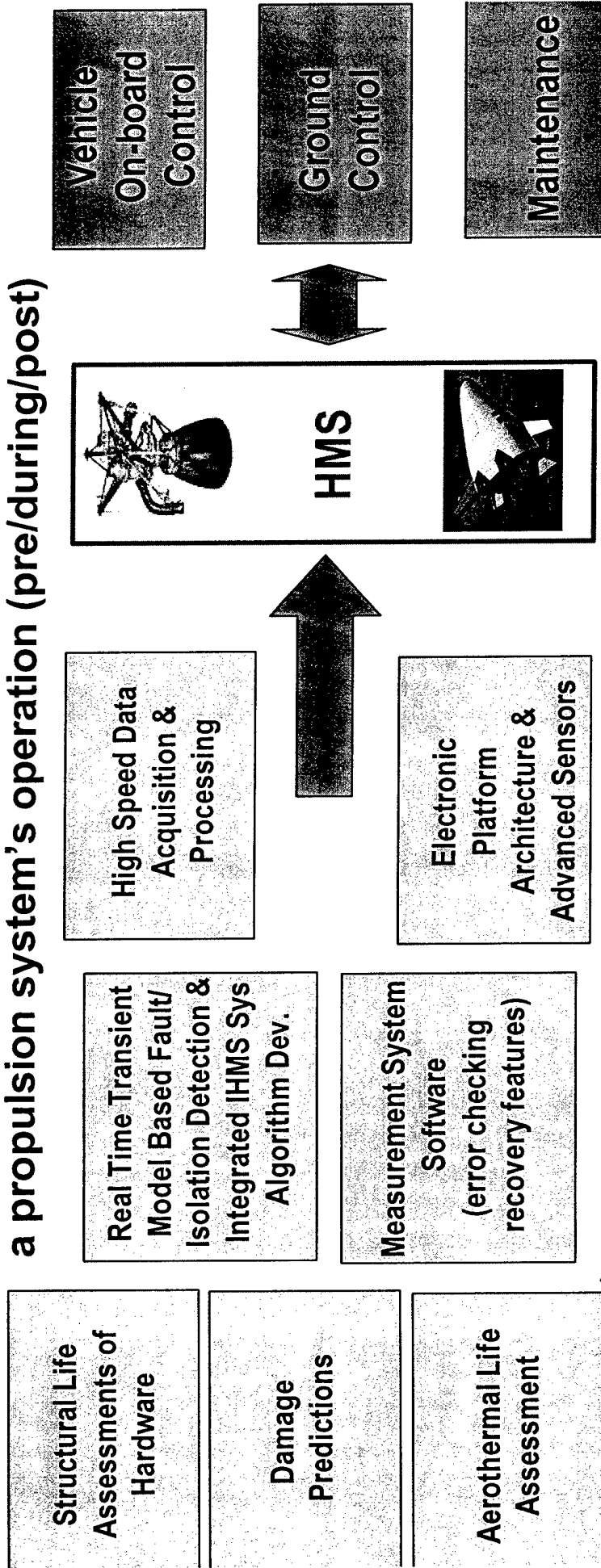
Purdue University

Munir M. Sindir, Ph.D.  
Director  
Advanced Analysis Processes  
The Boeing Company  
Rocketdyne Propulsion & Power Division  
818 586-1627  
[munir.m.sindir@boeing.com](mailto:munir.m.sindir@boeing.com)

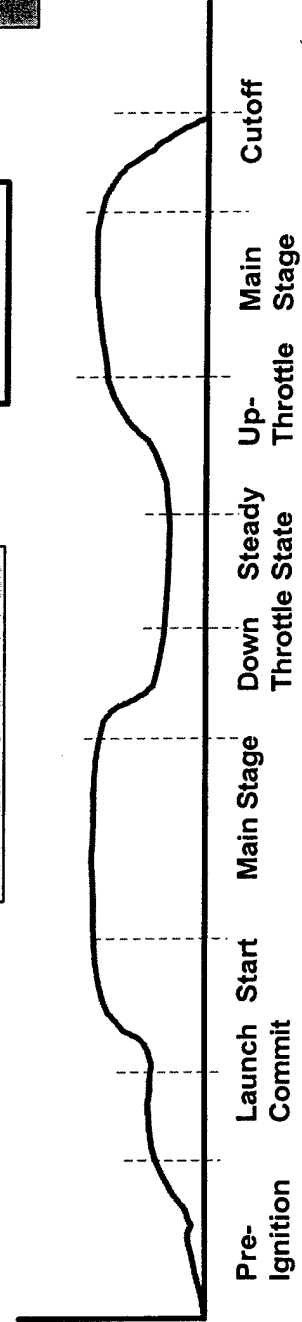


# Architecture of an Advanced Health Management System

Real-time "transient model" based health management system capable of detecting and identifying the source of anomalies/wear during all phases of a propulsion system's operation (pre/during/post)

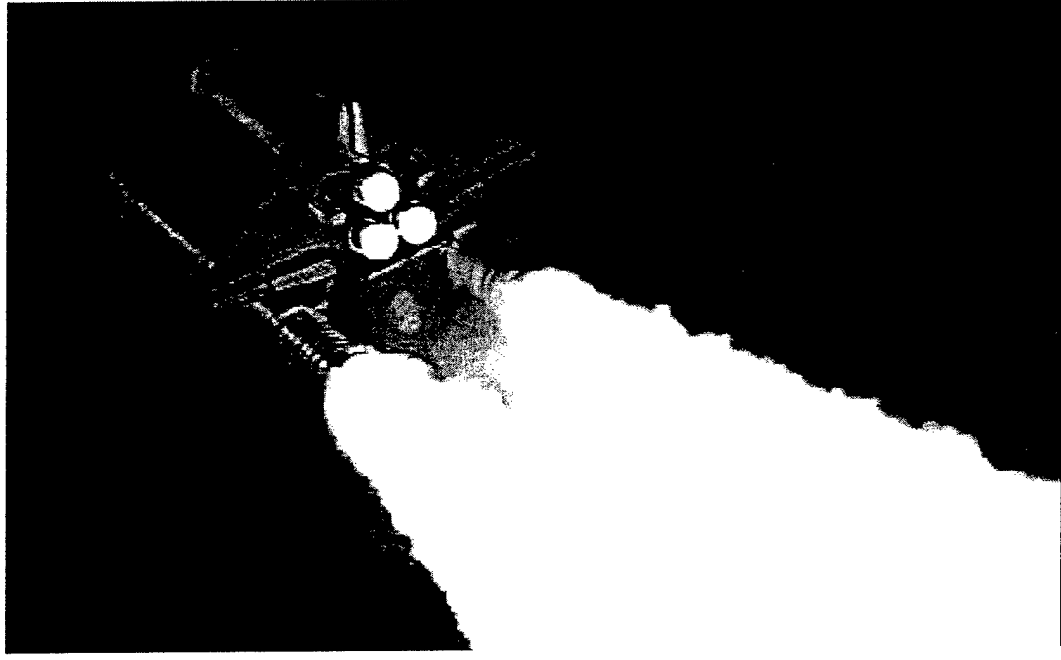


Typical Performance Parameter Profile



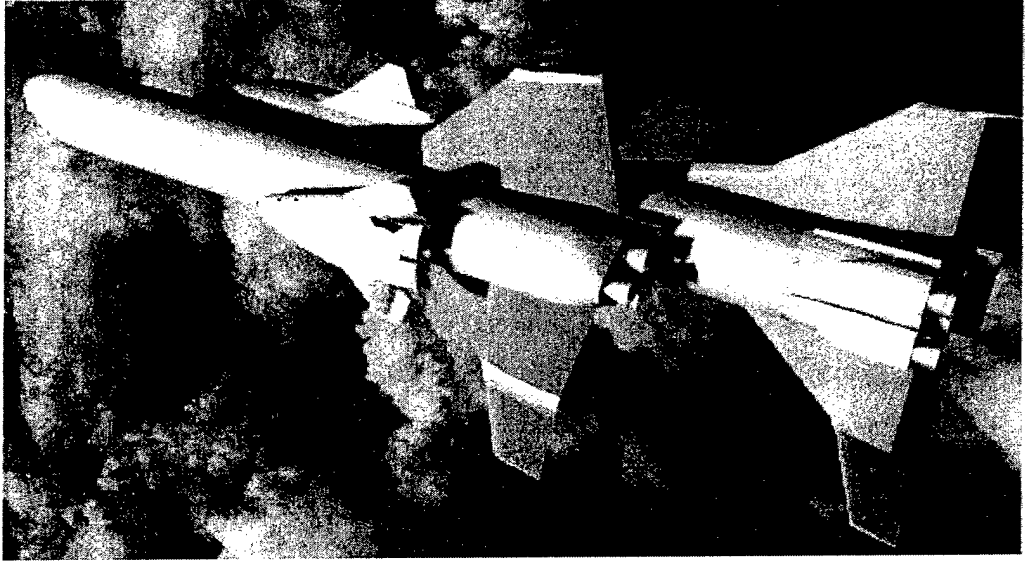
# Current Capabilities

- **Sensor Validation**
  - Reasonableness
  - Inter-channel / voting
  - Simple model
- **Detection / Isolation / Prognostics**
  - Dedicated sensors
  - Redlines
    - Flowpath
    - Vibration
- **Mitigation**
  - Channel switchover
  - Lock valves
  - Shutdown
- **Maintenance**
  - Schedule based on run time
  - Intrusive inspections



# Future Capabilities

- **Sensor Validation**
  - System consistency / full non-linear model comparison
  - Frequency analysis
  - Sensor correlation
  - Sensor replacement / virtual sensing
  - Smart sensors
- **Detection / Isolation / Prognostics**
  - Non-linear model comparison
  - Artificial intelligence
  - Cameras
  - Plume spectroscopy
  - Trending
- **Mitigation**
  - Channel switchover
  - Adaptive control
  - De-rating
  - Adjust mixture ratio
  - Shutdown
- **Maintenance**
  - Vehicle-to-ground data telemetry
  - Maintenance for cause
  - Non-intrusive inspection
  - Direct damage measurement
  - Centralized maintenance center – fleet operations



# Current / Future Capabilities

|                | <b>Sensor Qualification</b>  | <b>Detection/ Isolation/ Prognostics</b>   | <b>Mitigation</b>   | <b>Maintenance</b>  |
|----------------|--|--|---|---|
| <b>Current</b> | <ul style="list-style-type: none"> <li>• Reasonableness</li> <li>• Inter-channel / voting</li> <li>• Simple model</li> </ul>   | <ul style="list-style-type: none"> <li>• Dedicated sensors</li> <li>• Redlines                             <ul style="list-style-type: none"> <li>• Flowpath</li> <li>• Vibration</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• Channel switchover</li> <li>• Lock valves</li> <li>• Shutdown</li> </ul>   | <ul style="list-style-type: none"> <li>• Schedule based on run time</li> <li>• Intrusive inspections</li> </ul>   |
| <b>Future</b>  | <ul style="list-style-type: none"> <li>• System consistency/full non-linear model comparison</li> <li>• Frequency analysis</li> <li>• Sensor correlation</li> <li>• Sensor replacement / virtual sensing</li> <li>• Smart sensors</li> </ul> | <ul style="list-style-type: none"> <li>• Non-linear model comparison</li> <li>• Artificial intelligence</li> <li>• Cameras</li> <li>• Plume spectroscopy</li> <li>• Trending</li> </ul>                  | <ul style="list-style-type: none"> <li>• Channel switchover</li> <li>• Adaptive control</li> <li>• De-rating</li> <li>• Adjust mixture ratio</li> <li>• Shutdown</li> </ul> | <ul style="list-style-type: none"> <li>• Direct damage measurement</li> <li>• Maintenance for cause</li> <li>• Non-intrusive inspection</li> <li>• Centralized maintenance center – fleet operations</li> </ul> |

# Advanced Sensors

- **Functions**
  - High-frequency data measurements (e.g. pressure, vibration, stress)
  - Low-frequency data measurements (e.g. static pressure, temperature, mass flow, speed, displacement)
  - Plume spectroscopy measurements
- **Future characteristics**
  - Micro-sensors with built-in telemetry
  - Embedded sensors
  - Smart sensors

# High Speed Data Acquisition And Processing

- **Functions**
  - Data collection
  - Sensor validation
  - Analysis algorithm
  - Event/anomaly detection
- **Future characteristics**
  - Multiple parallel processors
  - Fiber optics transmission
  - Real-time spectral analysis
  - Real-time expert system
    - Automated “smart” analysis

# Real Time Transient Model Based Fault And Isolation Detection Algorithm

- **Functions**
  - Sensor output predictions based on actual engine operation
  - Fault predictions for anomalies
- **Future characteristics**
  - Real-time fault hypothesis testing and extrapolation
    - 1-D lumped parameter calculations
    - More sophisticated models
  - Multiple parallel processors

# Measurement System Software

*(Error checking, Recovery features)*

- **Functions**
  - Sensors monitoring and qualification
  - Monitoring of output of real time transient model
  - Engine operation recommendations
  - Virtual sensing
- **Future characteristics**
  - Neural network/artificial intelligence/expert systems
  - Multiple parallel processors
  - Kalman filters
  - Adaptive control with HMS
  - Performance management
  - Diagnostics/prognostics

# Aerothermo Life Assessments

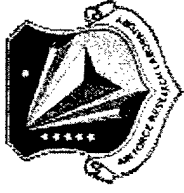
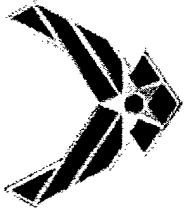
- **Function**
- Inputs:
  - Static pressure measurements
  - Temperature measurements
  - Mass flow measurements
- Algorithms to predict effects of temperature and flow on hardware
- **Future characteristics**
  - Concurrent stochastic thermal modeling and validation
  - Smart thermal structure

# Structural Life Assessment

- **Function**
  - Inputs
    - Vibration measurements
    - Stress measurements
    - Static pressure measurements
    - Temperature measurements
  - Algorithms to predict effects of vibration and stress on hardware
- **Future characteristics**
  - Probabilistic models to assess damage and structural integrity in real time
  - Numerical models to evaluate fault and fault propagation in real time

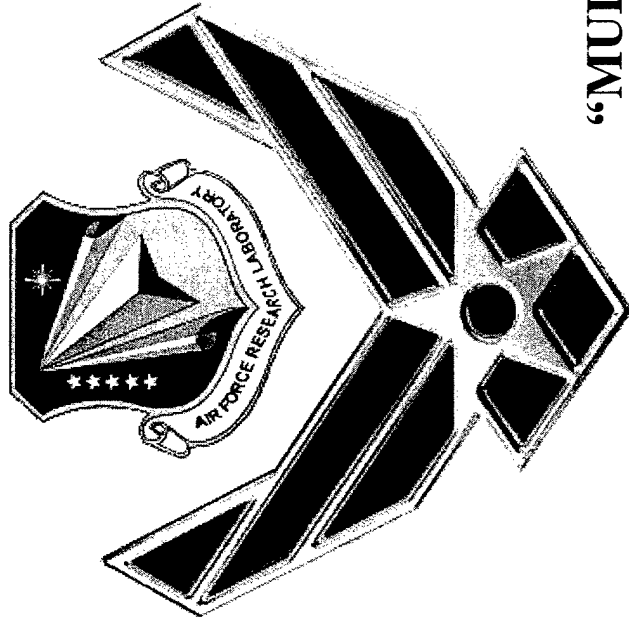
# HMS Interfaces

- **Vehicle on-board control**
  - Recommendation for engine shut-down
  - Recommendation for engine throttle
  - Recommendation for fuel and oxidizer adjustments
  - Controller re-configuration
- **Ground control**
  - Recommendation for engine shut-down
  - Recommendation for engine throttle
  - Recommendation for fuel and oxidizer adjustment
- **Maintenance**
  - Hardware status
  - Recommendations for:
    - Hardware adjustments
    - Hardware overall
    - Hardware replacement
  - Engine history



---

# Structural Health Monitoring of Aerospace Vehicles



**Mark M. Derriso**

**AFRL/VASM**

Structural Health Monitoring, Lead

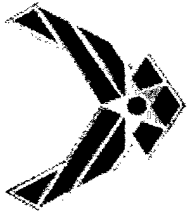
Presented to

**1<sup>st</sup> AIR FORCE WORKSHOP ON**

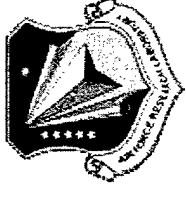
**“MULTIFUNCTIONAL AEROSPACE MATERIALS”**

**October 23-24, 2002, Purdue University,**

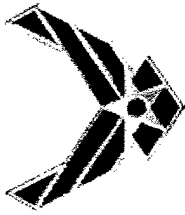
**W. Lafayette, IN**



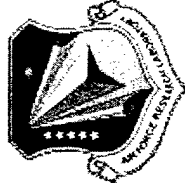
# Overview



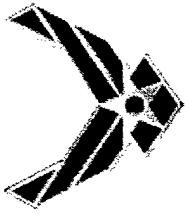
- **Purpose**
- **Introduction**
- **Applications**
- **Technical Challenges**
- **Technical Approach**
- **Key Technologies**
- **Summary**



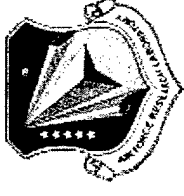
# Purpose



- To reduce the time and cost associated with scheduled inspections performed on structural components.
- **Benefits**
  - Reduce operation and support cost.
  - Reduce vehicle inspection times.
  - Maintain vehicle safety and availability.
- **Goals**
  - Reduce Air force O&M Cost.
  - Increase Operational Readiness.



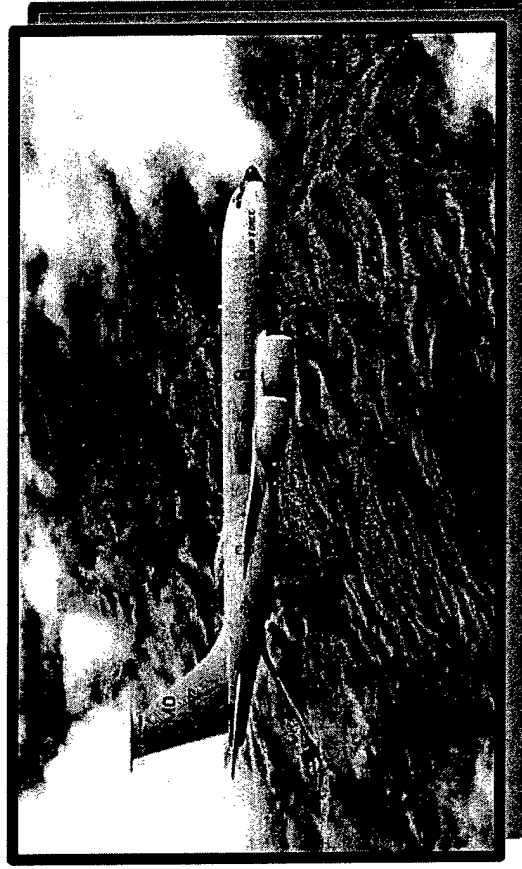
# Introduction



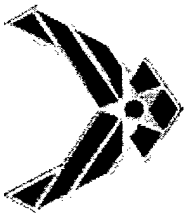
- It's a well-known fact that aircraft within the Department of Defense are aging rapidly.
- In many cases aircraft are operating well beyond their original design lives.



**B-52**



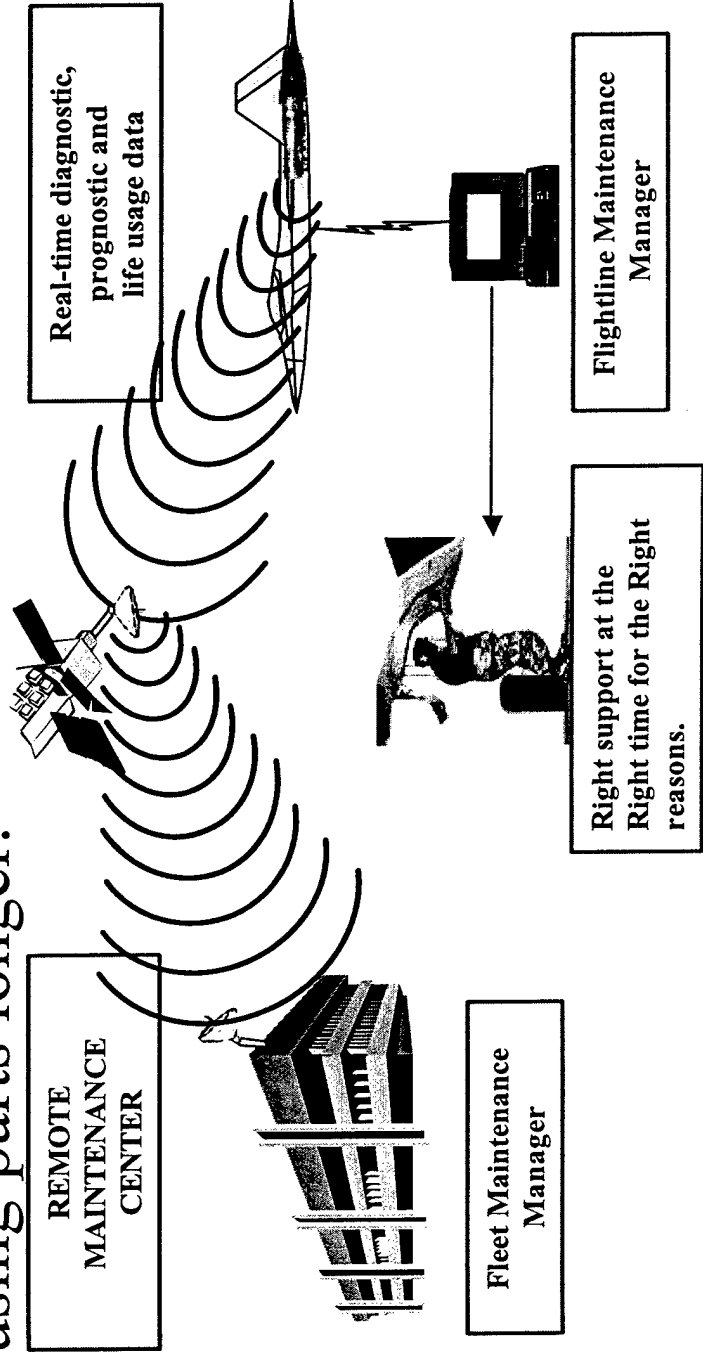
**KC-135**

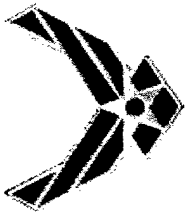


# Introduction

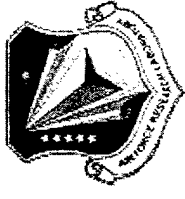


- In result, the Air Force emphasis has shifted from increasing performance to reducing the operational burden imposed by these older platforms.
- Decreasing the time required for maintenance and using parts longer.





# Introduction

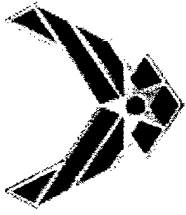


- “This study indicates that significant reduction in life cycle cost associated with maintaining and supporting structures could result in an operationally realistic return on investment. Specifically, if a 30% - 40% reduction in maintenance requirements is realized due to implementation and use of a health monitoring system.”

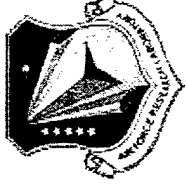
*Health Monitoring System Technology Assessment- Cost Benefits Analysis.*

*NASA/CR-2000-209848*

*Renee M. Kent and Dennis A. Murphy  
ARINC, Inc., Annapolis, Maryland*

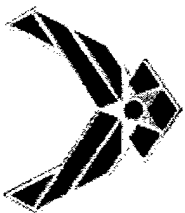


# Introduction

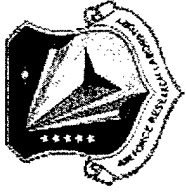


## Four Levels of Structural Health Monitoring(SHM)

- 1. Detect Damage**
  - Cracks, delaminations, corrosion
- 2. Locate Damage**
  - Structural location of damage
- 3. Quantify Damage**
  - Crack length, amount corroded, percent delaminated
- 4. Predict Remaining Life**
  - How long before component fails

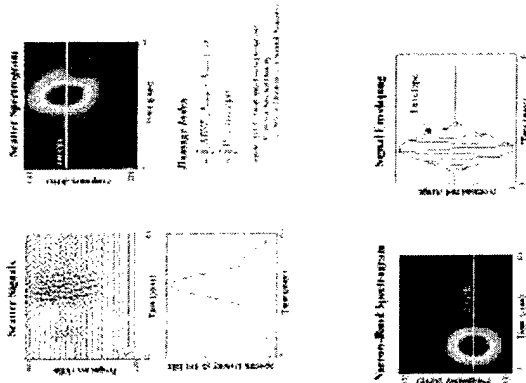
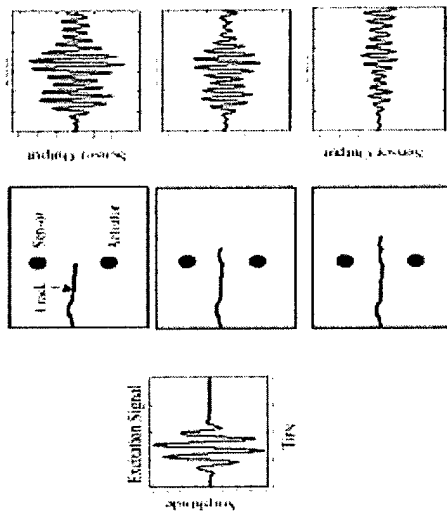


# Introduction



## Active SHM Technique (supervised)

### Approach for Crack Monitoring



An envelope gives:

- Amplitude
- Time-of-flight reference of a signal

Damage  
Algorithm  
Development

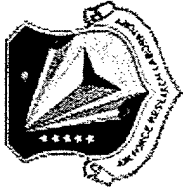
Forced Structural Excitation

Signal Processing

Damage Algorithm



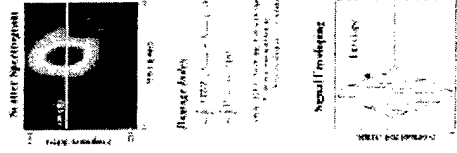
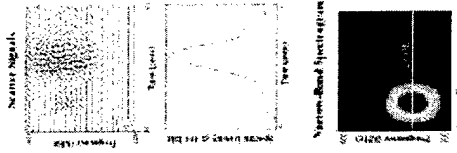
# Introduction



## Passive SHM Technique (unsupervised)



**Operational Structural  
Excitation**



An envelope gives

- Amplitude
- Time-of-flight reference of a signal

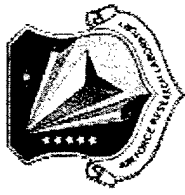
**Damage  
Algorithm  
Development**

**Damage Algorithm**

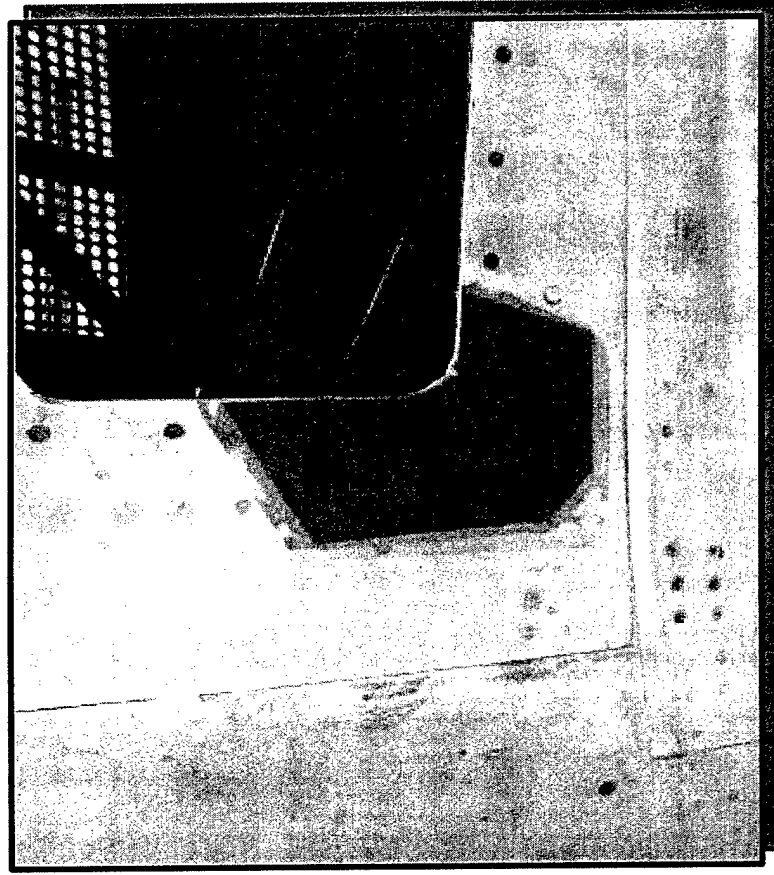
**Signal Processing**



# Applications



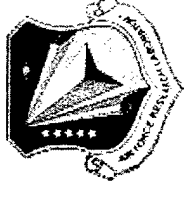
## Structural Health Monitoring of Bonded Repairs



- Bonded repair is one technique used to enhance the life of a damaged structure.
- Laboratory tests have proven that a bonded repair could extend the life of a damaged structure by as much as a factor of eight.
- Bonded repair technology is currently being used on commercial and military aircraft.



# Applications

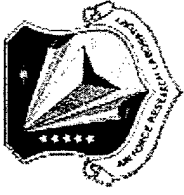


## Structural Health Monitoring of Bonded Repairs

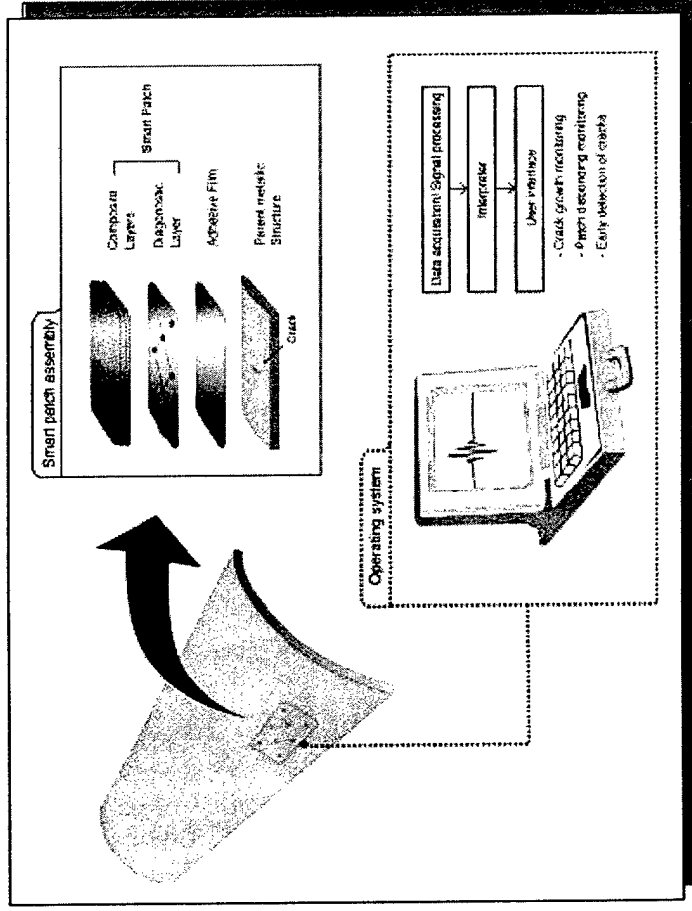
- However, the non-repaired inspection intervals of the damage under the patch is still performed because of the unknown condition of the bondline.
- By performing these non-repaired inspections, the Air Force is not receiving the full benefits of using the bonded repair technology.
- A possible solution to this problem is using a structural health monitoring system that would determine whether or not the integrity of the repair is decreasing.



# Applications



## Structural Health Monitoring of Bonded Repairs



### Objective:

- Develop structural health monitoring techniques that will detect structural crack growth, disbonds and patch integrity of a composite bonded repair patch.

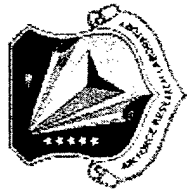
### Payoffs:

- Enhance the life of a damaged aircraft structure.
- Maintain structural safety and availability.
- Reduce operational and service cost.

## Structural Health Monitoring System

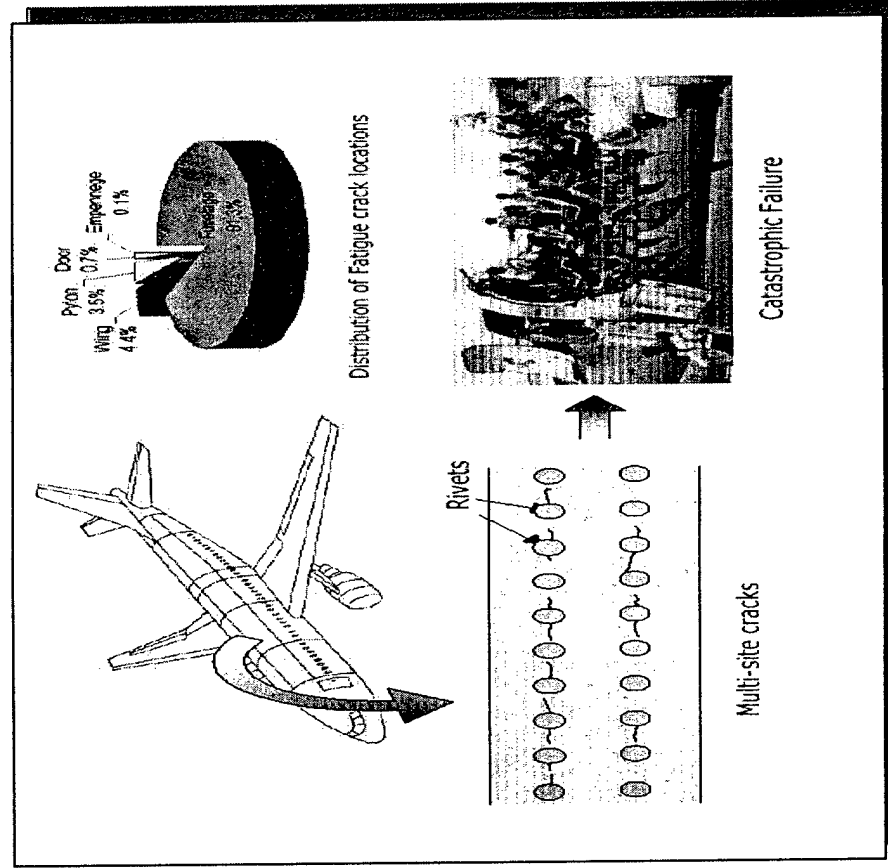


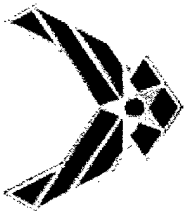
# Applications



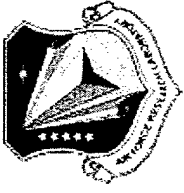
## Structural "HOT Spots" Health Monitoring

- Several aircraft in the Air Force fleet has known areas with structural problems.
- Maintainers have to inspect these problem areas at predefined intervals.
- In some cases the problem resides in an inaccessible location such as the upper or lower wing spar which requires de-skinning the wing.
- Some of these inspections are quite costly.





# Applications



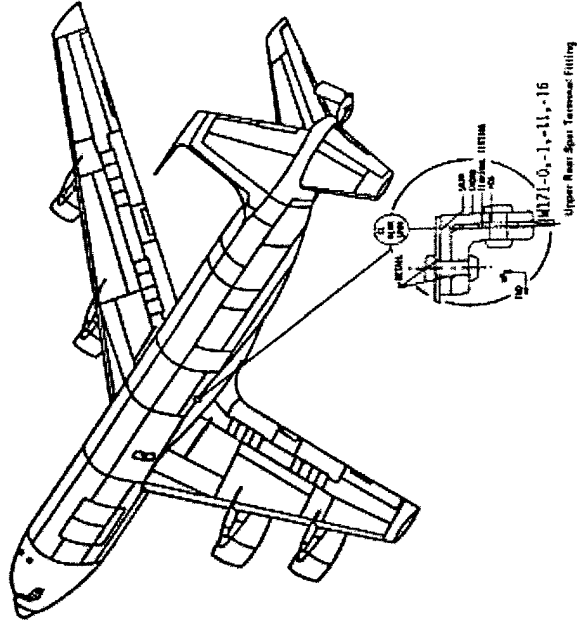
## Structural "HOT Spots" Health Monitoring

### Objective:

- Develop structural health monitoring techniques that would detect and quantify structural cracks and corrosion in known problem areas on existing aircraft.

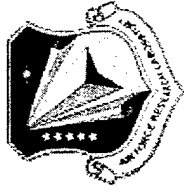
### Payoffs:

- Reduce operation and support cost.
- Reduce vehicle inspection intervals.
- Maintain structural safety.



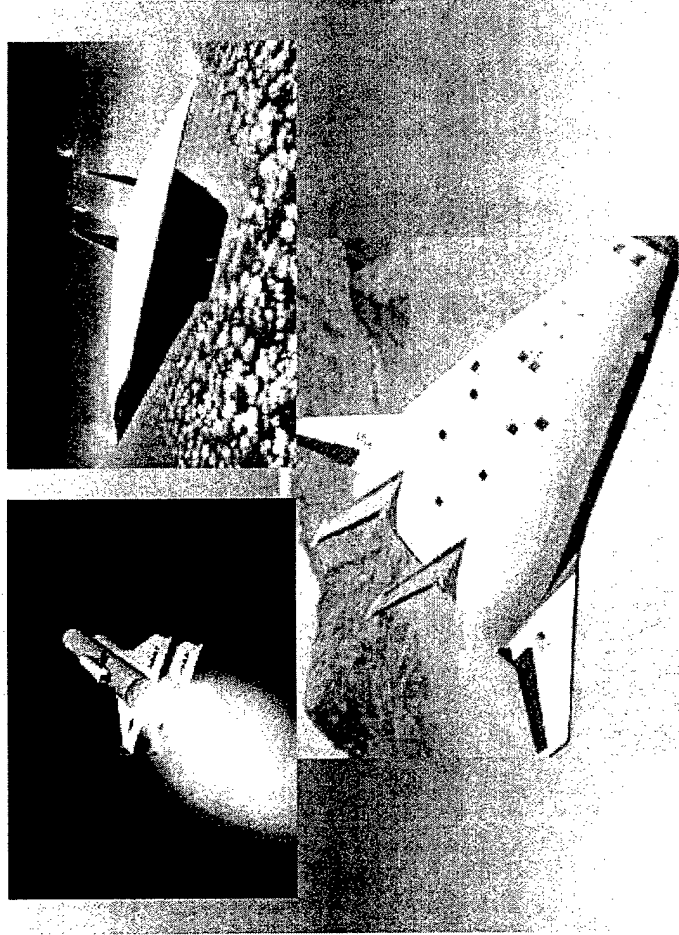


# Applications



## Space Operational Vehicle (SOV) Structural

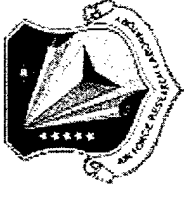
### Health Monitoring



- The Space Operations Vehicle (SOV) is a key vehicle to meet future Air Force requirements in the areas of Control of Space and Global Engagement.
- The launch costs of the SOV must be one order of magnitude less than current state of the art in order to be successful.

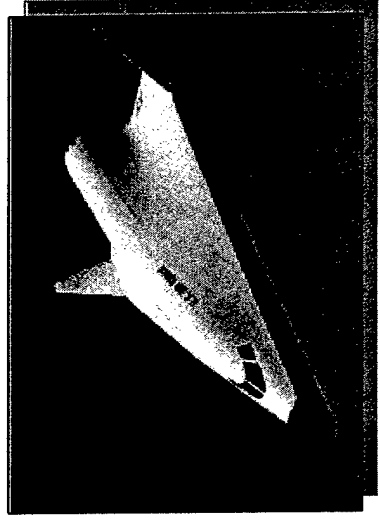
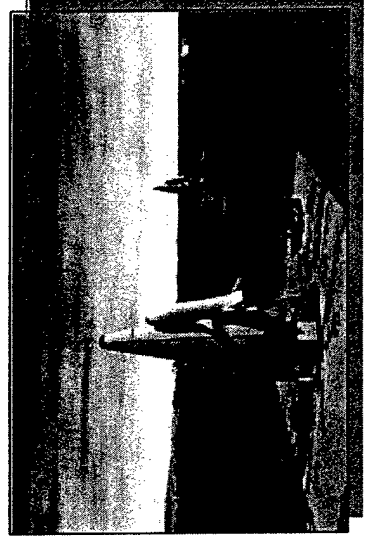


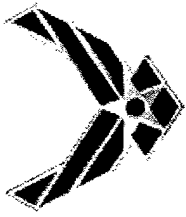
# Applications



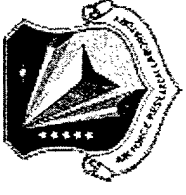
## SOV Structural Health Monitoring

- The key to reducing launch costs is reducing turn-around time.
- The System Requirements Document (SRD) for the SOV lists several requirements that have the purpose of reducing maintenance costs. In this presentation, we will concentrate on one of these objectives.
  - During normal conditions, the SOV shall have a turn-around time of 24 hours, with an objective of 12.
- To meet this goal, the assessment of the structure/TPS condition has to be reduced significantly.





# Applications

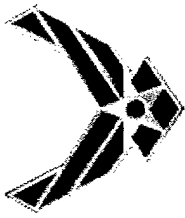


## SOV Structural Health Monitoring

### System Requirements

- An automated system that assess the health of the entire vehicles' structure/TPS within hours of completed mission and certify it for re-flight.
  - Acreage TPS
  - Leading edge TPS
  - Wing structure
  - Fuel tanks
- SHM system needs to be able to do the following:
  - Detect damage in the structure/TPS
  - Locate damage
  - Diagnose damage (delamination, impact damage, mechanical attachments state etc.)
  - Prognosis of the health of the structure/TPS.

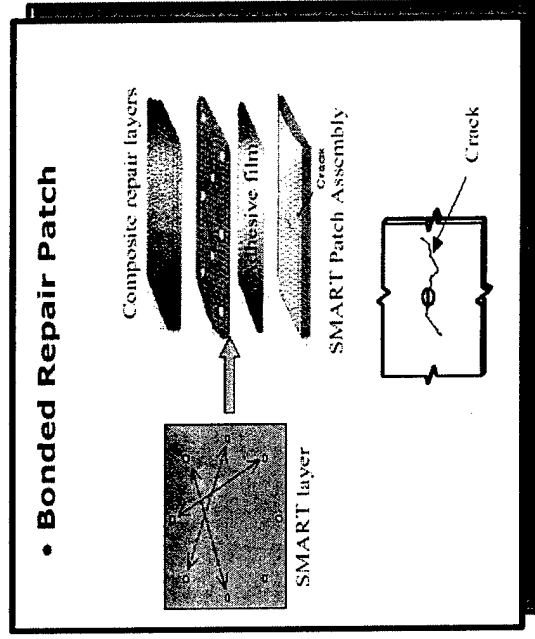


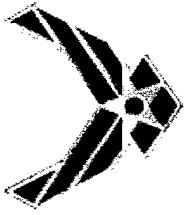


# Technical Challenges

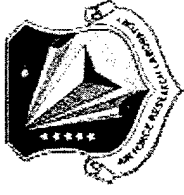


- **Sensors development**
  - high temperature (space)
  - wireless
  - reliable
- **Sensor optimization**
  - location
  - quantity
- **Data assimilation**
- **Data interpretation**
- **Structural life prediction methods**





# Technical Approach



- Empirical Methods
  - Neural Networks
  - Pattern Recognition



- Analytical Methods
  - Physics-based Modeling
  - Statistical Analysis



## Hybrid Approach

Combine

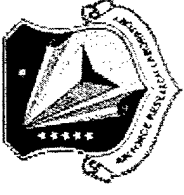
Analytical and Empirical

Means for Optimum

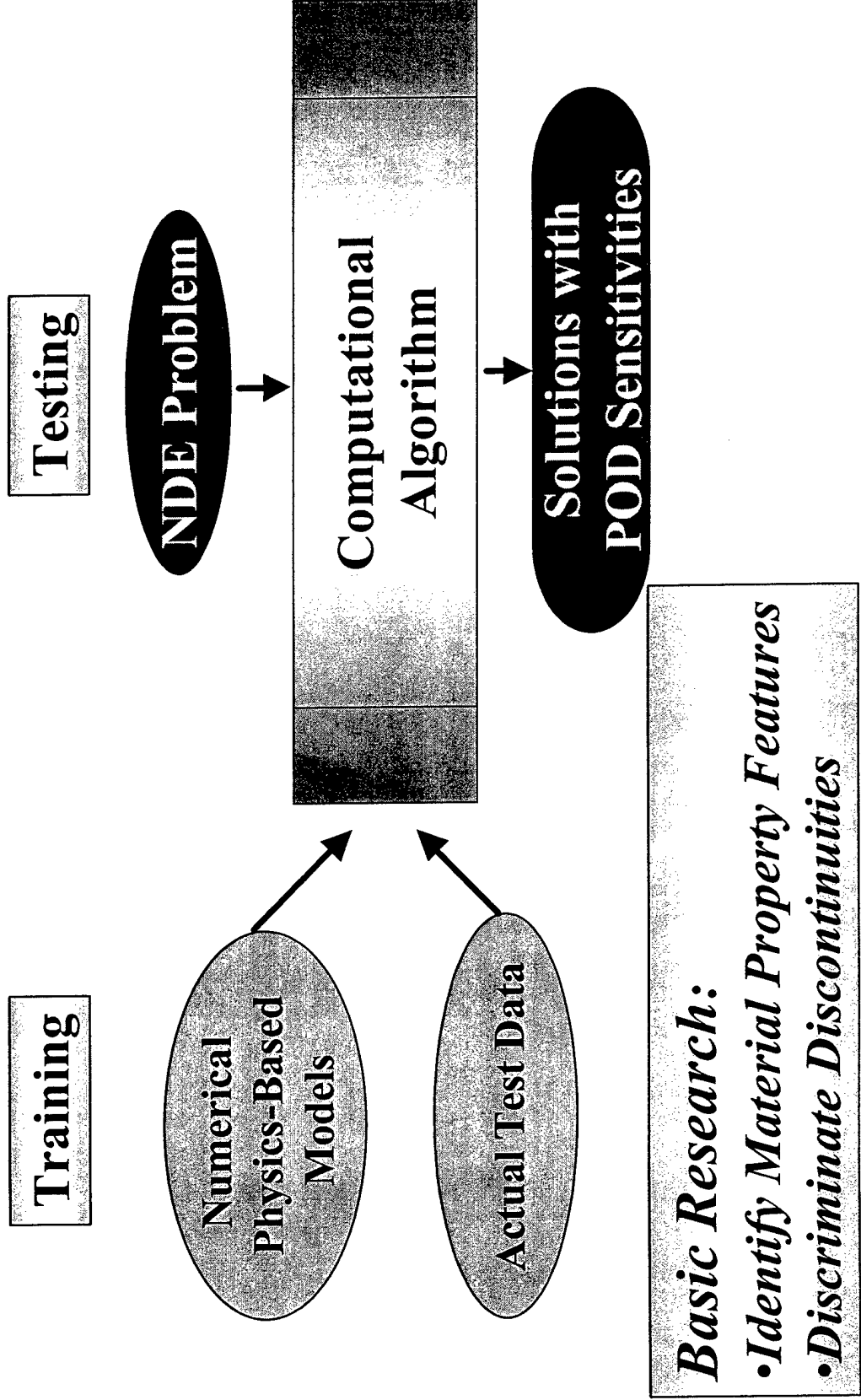
Solution



# Technical Approach

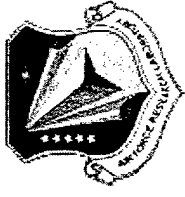


## Pattern Recognition Approach



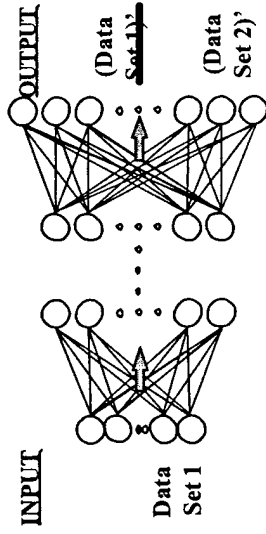


# Technical Approach



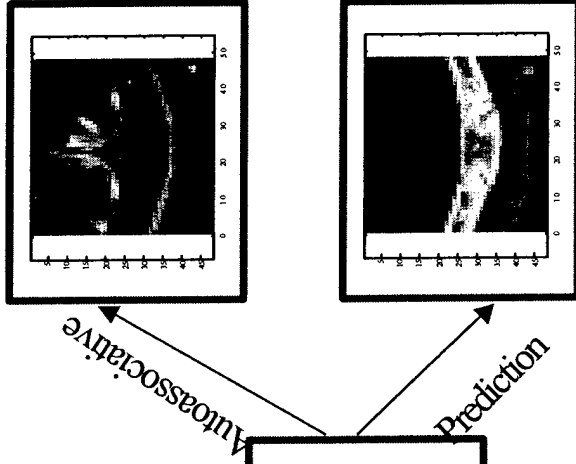
## Data Fusion Approach

Autoassociative - Heteroassociative Neural Network (A-HNN)



**Mathematical Transformation:  
Maps One Data Set to Two!**

Patent Pending



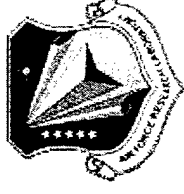
**Basic Research:  
Identify Common Invariant Features of "Relationship" Between Data Sets**

## Technical Approach:

- Derive Transformation Matrix
- Establish Reliability Metric
- Experimental Validation



# Technical Approach



## Modeling Approach

Optimal Design of NDE Devices Using Ideal Concepts

Specifying Design Objectives →

Numerical  
Physics-Based  
Model

→ NDE Tool  
Design

Optimization

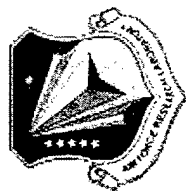
Basic Research:

Identify Basic Design Principles

Identify Basic Design Axioms



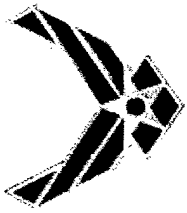
# Technical Approach



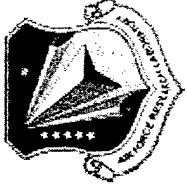
- Finite element modeling is done to determine the response of the panel.
- Advanced features are included such as the fasteners, contact, etc.
- Comparison is made with the experimentally observed response(s) to validate the model
- Sensitivities of the response(s) with respect to the damage states can be evaluated via analysis.



FEM of a TPS panel



# Key Technologies



- **Advanced Digital Signal Processing (DSP)**

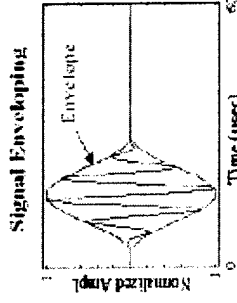
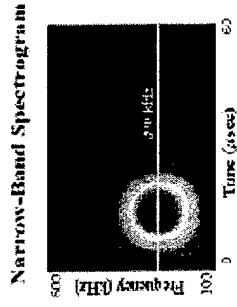
- Discrete Fourier Transforms (DFT)
- Wavelet transforms
- Digital filters

- **Advanced data analysis**

- Feature extraction
- Pattern recognition
- Data fusion

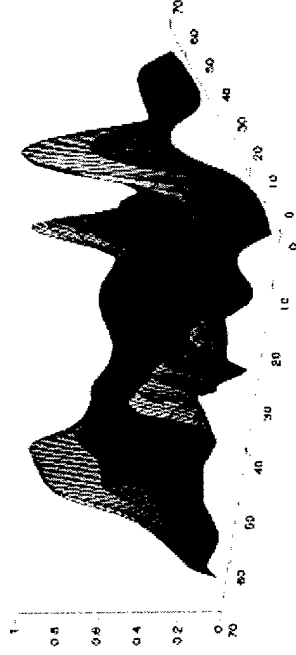
- **Structural characterization**

- Impact damage analysis
- Structural fatigue analysis
- Acoustics fatigue analysis



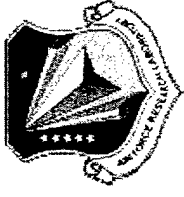
An envelope gives:

- Amplitude
- Time-of flight reference of a signal





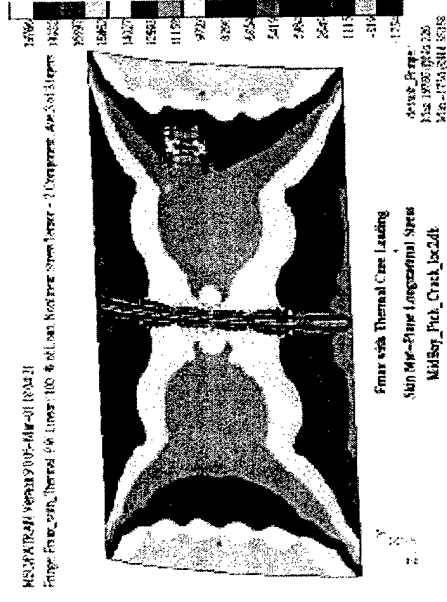
# Key Technologies

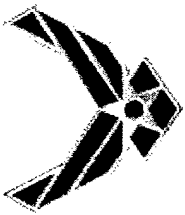


- **Physics Based Models**
  - Structural Impact damage models
  - Structural Fatigue models
  - Life prediction models

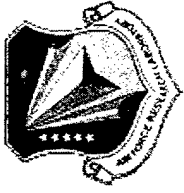
- **Data acquisition and instrumentation**

- Sensor installation
- Sensor integration
- Sensor interrogation

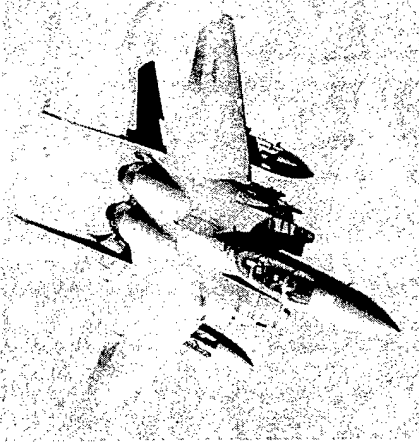




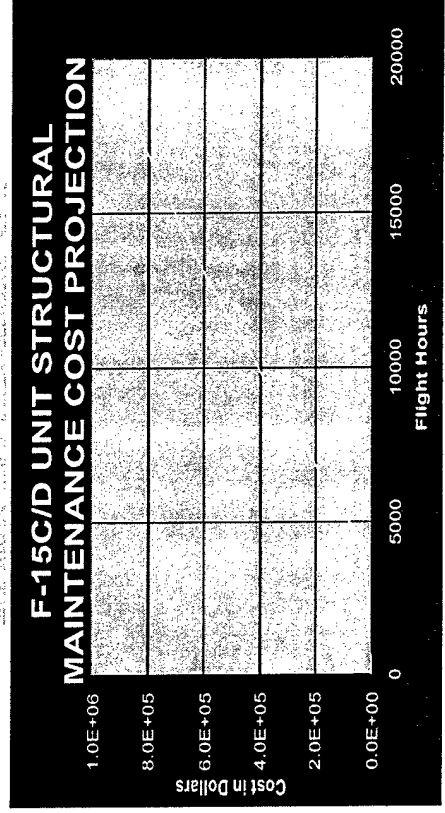
# Summary



- Warfighters have a need for this technology
- Reduction in O&M cost
- Maintain structural safety and availability



| Technology Area | Technology Number | Concepts | Technologies            | # Concepts technology is Enabling |
|-----------------|-------------------|----------|-------------------------|-----------------------------------|
| Propulsion      | PROP5             |          | Affordable Prop Systems | 14                                |
| Com             | COM3              |          | Secure COMMS            | 13                                |





VG02-275

## ***Materials That Sense Their Environment***

B. D. Green and P. B. Joshi  
Physical Sciences Inc.  
Andover, MA  
green@psicorp.com

Presentation at:  
Multifunctional Aerospace Materials Workshop

Purdue University  
24 October 2002

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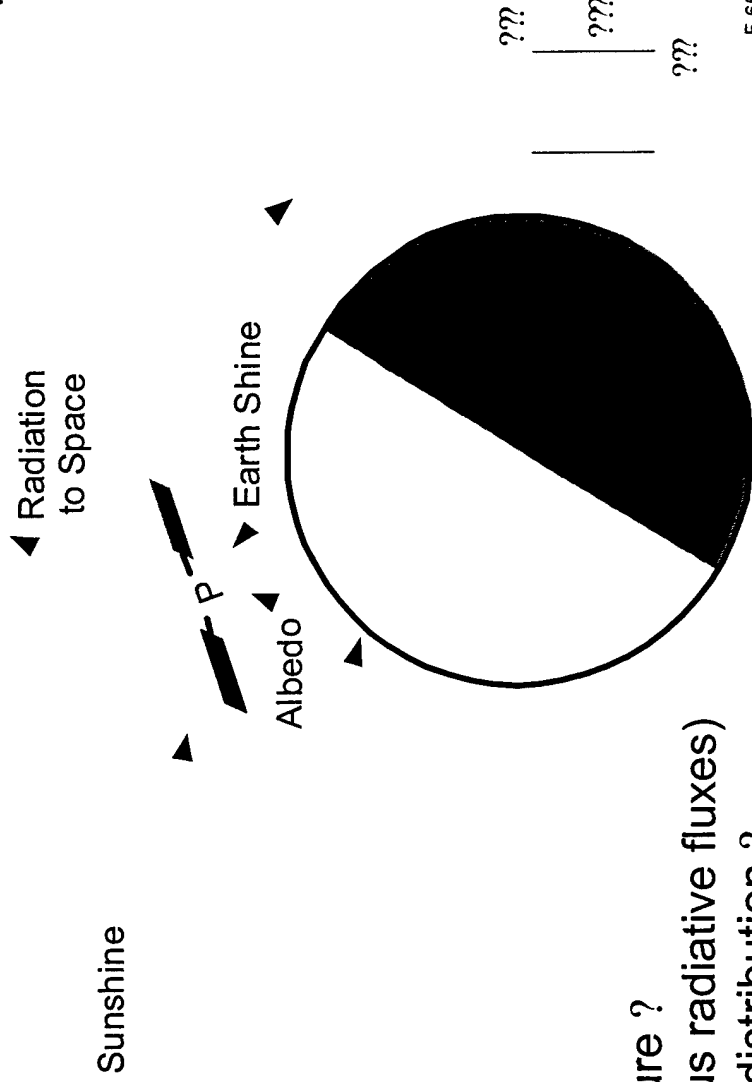
Physical Sciences Inc.

20 New England Business Center

Andover, MA 01810

# Near-Earth Spacecraft Thermal Environment

VG02-275-1



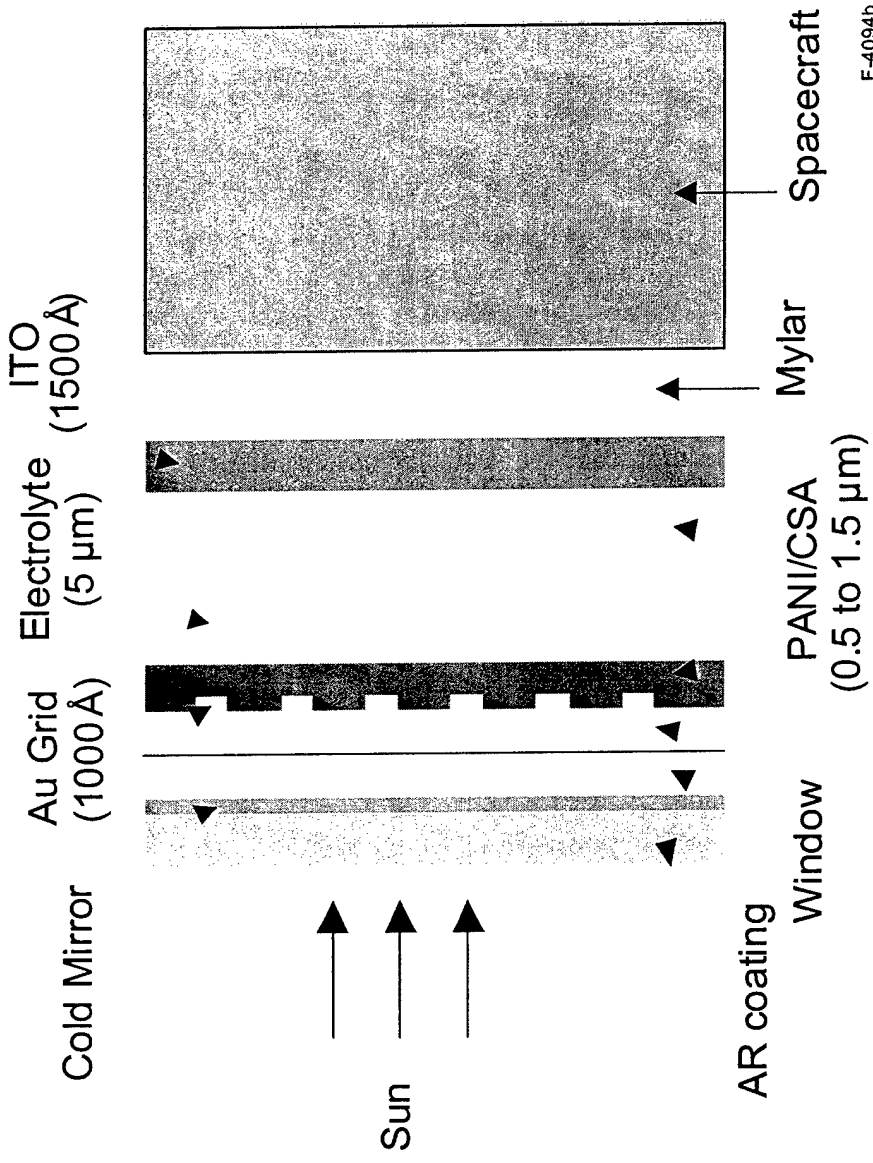
F-6504

- ? Spacecraft temperature ?
- f(equilibrium of various radiative fluxes)
- ? Internal temperature distribution ?
- f(conduction within spacecraft structure)
- ? Temperature cycling as spacecraft moves in/out of eclipse
- ? Radiation to space, solar input, internal power must be controlled to maintain spacecraft systems (especially electronics) within operating temperature (-30 C to 65 C, typical)



# Electrochromic Thermal Control Device Structure

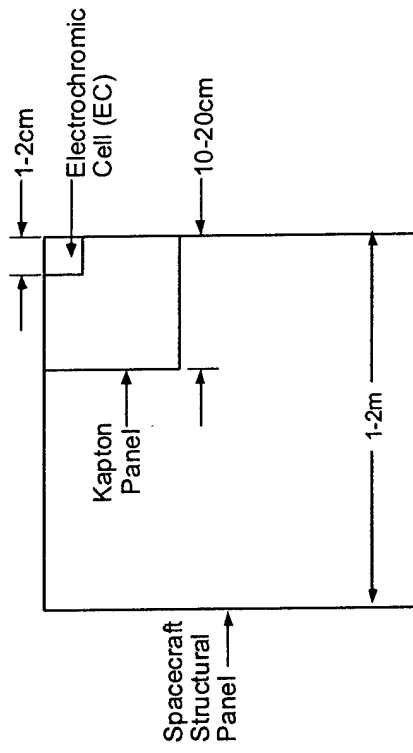
VG02-275-2



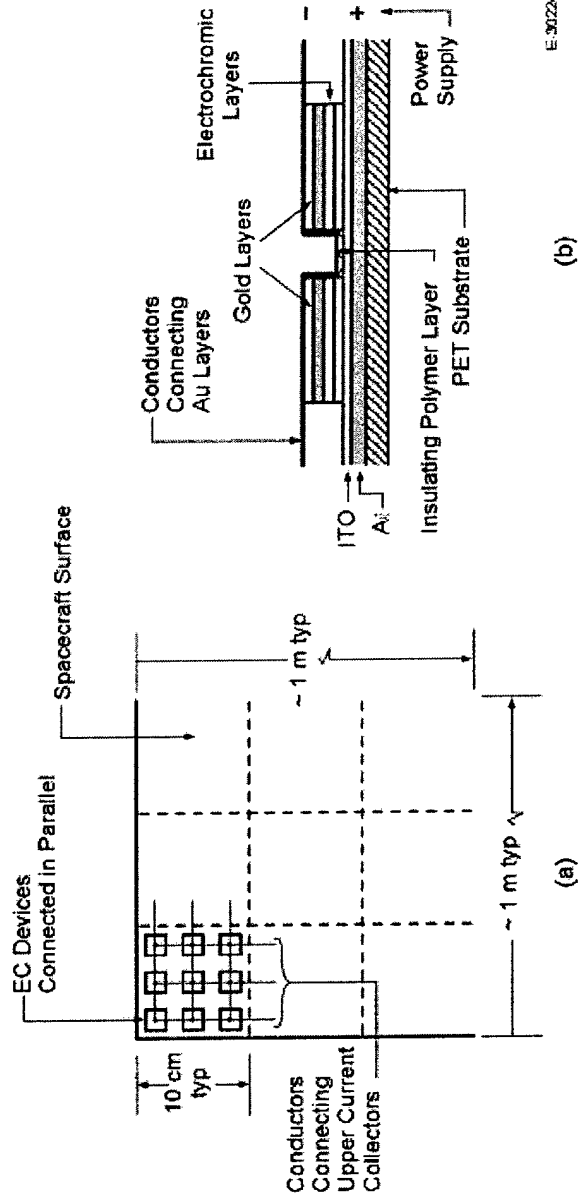
- ? Battery-like cell; charge changes optical properties
- ? The entire EC device is no more than 7 mils thick (0.177 mm) dominated by Mylar substrate (can be reduced to 0.9 mil)
- ? Goal: thin-film flexible device thermostatically controlled

# Concept for Integration of Electrochromic Devices into Spacecraft Structure

VG02-275-3



D-8280

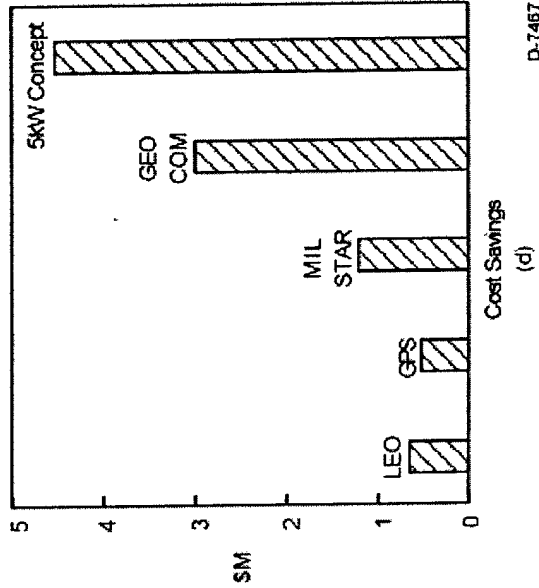
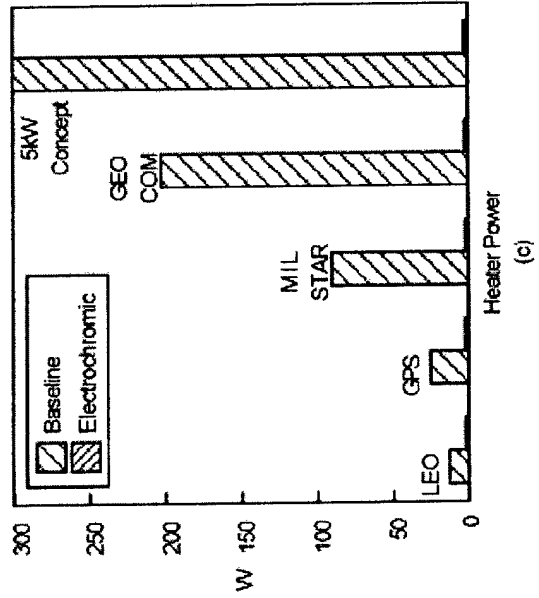
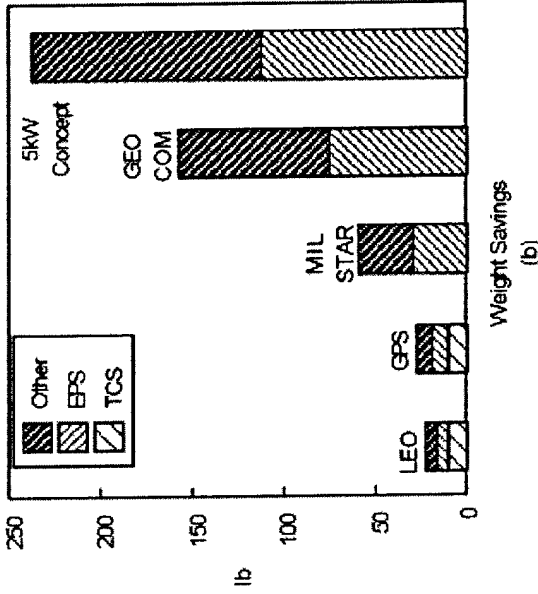
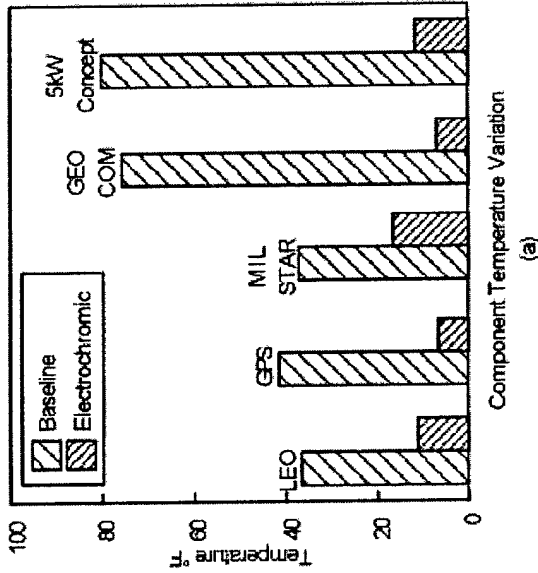


E-302284



# Benefits of Thermal Control with Electrochromics Technology

VG02-275-4



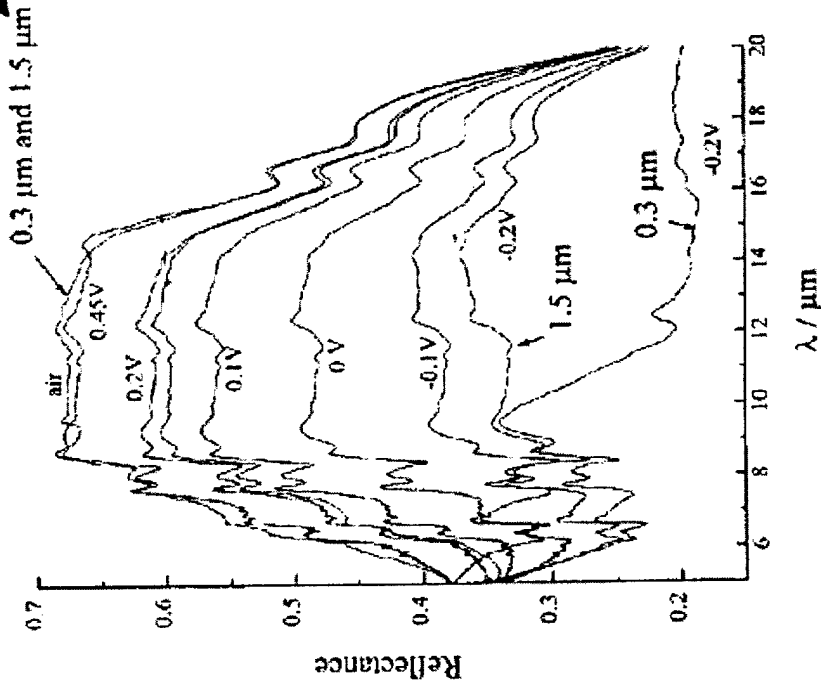
D-7487

PHYSICAL SCIENCES INC.

# Reflectance Variation with Film Oxidation

VG02-275-5

Film Thicknesses



Emeraldine Salt

Oxidized

Reduced

Leucoemeraldine Salt

E-4537a

? PANI-CSA films 0.3 and 1.5 ? m, m-cresol solvent

? IR reflectivity variation between 0.7 and 0.2

Reference: Topart and Hourguebie, *Thin Solid Films*, 352, p. 243, 1999.

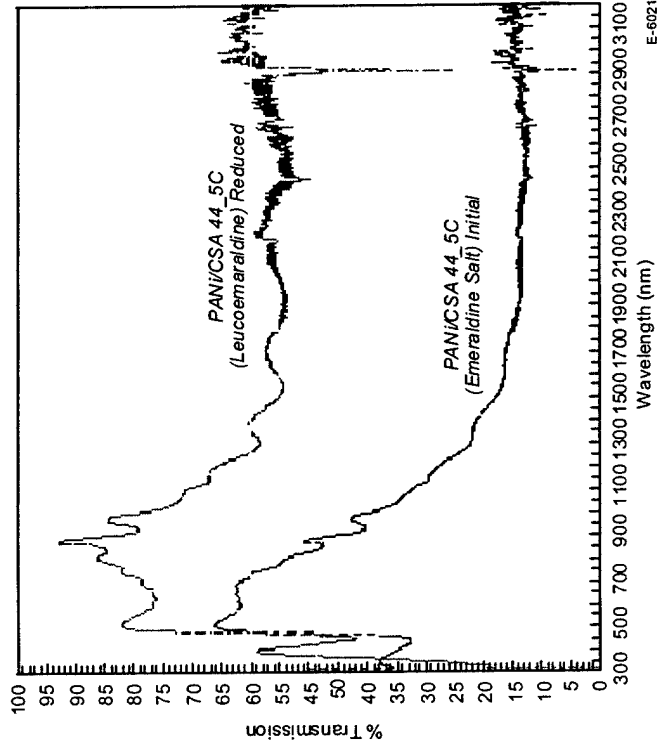
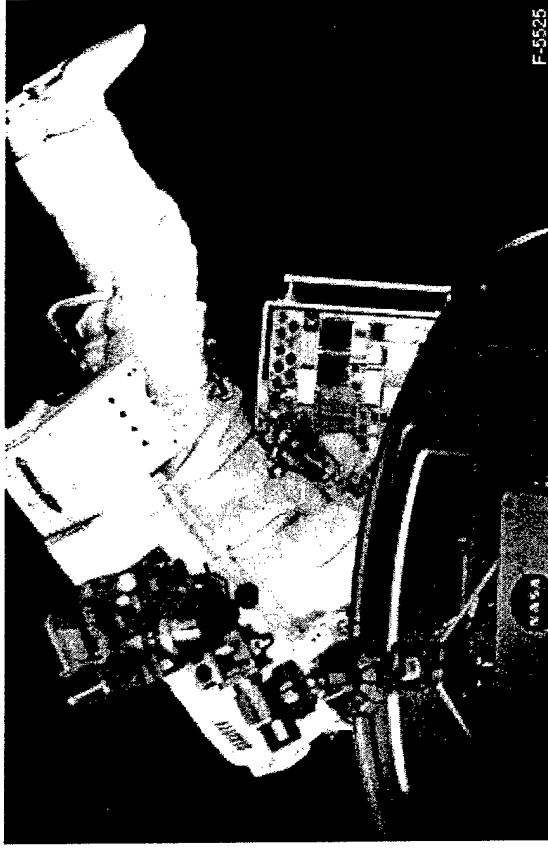
ISI

PHYSICS AND CHEMISTRY

# Variable Emissivity/Reflectivity Materials First Flight Test

VG02-275-6

- ? Electrochromic materials for spacecraft thermal control, propulsion
- ? Vary R,  $\alpha$ , ? in the visible IR by choice of substrate, active materials
- ? Alter optical properties via electro-chemical switching of polymeric materials



- ? Application to solar sails, s/c and subsystem thermal management
- ? Passive samples on MISSE carrier – first attached payload outside ISS (Aug 01)

PSI

Physical Sciences Inc.

E-6021

# Molecular Sensing Using Conductive Polymers

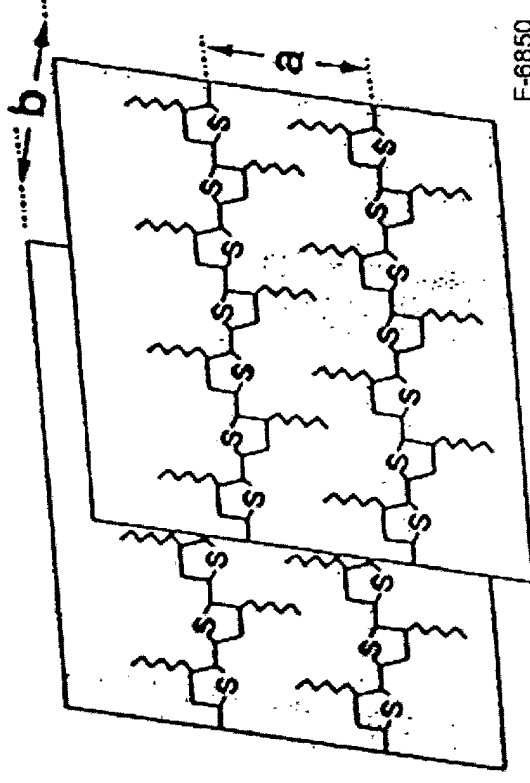
VG02-275-7

## ? Inhibition of transduction

- disrupt planarity of polymer backbone
  - swelling
  - chemical reaction with an additive
- dedoping
  - chemical reaction to remove dopant from polymer

## ? Enhancement of transduction

- target compound acts as a dopant to increase conductivity of the polymer
- interaction of target compound with sensing material increases planarity of polymer backbone



ISI

Physical Sciences Dept.

# ***Individual Chemical Alarm System (ICAS)***

VG02-275-8



E-9183

? **Conductive polymer sensor system for**

- chemical warfare agents
- toxic industrial compounds

? **Real time detection**

- alerts wearer upon exposure
- stores exposure history

**ISI**

PHYSICAL SCIENCES INC.

# ICAS Prototype Badge Design

VG02-275-9

## ? Simple user interface

- on/off switch
- self-test feature
- sampling interval selection
- audible alert
- tox class indication

## ? Insertable sensor array chip

## ? AAA battery - 5-day lifetime

## ? Size

- 2.5 x 4.75 inches
- 3.5 ounces

## ? Downloads exposure data to Access database

## ? Exposure records

- exposure dose = concentration x time
- logged every 30 minutes or + 20% dose increase

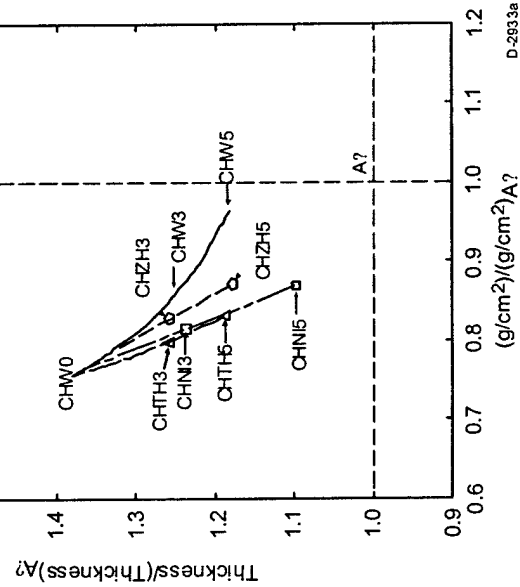
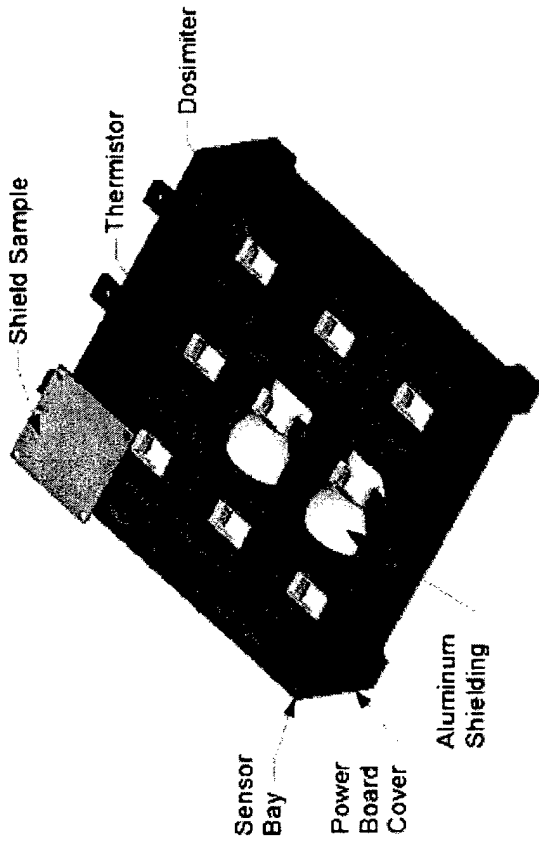
ISI

PHYSICS & CHEMISTRY

# Advanced Radiation Shielding Materials SBIR

VG02-275-10

- ? Develop composites that provide more shielding per gram than Al
- ? Tailor composition to enhance e or p shielding for specific mission
- ? Benefit: significant mass savings reduce s/c weight or increase payload



D-2833a

E-0081

- ? Commercial partner: Space Systems Loral
- ? Phase 3: Develop evaluation experiment
- ? Manifest: Geosynchronous telecom satellite: Brazilsat (2002 launch)
- ? Following activities: STRV1D, LMA panel



Ballistic Shielding Inc.

## **Summary**

---

VG02-275-11

- ? **Conductive polymer compounds have been synthesized to maximize**
  - optical properties changes
  - response to toxic compounds
  
- ? **Sensors for control network**
  
- ? **Undergoing demonstrations under real world conditions**
  
- ? **Polymer compounds are a useful accessory to composite structures**

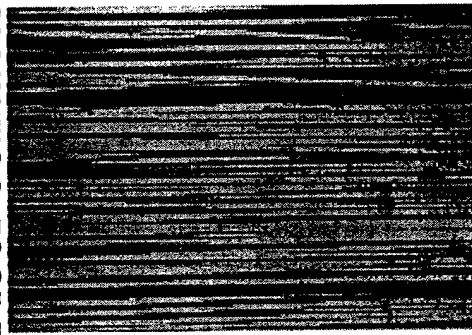
**ISI**

PHYSICS AND STRUCTURES

# Self-Diagnosis of Damage in CFRP by Electrical Resistance

W. A. Curtin, Brown University, N. Takeda, T. Okabe, J. B. Park, U. Tokyo

- Carbon fibers: electrically conducting
- Fiber contacts  $\nabla$  conducting network

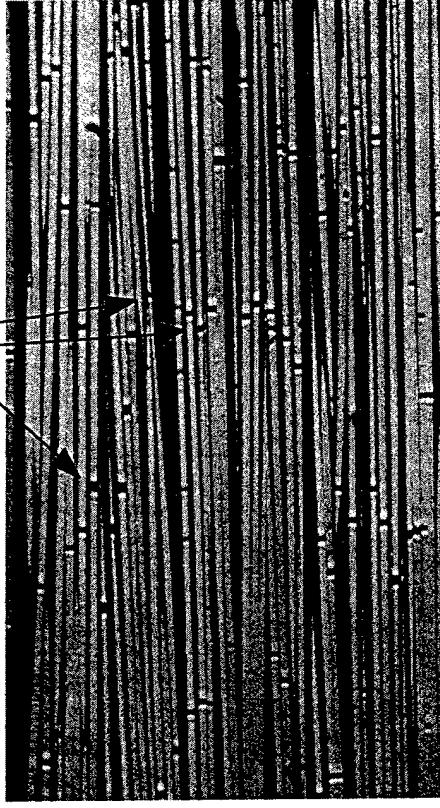


50  $\mu$ m

Contacts Between Fibers

Due to Misalignment

breakage of carbon fiber



Fiber breaks (mechanical damage)

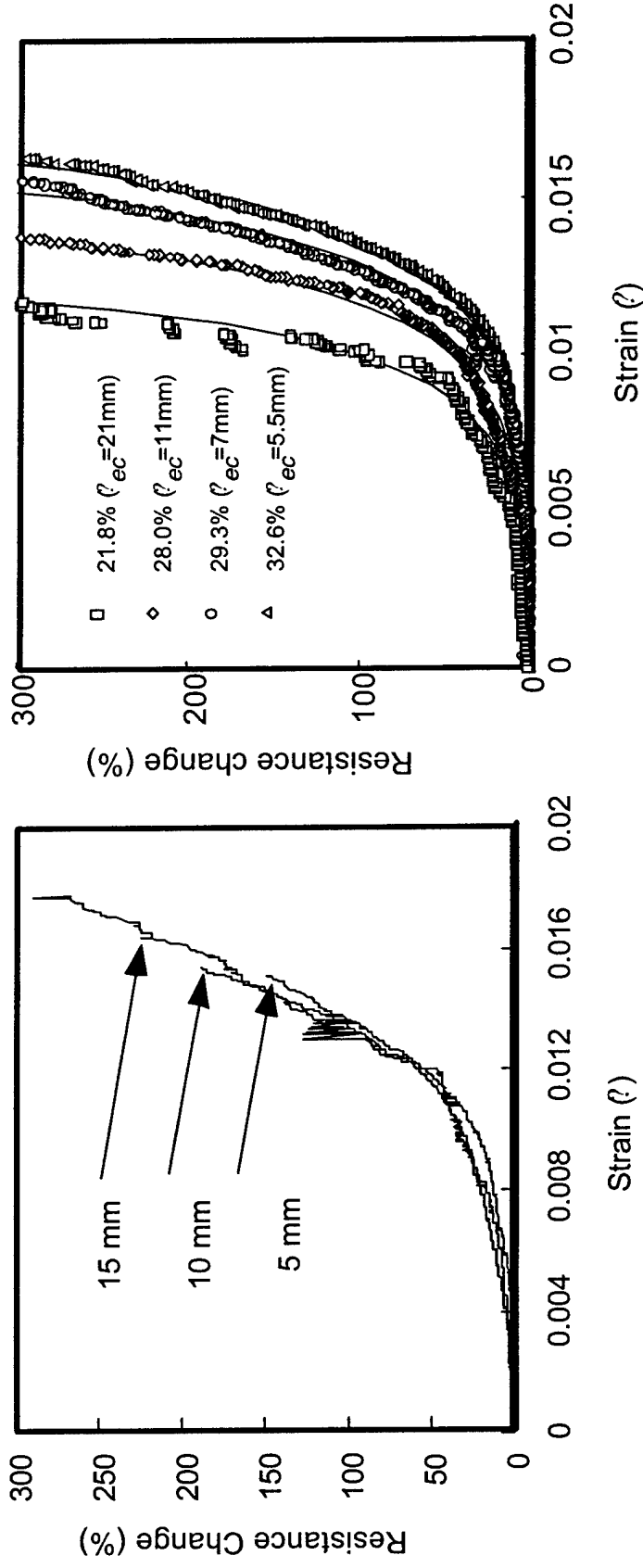
$\nabla$  electrical "damage"

Electrical resistance monitors damage evolution

On-Board Damage Detection, Failure Prediction from Resistance

Large changes in resistance at small strains

Highly non-linear response with strain;  
Can tune to coincide with failure strain

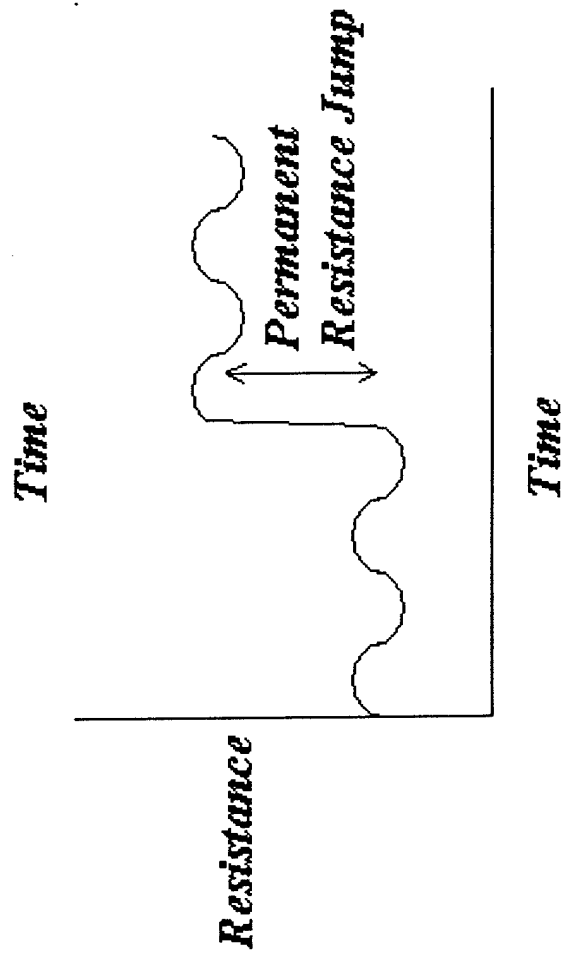
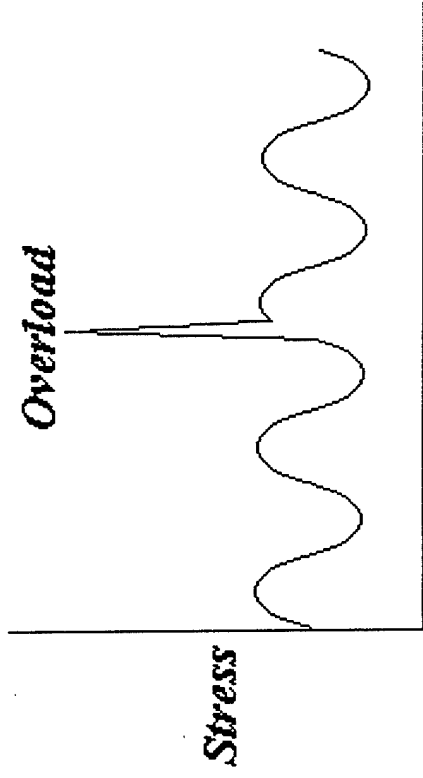


Resistance response can be tuned using fiber volume fraction

Resistance is independent of sample gauge length (spatial sensitivity)

Resistance carries a permanent record of prior damage

Critical for damage due to overloads



Some Issues:

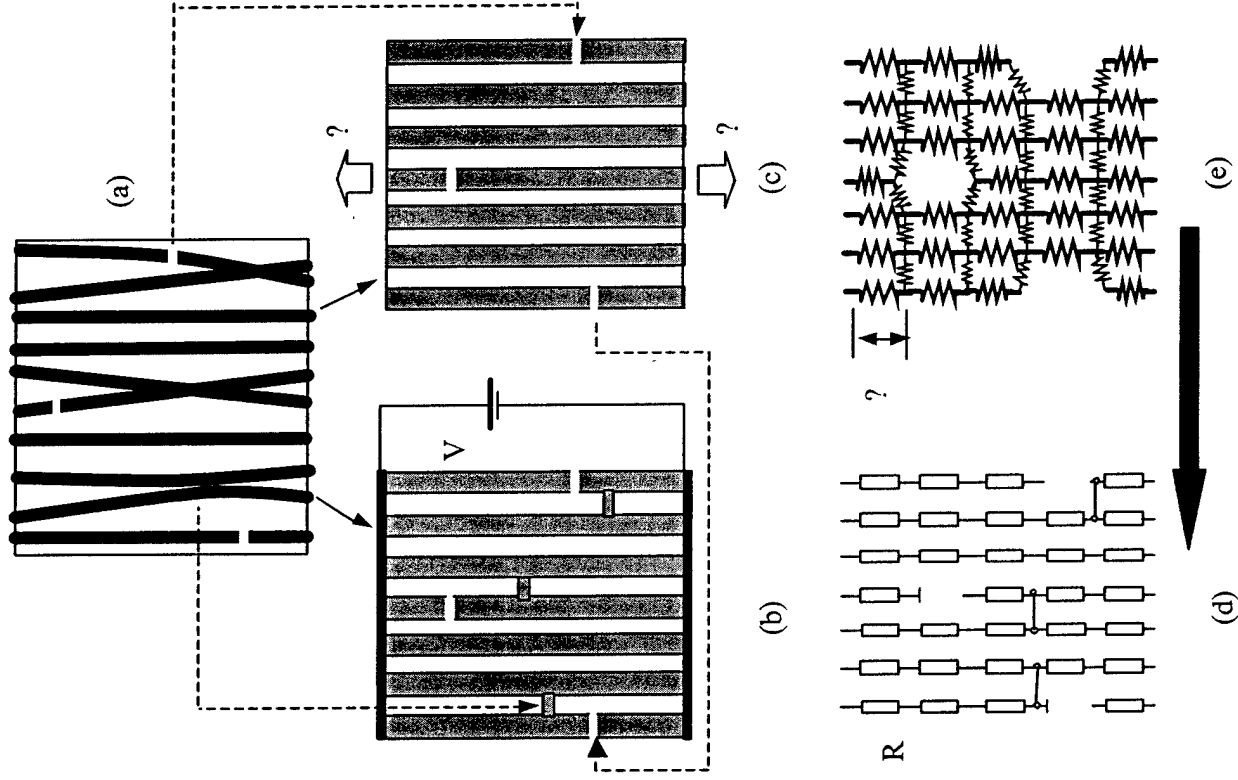
- What controls relationship between resistance and failure?
- How locally can damage be detected?
- How can signals be interpreted?
- How can this be used practically (outside the lab)?

Current effort:

Address some issues through computational modeling

Clearly need a coupled experimental effort

# Coupled Mechanical, Electrical Models



Electrical Model:  
Local resistances



Resistance vs.  
stress/strain/damage

Mechanical Model:  
Damage, local stresses



Stress vs. strain, failure

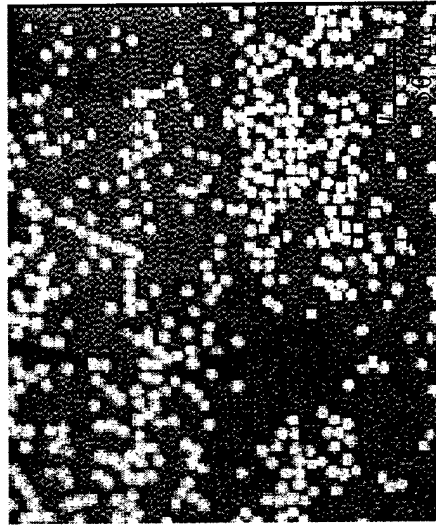
Length scales associated with fiber damage:

Old concept: Mechanical “ineffective length” ?  $l_c$  :

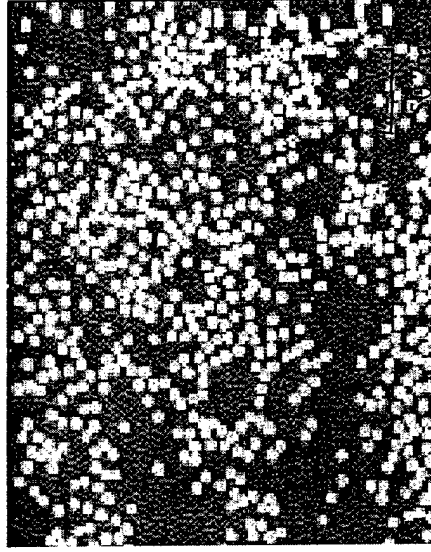
loss of load carrying capability depends on fiber, matrix, interface mechanical properties

New concept: Electrical “ineffective length” ?  $l_{ce}$  :

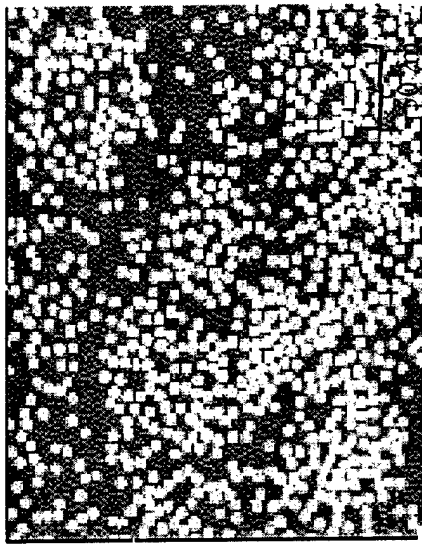
loss of current carrying capability depends on inter-fiber contacts, geometry, volume fraction



(a)  $V_f = 22\%$



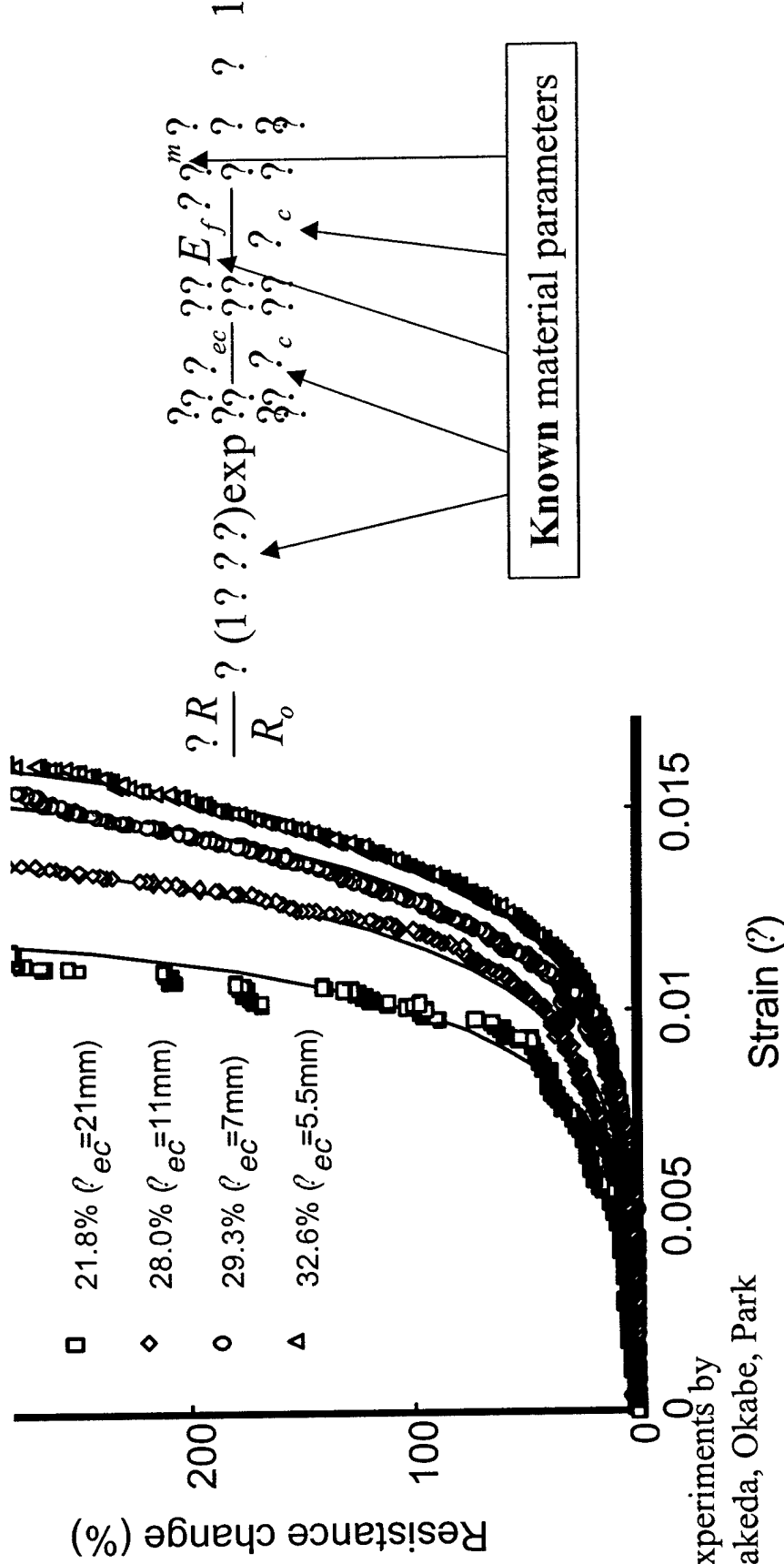
(b)  $V_f = 28\%$



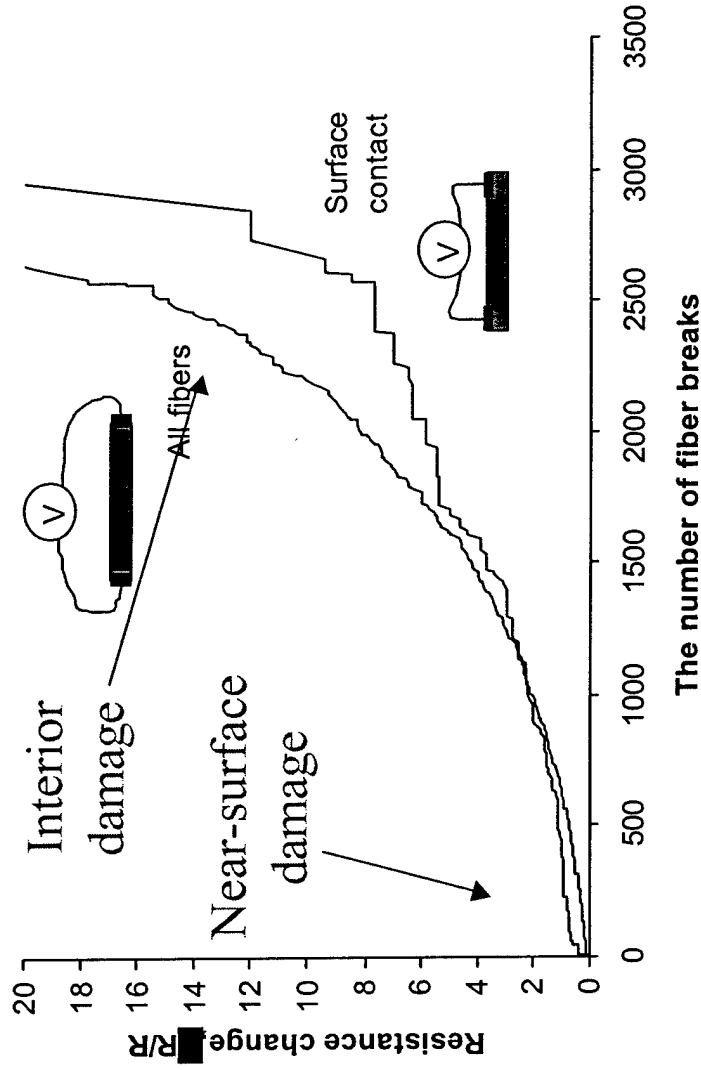
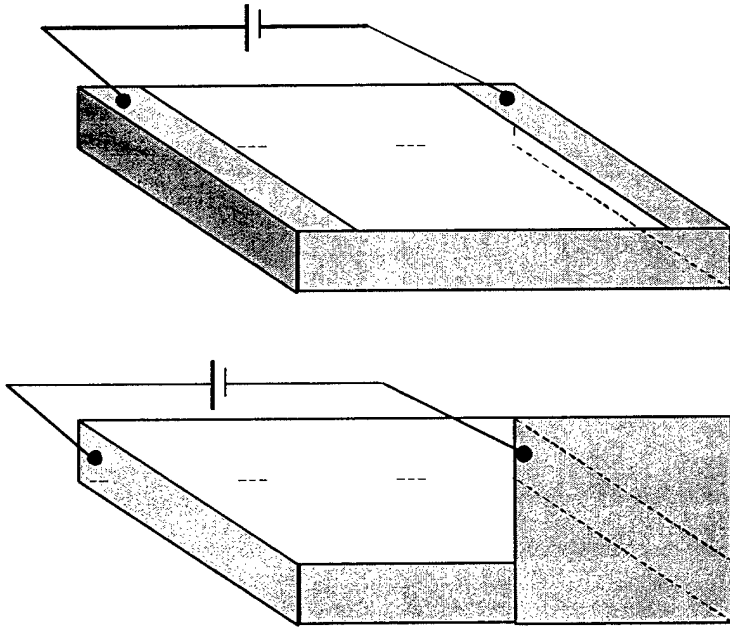
(c)  $V_f = 32\%$

# Modeling of Damage Detection by Electrical Resistance

Stochastic fiber damage + Mechanics Models + Electrical Models  
 ↗ Mechanical damage & Electrical resistance predictions



How locally can damage be detected?

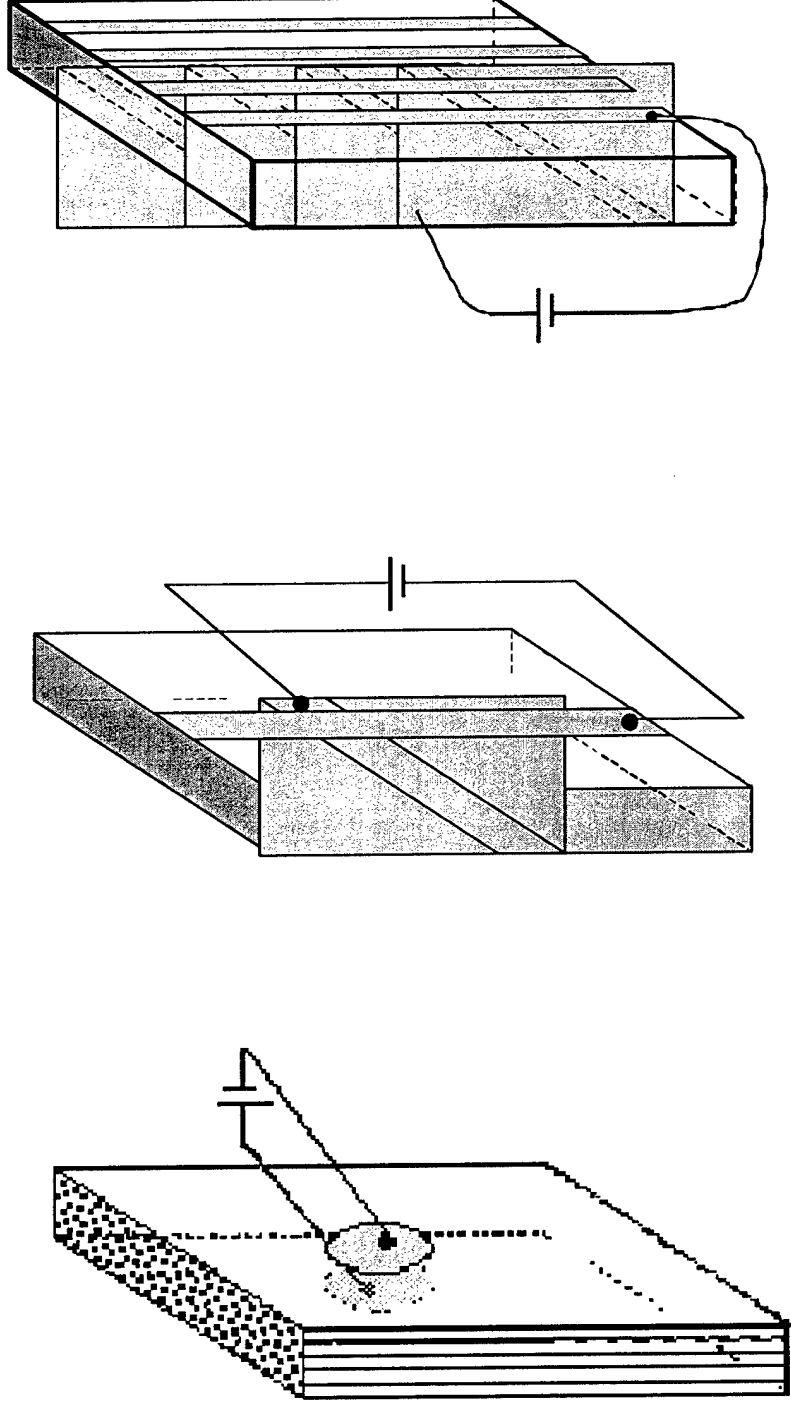


Damage sensing depends on Detection geometry

Design for LOCALIZED damage sensing

# Sensing Depends on Detection Geometry

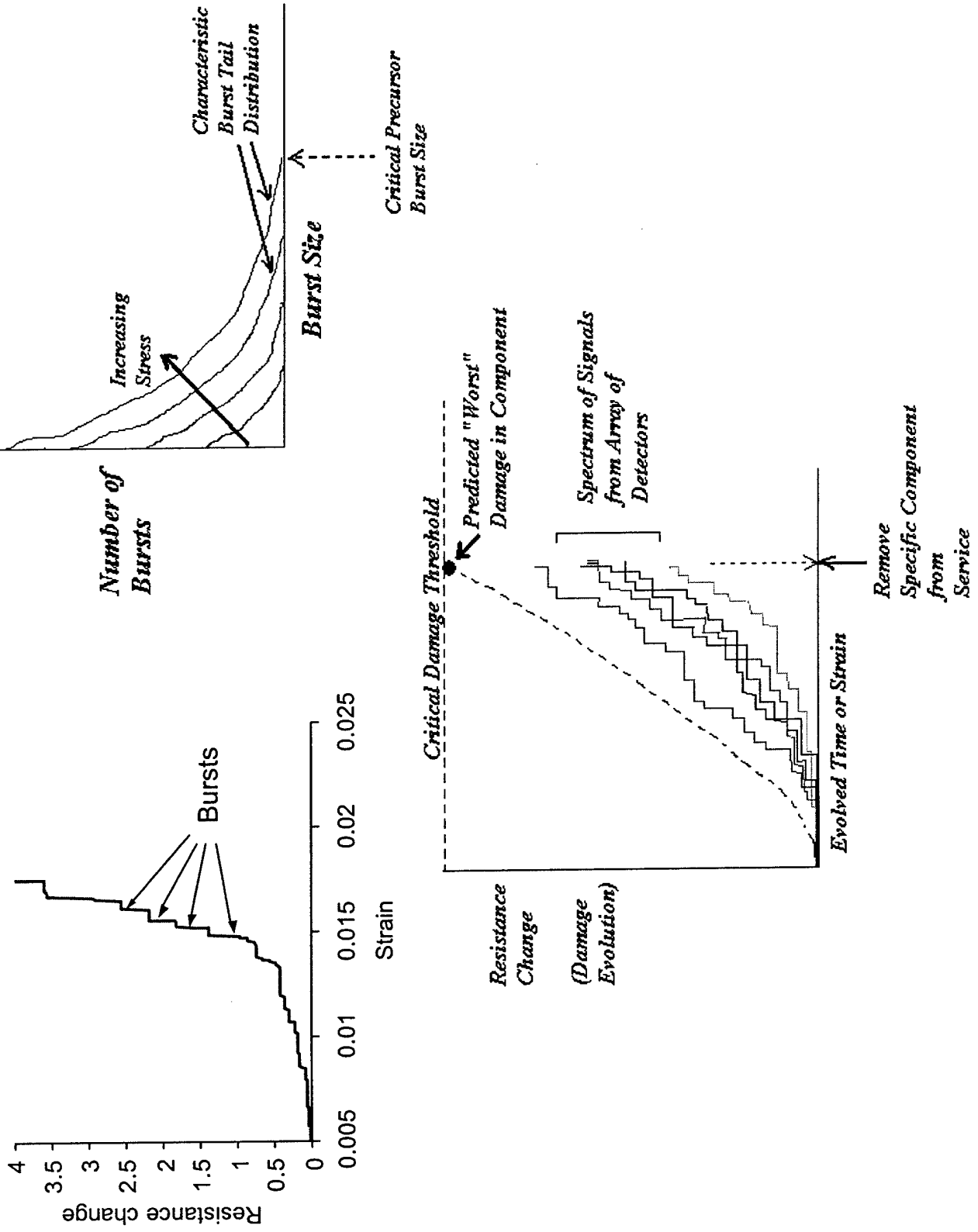
## Detection Geometries to Measure Localized Damage



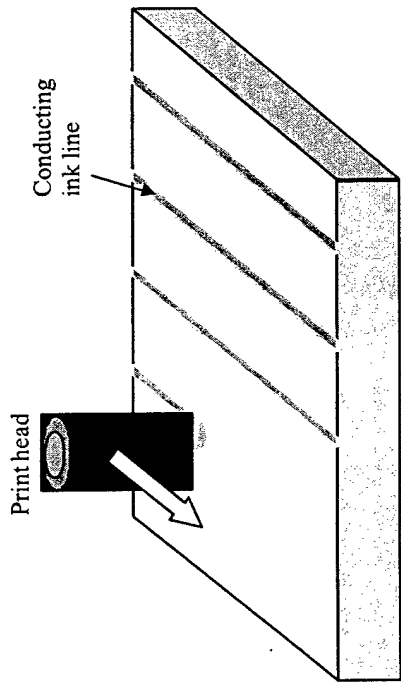
Use model to test simple geometries;  
determine spatial resolution

Realistic ply-level  
detection geometry

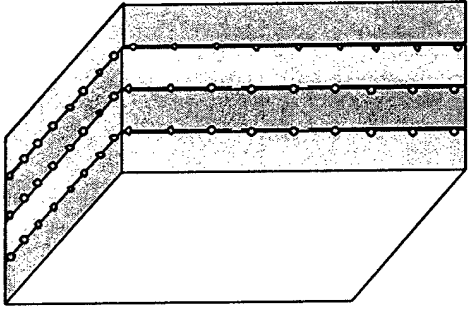
# How can signals be interpreted? Need stochastic analyses



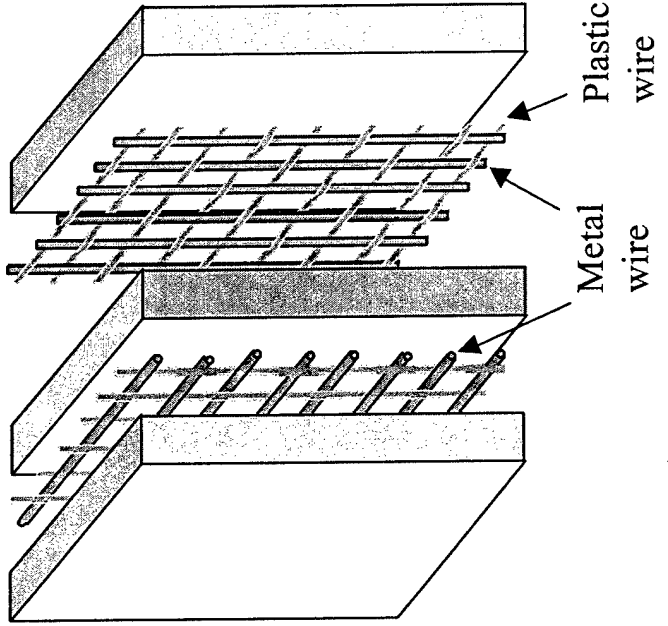
# Feasible Fabrication of "sensor array"?



Ink-jet printing of conducting ink



Lamination into structure



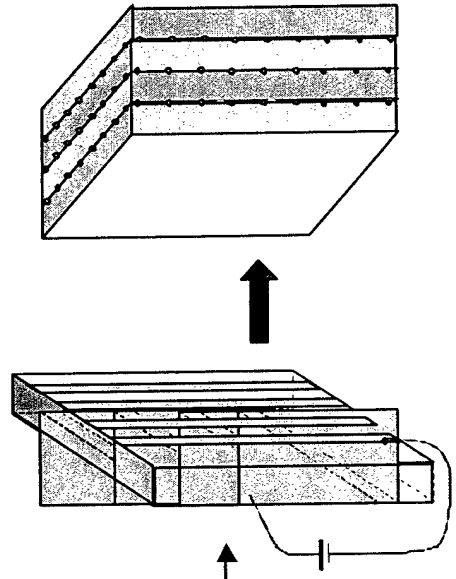
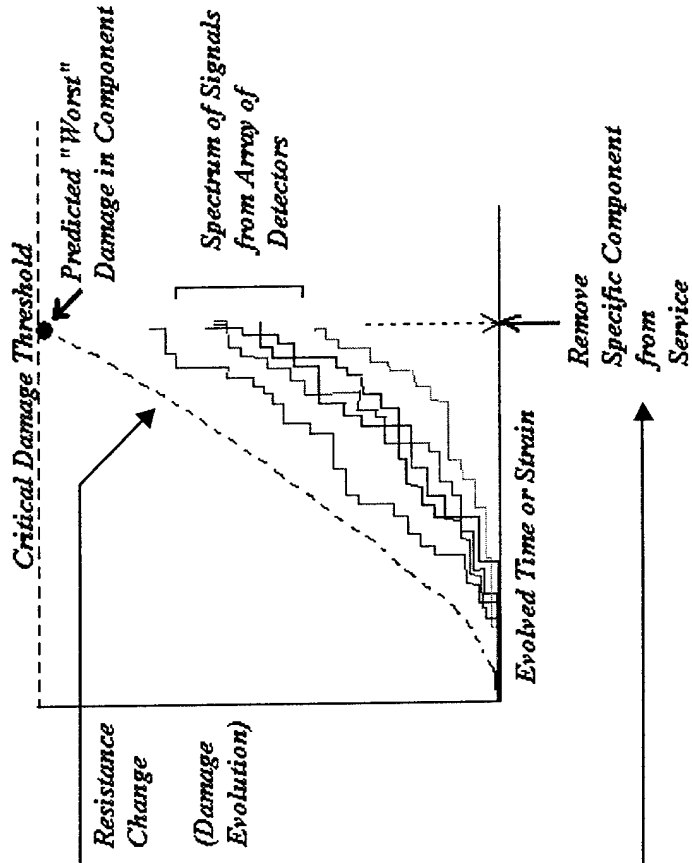
# Innovation in Design:

Design = Fundamental Materials Design

- Optimization of constituent materials for damage and sensing; control mechanical  $\rho_c$  vs. electrical  $\rho_{ce}$  characteristics

Design = Engineering Design

- Design of sensor arrays
- Design of sensor signal analysis
- Prediction of strength, life, reliability of in-service components



# **Demand and Challenges in Structural Health Monitoring**

**1<sup>st</sup> AIR FORCE WORKSHOP ON  
“MULTIFUNCTIONAL AEROSPACE MATERIALS”  
October 23-24, 2002, Purdue University, W. Lafayette,  
IN**

**Fu-Kuo Chang**  
Dept. of Aeronautics and Astronautics  
Stanford University  
Stanford, CA 94305

# Problem Statement

**GIVEN SENSOR MEASUREMENTS, DETERMINE EXTERNAL AND/OR INTERNAL PARAMETERS.**

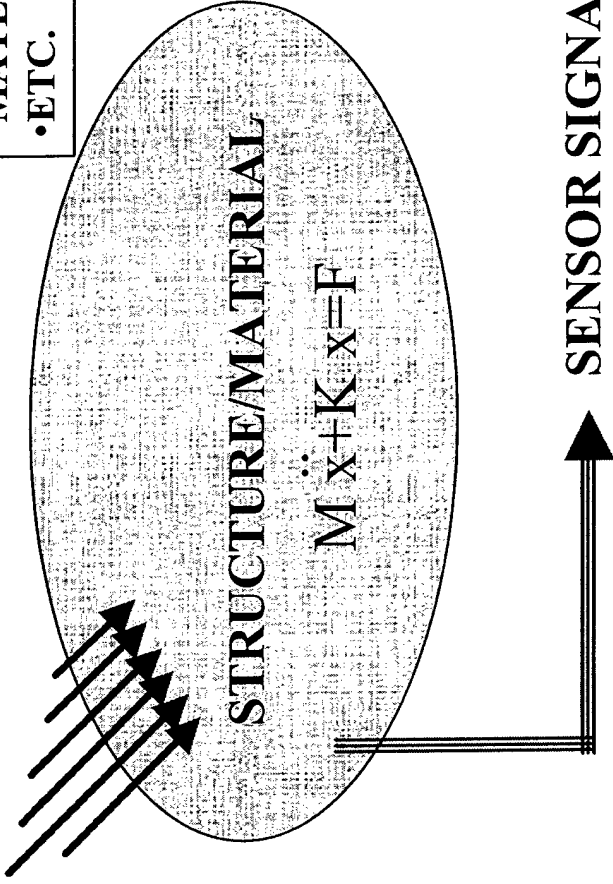
**(NONLINEAR INVERSE AND NON-UNIQUENESS)**

**EXTERNAL:**

- LOAD
- TEMPERATURE
- MOISTURE
- ETC.

**INTERNAL:**

- DAMAGE LOCATION
- DAMAGE SIZE/TYPE
- MATERIAL PROPERTIES
- ETC.



# Sensors

## ☞ **PASSIVE (receive signals only)**

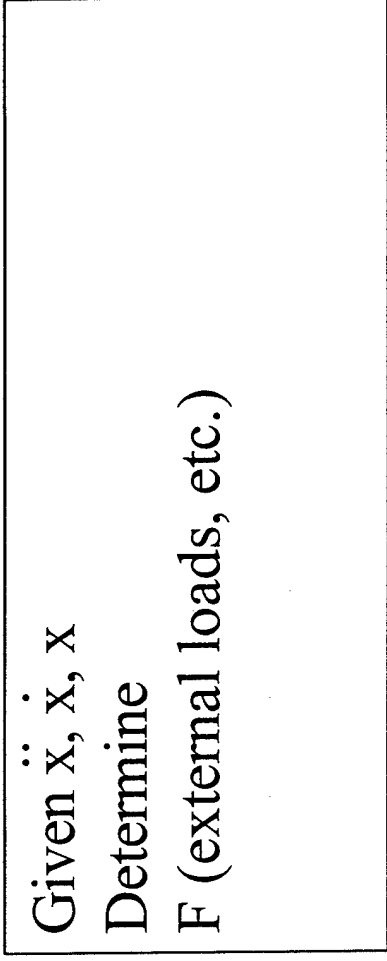
- **OPTICAL FIBER**
- **STRAIN GAUGE**
- **MICROELECTRONIC SENSORS**
- **Etc.**

## ☞ **ACTIVE (receive and generate signals)**

- **PIEZOELECTRIC MATERIALS**
- **Etc.**

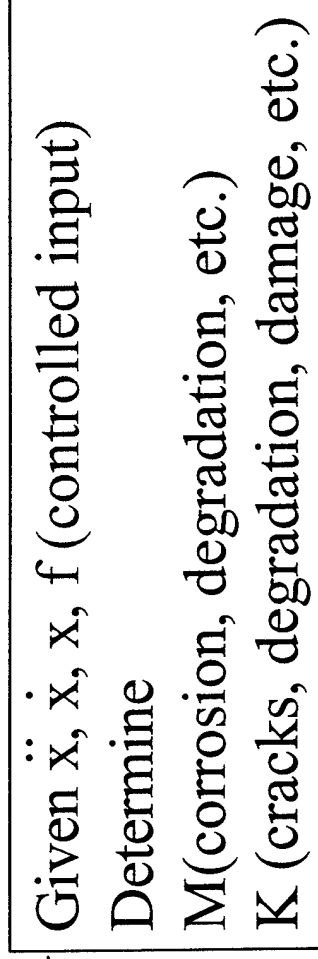
## PASSIVE SENSING

$$M \ddot{x} + K x = F$$



## ACTIVE SENSING

$$M \ddot{x} + K x = f$$



# Technical Challenges

✍ **SENSORS**

✍ **SENSOR/MATERIAL INTEGRATION**

✍ **HARDWARE DESIGN/IMPLEMENTATION**

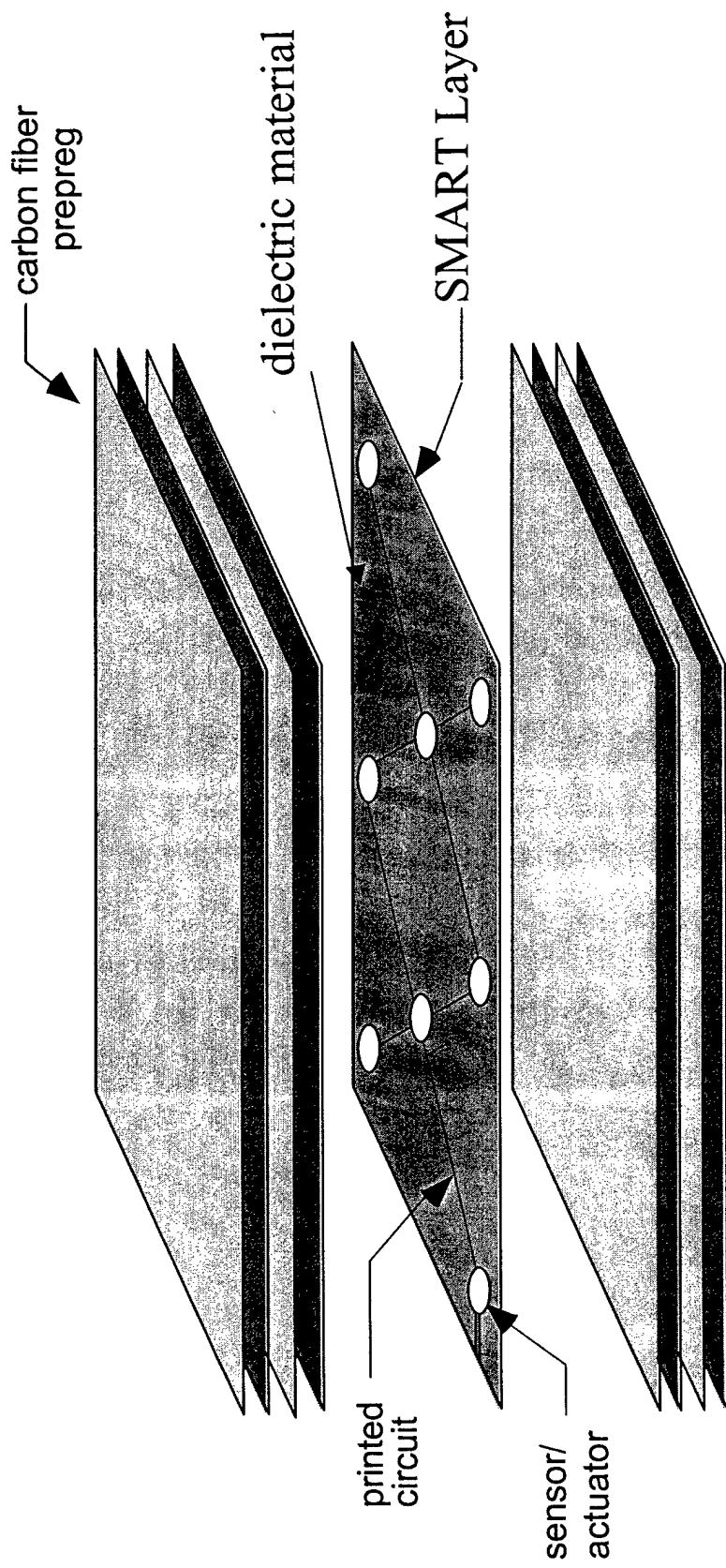
✍ **SIGNAL PROCESSING AND  
INTERPRETATION**

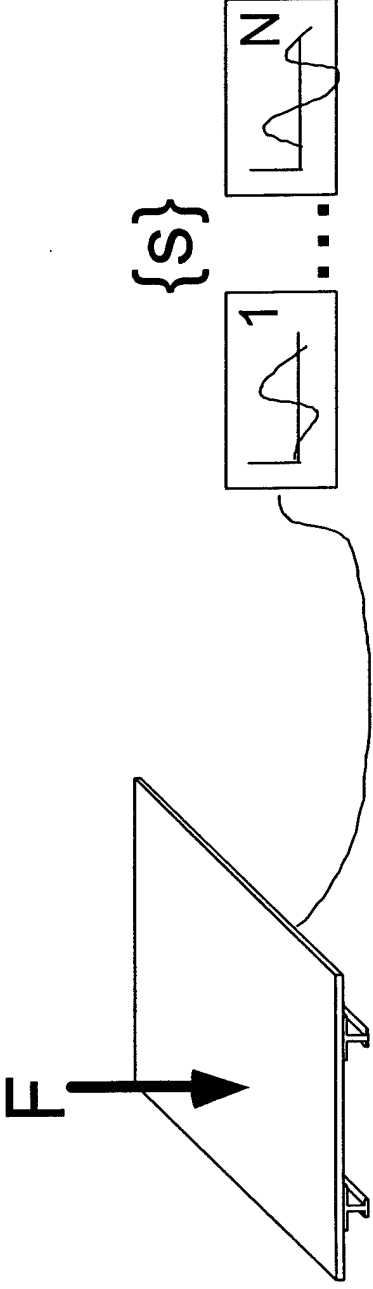
✍ **RESIDUAL STRENGTH AND LIFE  
PREDICTION**

# Piezoelectric Sensor Network

SMART (Stanford Multi-Actuator Receiver Transduction) Layer

## ☞ FLEXIBLE PRINTED-CIRCUIT BOARD TECHNIQUE





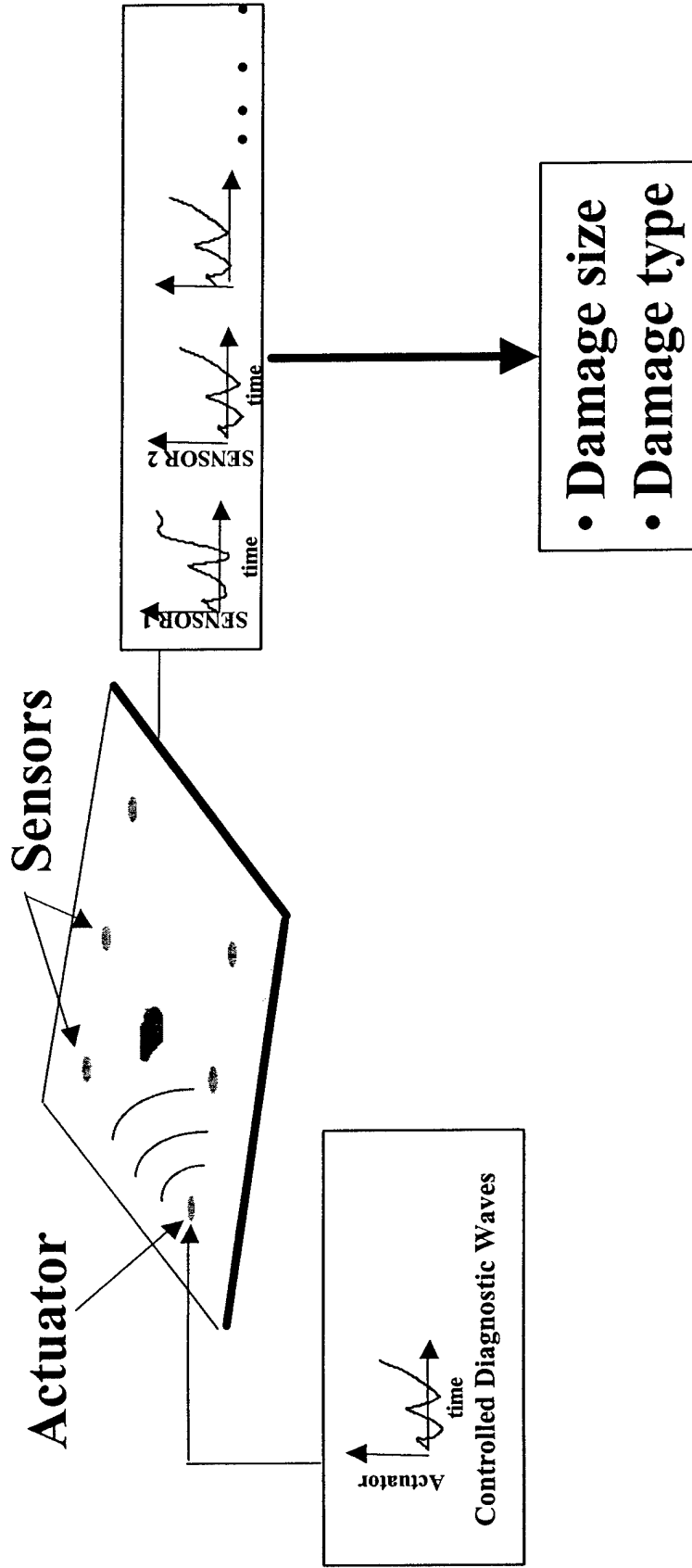
**Given:  $\{s\}$**

- Sensor data from impact on stiffened panel

**Determine:  $F$**

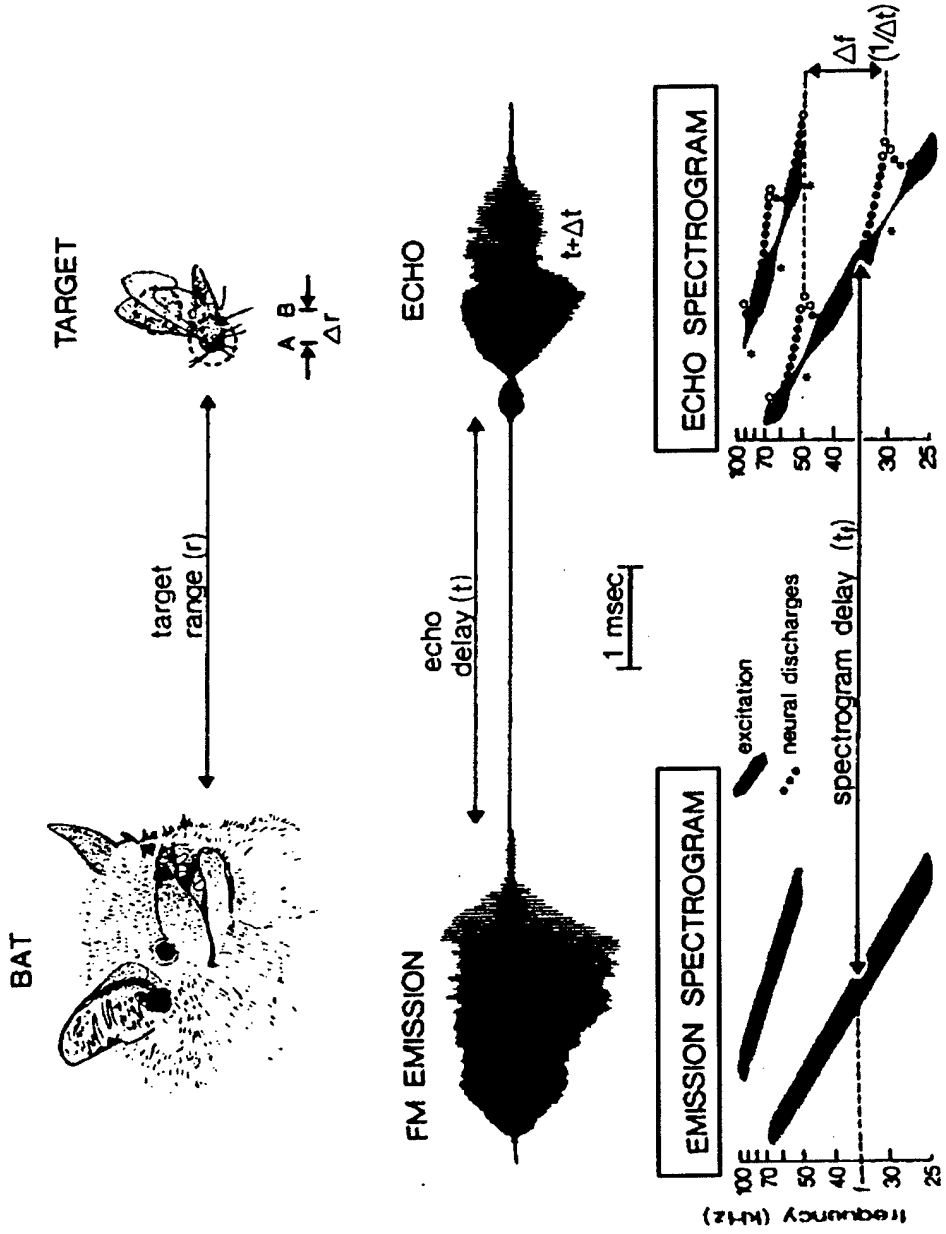
- Impact location  $(x,y)$
- Impact force history  $f(t)$

# Active Damage Detection



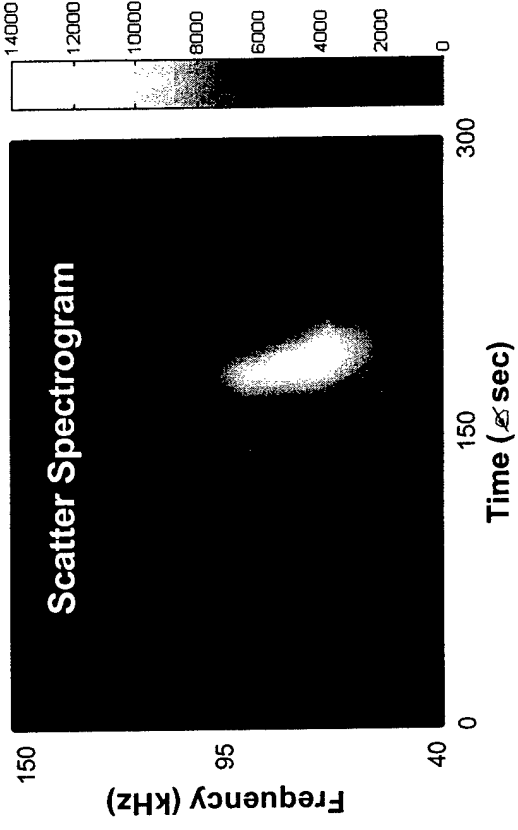
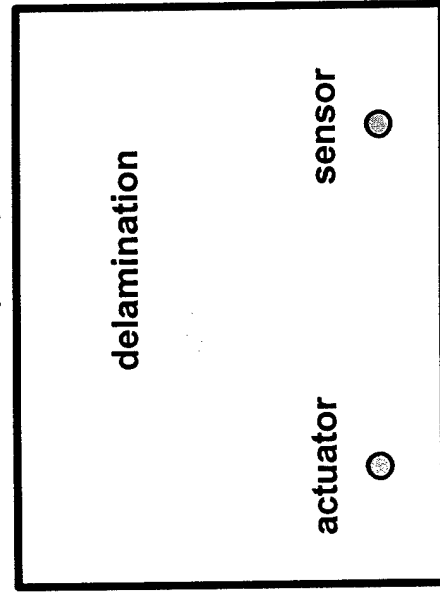
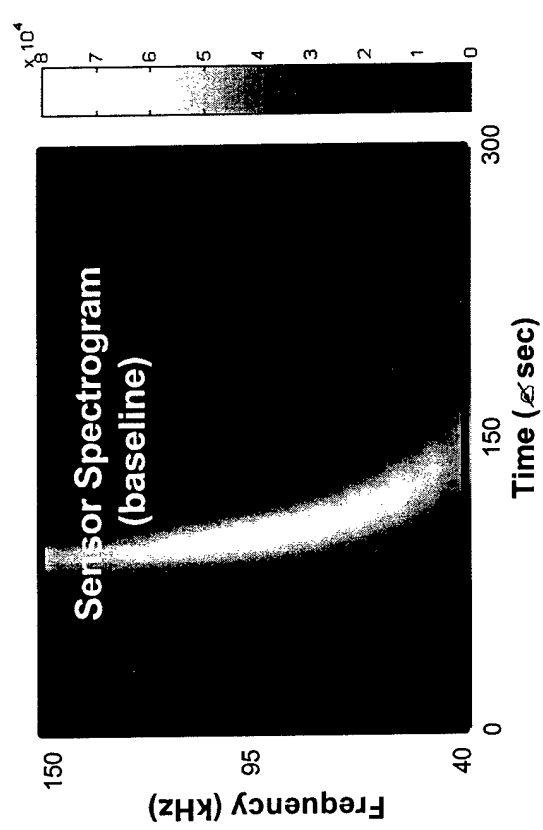
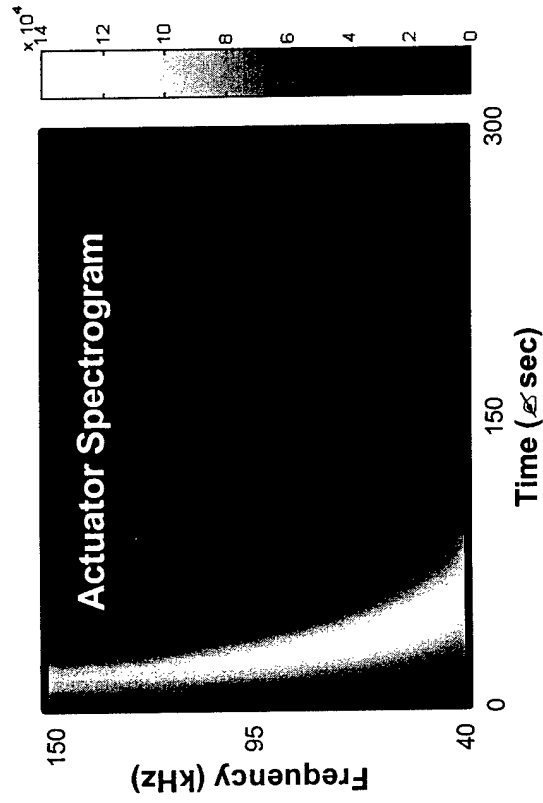
# Bat Echolocation

- Bat uses time-of-flight for ranging.
- FM bats use frequency spectrum change for sizing.



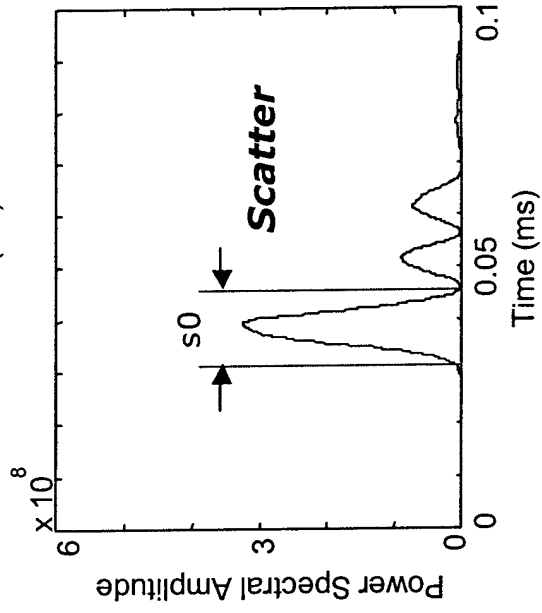
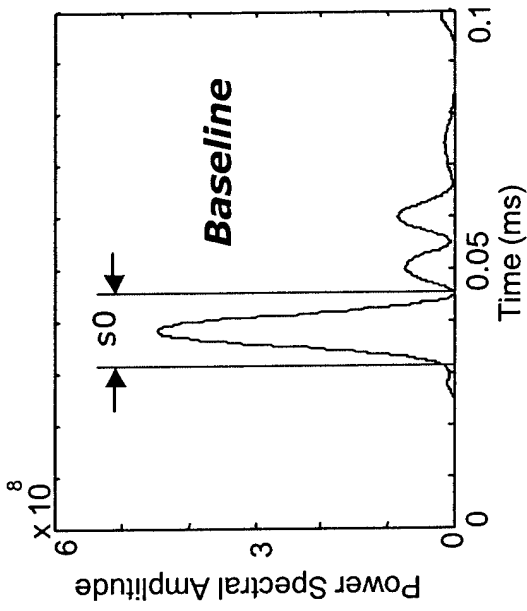
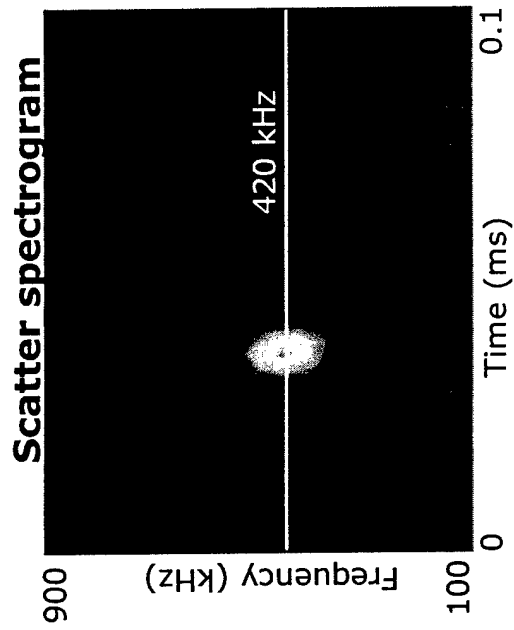
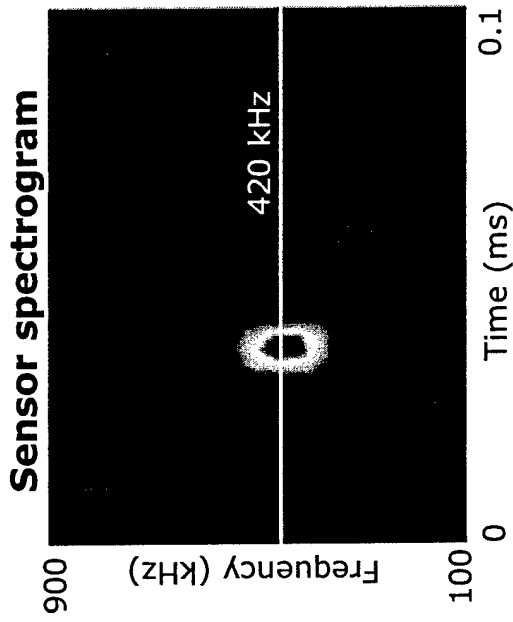
From J.A. Simmons, et al,  
 J. Comp. Physiol. A (1990)  
 166:449-470

# Spectrogram



QuickTime™ and a  
Photo - JPEG decompressor  
are needed to see this picture.

# Signal Processing



# Interpretation - Damage index

Source: <https://www.researchgate.net/publication/312111111>

• Damage Index

$$\frac{\int_{t_i}^{t_f} |S_{sc}(t)|^2 dt}{\int_{t_i}^{t_f} |S_b(t)|^2 dt} = \frac{\text{Scatter energy of s0 wave}}{\text{Baseline energy of s0 wave}} \quad a$$

where

$a=0.5$ : gain factor, 0 ? ? ? 1

$S_{sc}$ : STFT of a scatter signal

$S_b$ : STFT of a baseline signal

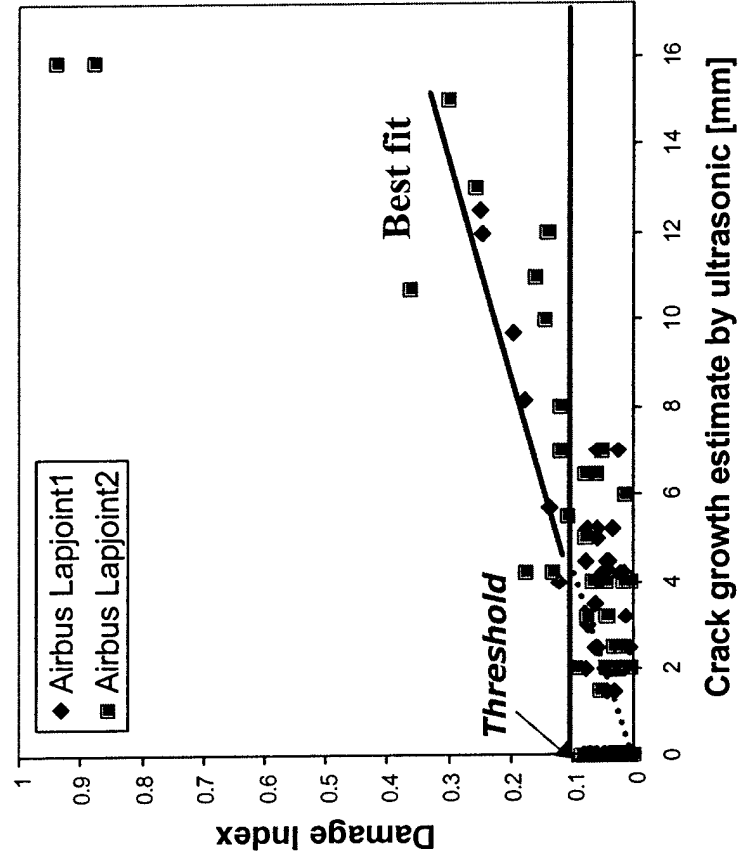
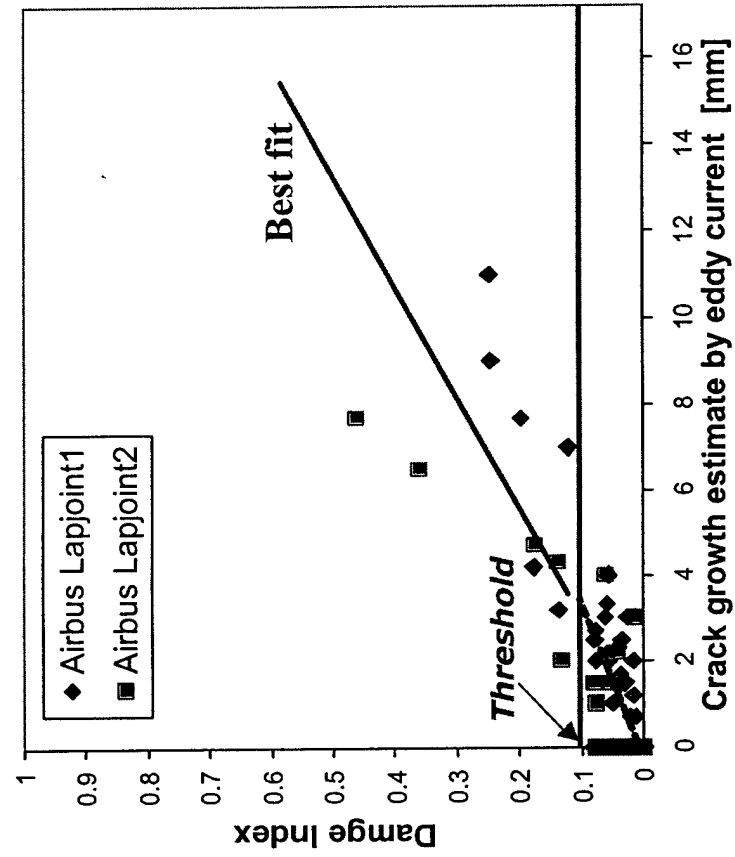
$t_l$ : lower bound of s0 wave packet in time domain

$t_f$ : upper bound of s0 wave packet in time domain

?? ? selected driving frequency

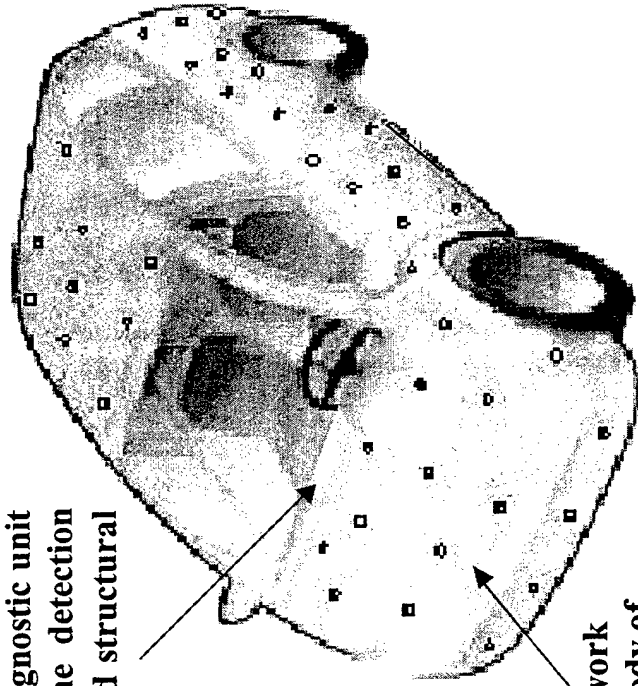
?

# Damage Index of SHM vs. NDT



# SHM System for Vehicles

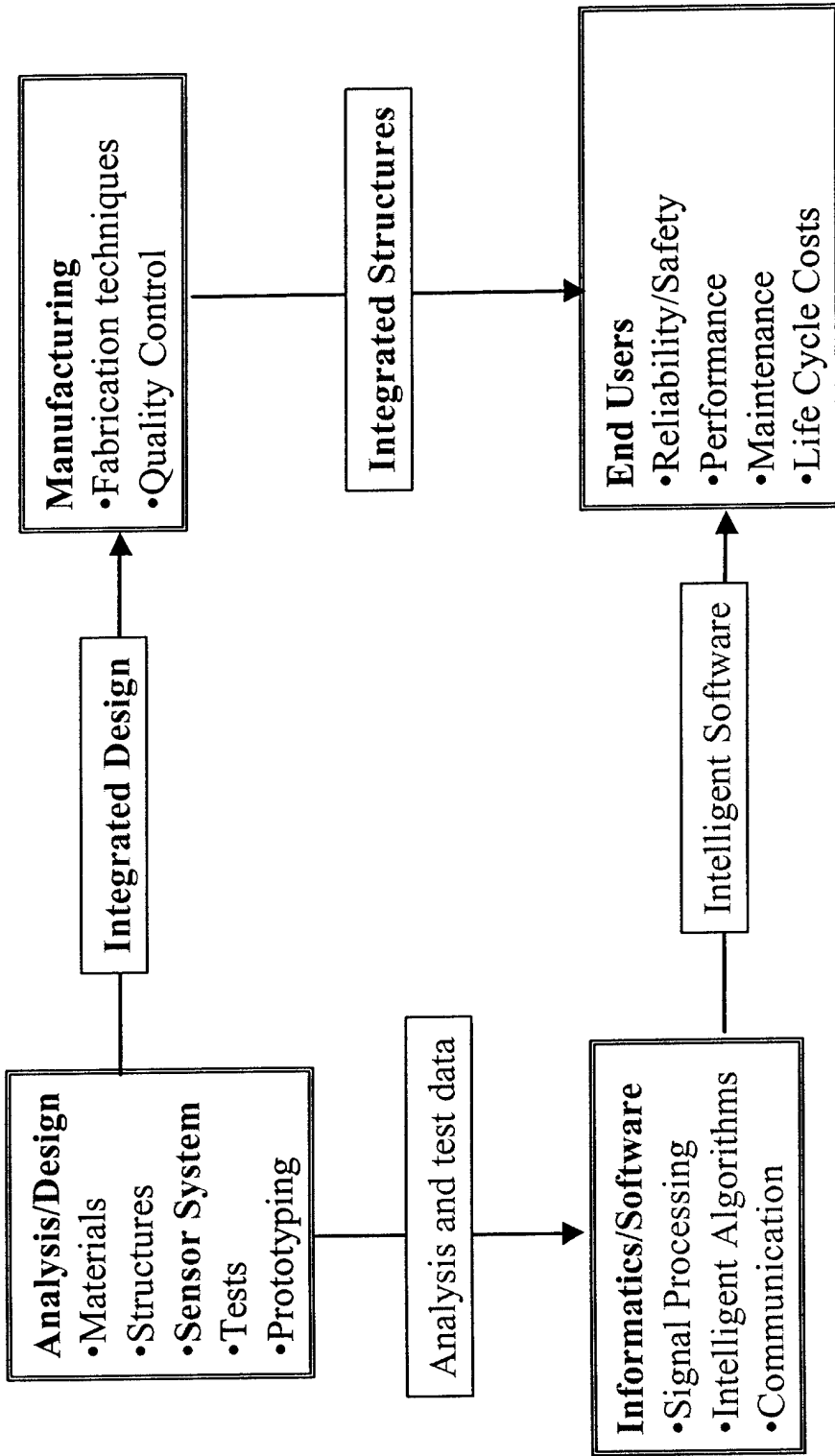
Internal diagnostic unit  
for real-time detection  
of crash and structural  
condition



Sensor network  
built into body of  
the car

- Condition Monitoring
- Crash Detection
- Active Suspension Control

# SHM-based Structural Design Diagram



# 1st Air Force Workshop on “Multifunctional Aerospace Materials”

Oct 23-24 2002

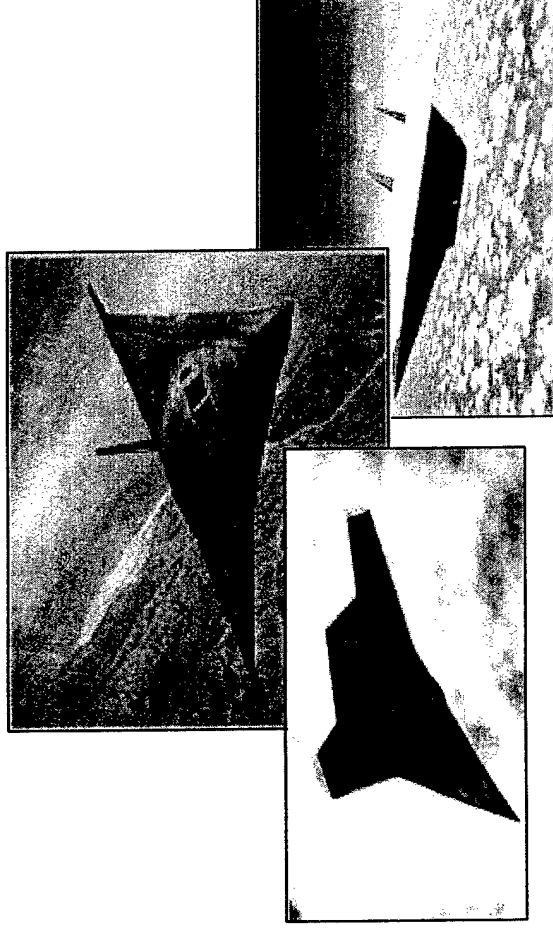
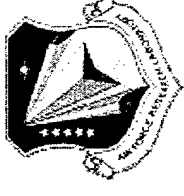


## Thermal Structures for High Speed Aircraft

David A Brown  
Air Vehicles Directorate  
Structures Division



# Thermal Structures for Future High Speed Vehicles



Current Air Force Studies  
Evaluating Long Range  
High Mach Vehicles

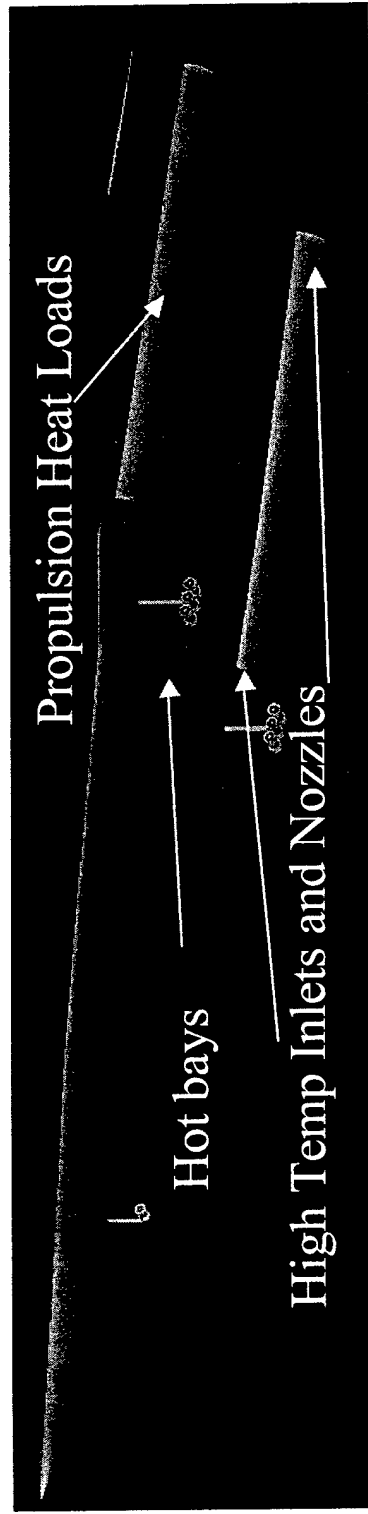
- Many Thermal and Structural Needs because of Aerodynamic and Propulsion Heat Loads
  - Material Compatibility
  - Lightweight High Temperature Structures
  - Insulation/Thermal Management
- Multifunctional Technologies may be Key to Lightweight Affordable Solutions



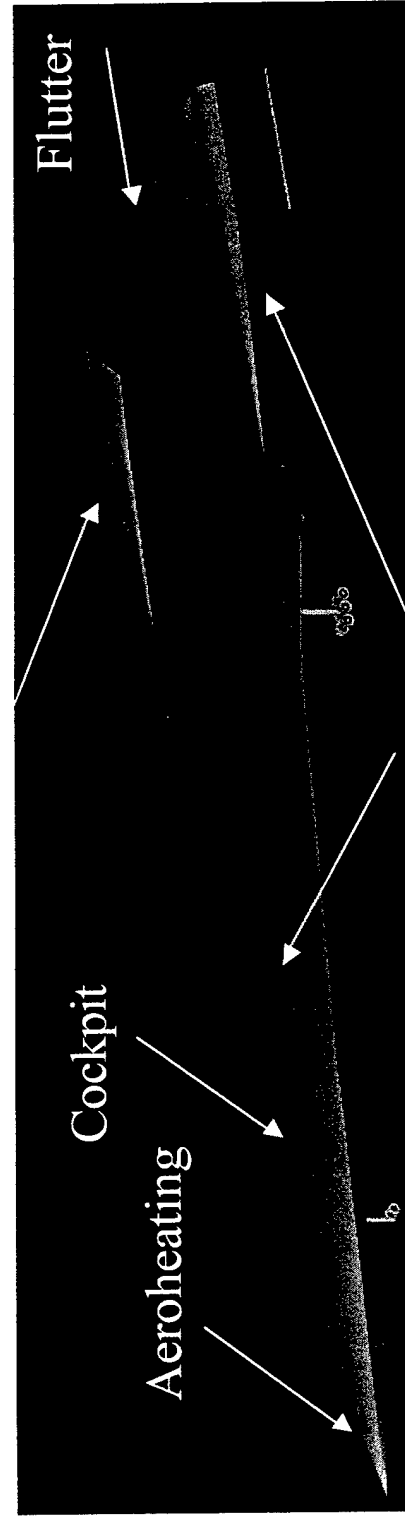
# Thermal Structures for Future High Speed Vehicles



Mach 2-4 Conceptual Vehicle



Thin wings

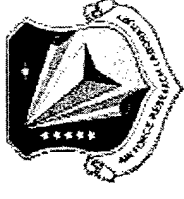


High Temperature Fuel Tanks

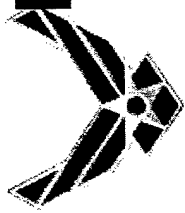


# Structural Concepts for Consideration

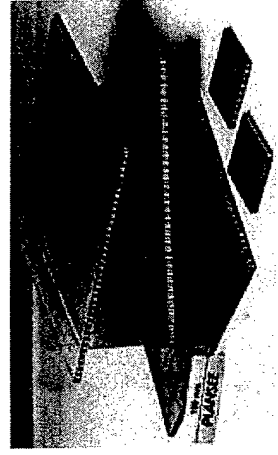
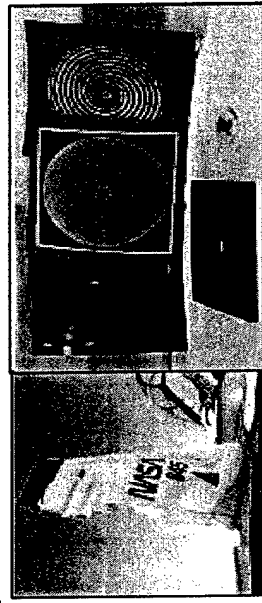
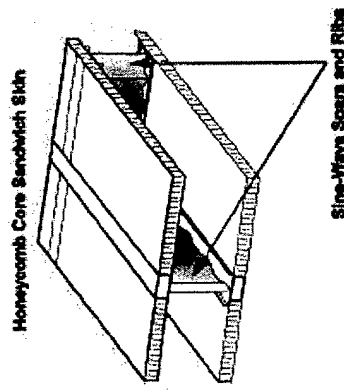
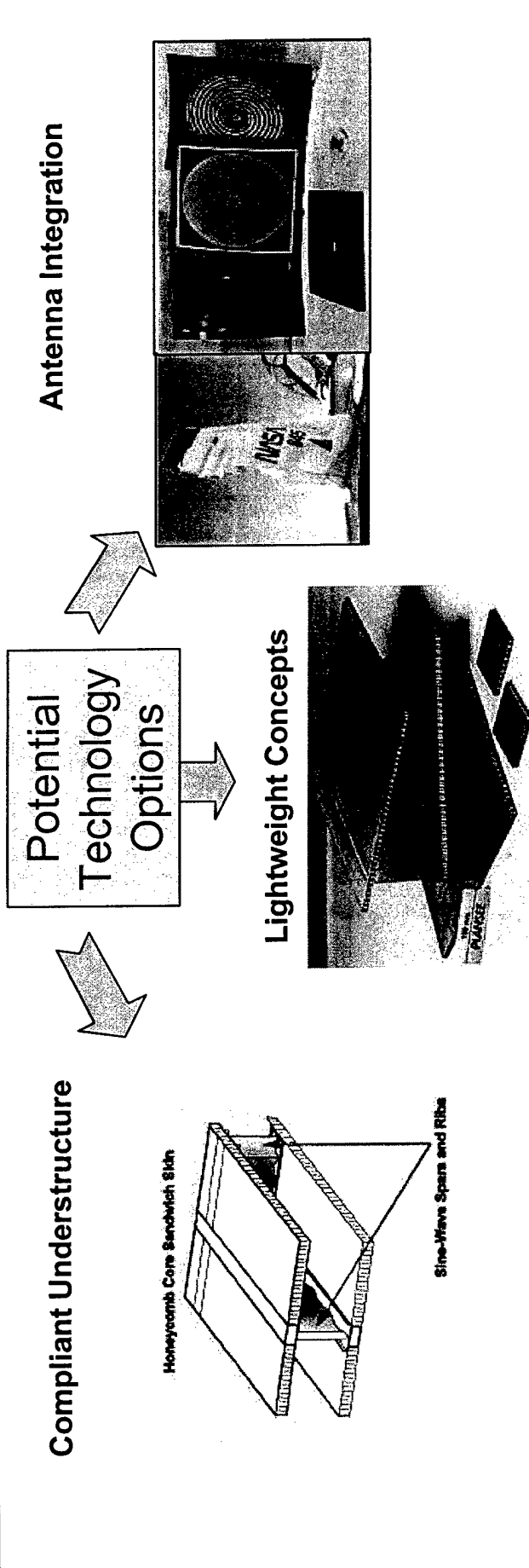
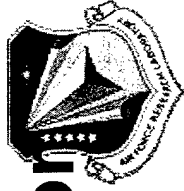
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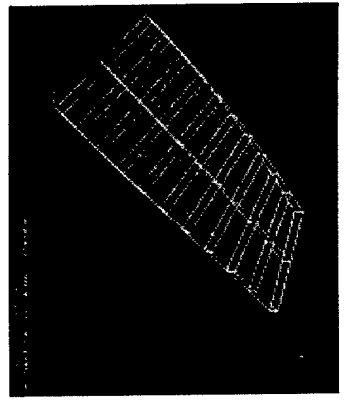
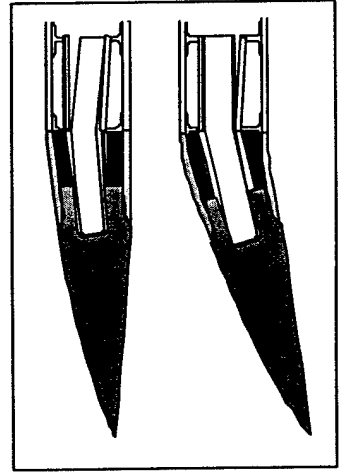
- Unitized Structure
  - Integral Composites, Formed Metallic, Preformed Joints
- Smart Structures
  - Health Monitoring, Imbedded Sensors
- Adaptive Structures
  - Adaptive Leading Edges, Fuel Integration, “Morphing Technologies”
- High Temperature Metals & Composites
  - CMCs, Alum/Titanium,
- Structures/Propulsion/Subsystem Integration
  - Inlet, Engine, Nozzle, Integrated Subsystems
- Active/Passive Structural Cooling
- Advanced Analytical Techniques
  - MDO, Probabilistic Analysis



# Multifunctional Structural Concepts for Future High Speed Vehicles



## Adaptive Structure



## Optimized Design Methods

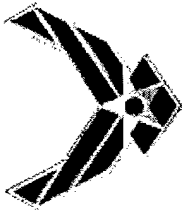
**Weight & Cost Trades**

T=600°F  
Nx=2500lbs/in

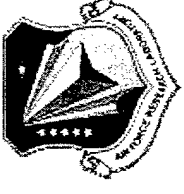
| Load<br>[lbs/in] | 1250   |     |     |     |     | 2500 |     |     |     |     |
|------------------|--------|-----|-----|-----|-----|------|-----|-----|-----|-----|
|                  | Nx/Nxy | 1.0 | 0.5 | 0.0 | 1.0 | 0.5  | 0.0 | 1.0 | 0.5 | 0.0 |
| 200 °F           |        |     |     |     |     |      |     |     |     |     |
| 400 °F           |        |     |     |     |     |      |     |     |     |     |
| 600 °F           |        |     |     |     |     |      |     |     |     |     |
| 800 °F           |        |     |     |     |     |      |     |     |     |     |
| 1000 °F          |        |     |     |     |     |      |     |     |     |     |

Concept W \$

|   |    |    |
|---|----|----|
| 1 | 12 | 50 |
| 2 | 15 | 40 |
| 3 | 21 | 30 |

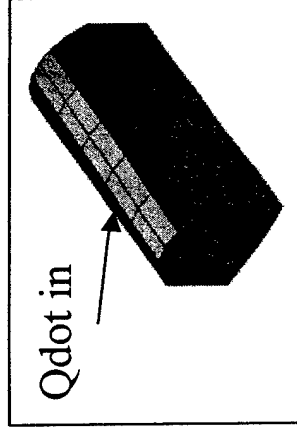


# Thermal Management for High Mach Vehicles

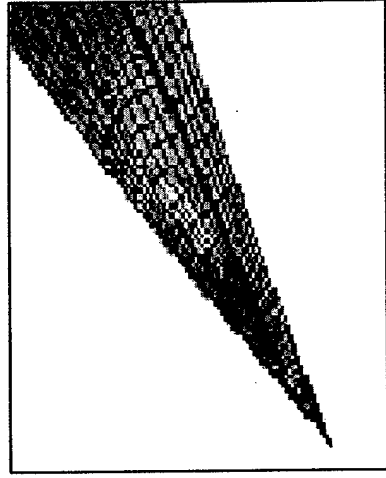


Aeroheating and Propulsion Heat Loads Drive Fuel Tank Temperatures

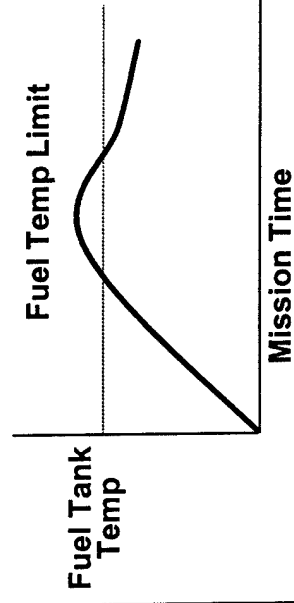
Fuel Tank Model

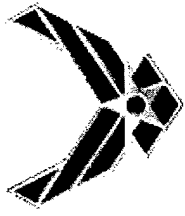


Aerodynamic Heating

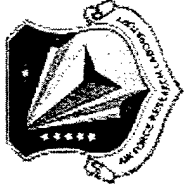


Fuel Temperature

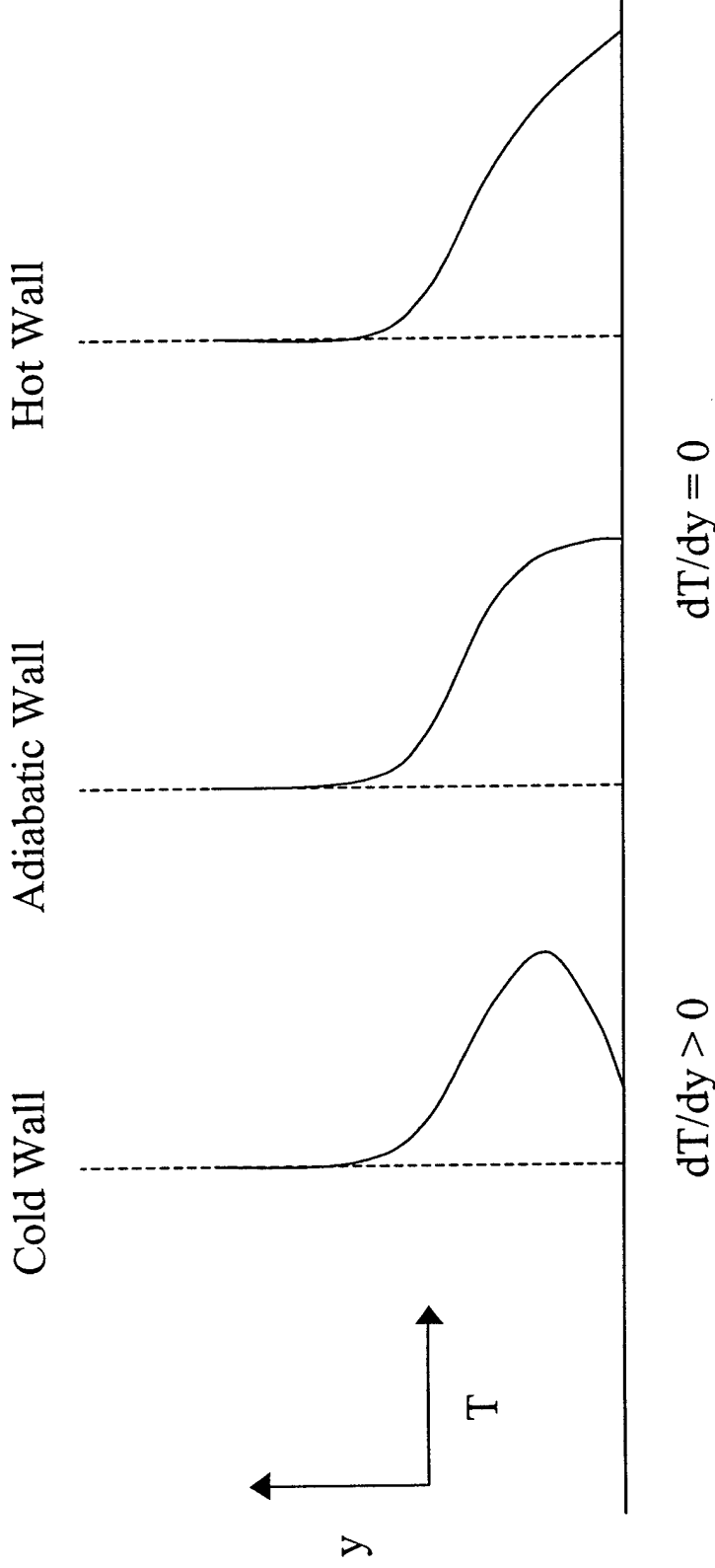




# Boundary Layer Heat Transfer Rate to Wall



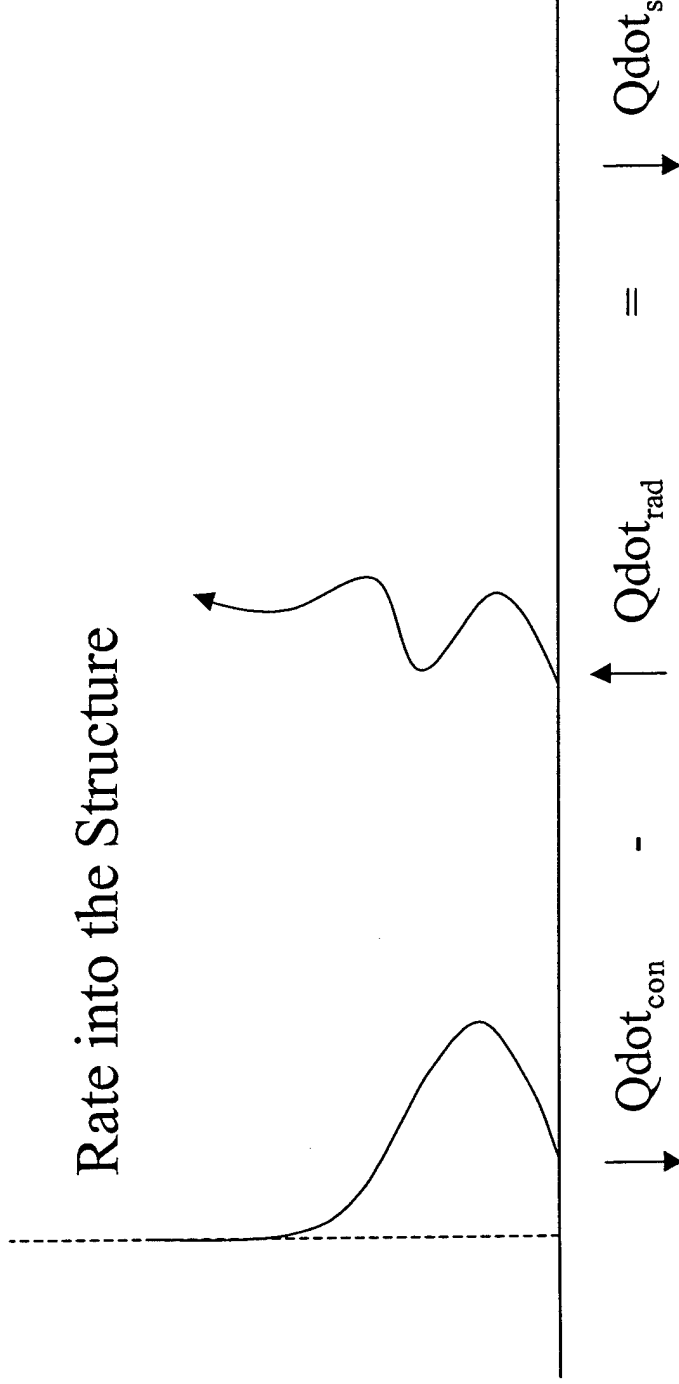
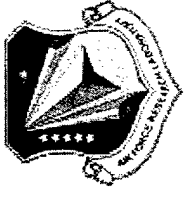
Depends on Wall Temperature for a Given Flow



Wall Heat Transfer Rate (BTU/ft<sup>2</sup>-sec) =  $Q_{\text{dot}} = k \cdot \frac{dT}{dy}$ ,  
where  $k$  is air's thermal conductivity at the wall conditions,  
and  $dT/dy$  is the temperature gradient at the wall.



# The Difference Between Convective and Radiative Heat Transfer Rates



$$\dot{Q}_{str} = h^*(T_{adw} - T_w) - ?? (T_w)^4$$

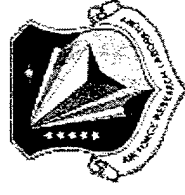
When  $\dot{Q}_{str}$  is 0 (insulated),  $T_w$  will equal the radiation equilibrium temperature,  $T_{RET}$ , otherwise  $\dot{Q}_{str}$  and heat capacity determine the rate of temperature change of the surface material.



# Structures and Materials

## Key Technical Challenges

---



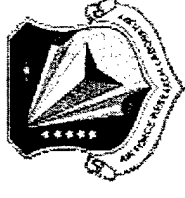
- ✍ Reduce Structural Weight Fraction (high temperature composites, Ti-Al, Al-Li Sandwich, composite landing gear, lightweight insulation, stitched composites, structurally integrated inlet and nozzle)
- ✍ Develop Structural Arrangements Capable of Surviving Extreme Aerodynamic and Propulsion Heat Loads (high temperature structures, ceramics, active/passive cooling)
- ✍ Insulate Subsystem and Critical Components from Aerodynamic and Propulsion Heat Loads (lightweight insulation, active cooling, coatings)
- ✍ Develop Optimized Design Methods Structural/Thermal/Aero (advanced design tools, load optimization, probabilistic methods, thin fuselage design)



# Structures and Materials

## Key Technical Challenges (Cont)

---



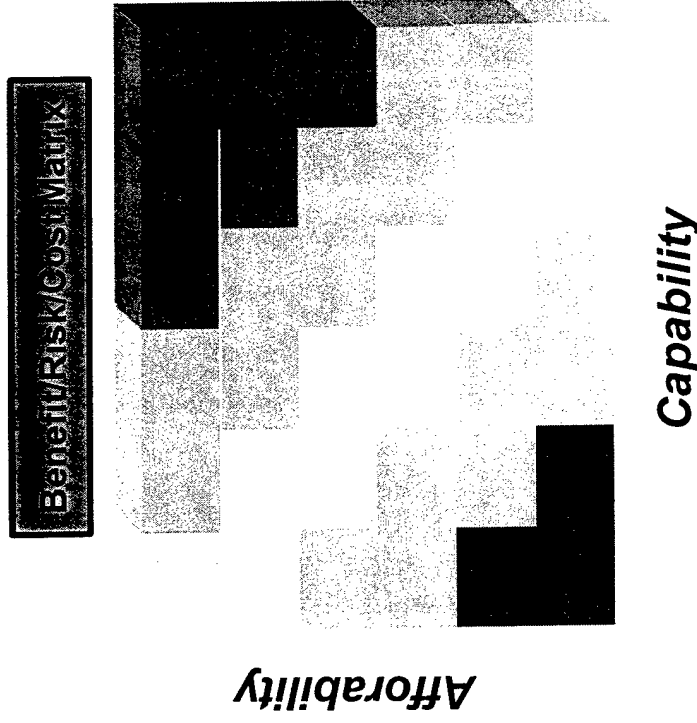
- ✍ Provide Adequate Heat Sink for the Aerodynamic and Propulsion Heat Loads (high heat sink fuels, high temperature seals, expendables)
- ✍ Develop Lightweight High Temperature Structural Arrangements (stiffness vs. thermal compliance, unitized structures)
- ✍ Provide Cooling to High Temperature Components such as inlets, nozzles, propulsion components, generators (high temperature lightweight heat exchangers, fuel-air heat exchangers)
- ✍ Minimize Aeroheating and Propulsion Heating to Vehicle Components (high emissivity coatings, high performance insulation)



# Technology Risk Elements

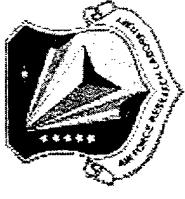


- Performance
  - How difficult is the technology to mature ?
  - What is the probability of failure?
  - What is the impact of failure to the related system?
- Schedule
  - Can the technology be matured? When?
- Cost
  - What is the ROM cost to mature the technology





# Summary



- ✧ Long Range High Mach Vehicles have Unique Structural and Thermal Requirements
- ? Multidisciplinary Interactions Require New Solutions
- ? Multidisciplinary Tools Needed
- ? Multifunctional Concepts Needed to Meet Weight and Affordability Objectives

**AFRL/MLB**  
**OMC Thermal Management**  
**&**  
**Leading Edge Thermal Protection**

**24 Oct 2002**



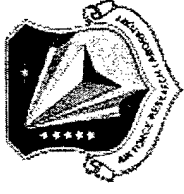
**Keith B. Bowman, Ph.D., P.E.**  
**(937) 255-9076**

**keith.bowman@wpafb.af.mil**

**Air Force Research Laboratory**



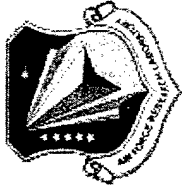
# Agenda



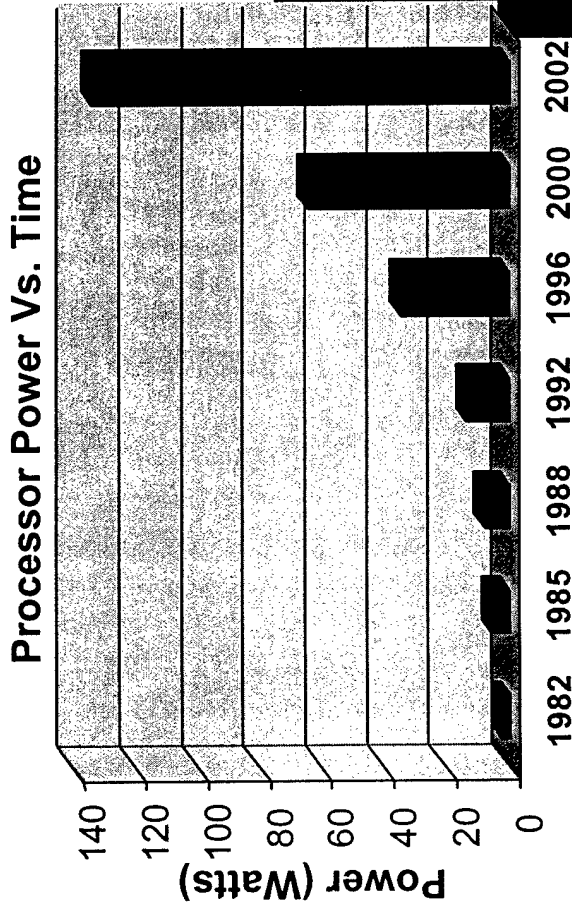
- Overview
- Thermal Management for Air Applications
  - Historical
  - Present
  - Planned
- Thermal Management/Protection for Space Applications
  - Historical
  - Space Operations Vehicle
  - Present
  - Planned
- Summary



# Thermal Management Requirements



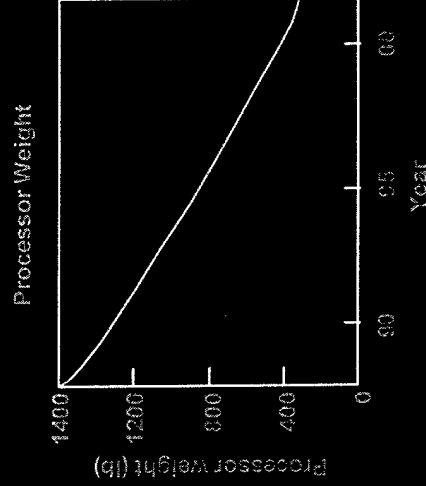
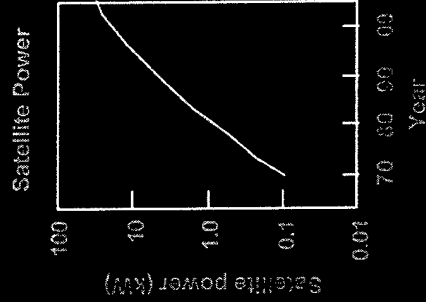
## The "Why" Chart



## Power Requirements and Weight Target



### Trending



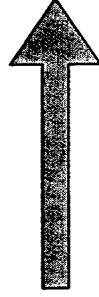


# Thermal Management Needs and Solutions



## Electronic Push

Increased communications, and electronic capabilities (Directed Energy/Microwave ect.) More chips require more cooling.



Waste heat can be dissipated using advanced materials. 2 to 4 times better than copper.

## Component Strength/Capability

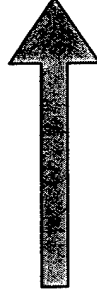
With the number of systems on aircraft/spacecraft increasing, consolidation of capabilities and space become imperative.



Lightweight, stiff components can be designed/build out of Advanced Materials offering high performance.

## Compact/Size

Efficient use of space/resources is becoming more critical. Upgrades in capability result in more equipment stuffed into space it was not designed for.



Carbon based Materials (foam and Pyrolytic graphite etc..) can move more heat per unit area/unit density hands down.

## Retrofitting

Aging aircraft are upgraded and augmented with new components requiring creative design and compromises.



Advanced materials offer new opportunities/possibilities for higher performance retrofit components and systems

## Less Maintenance

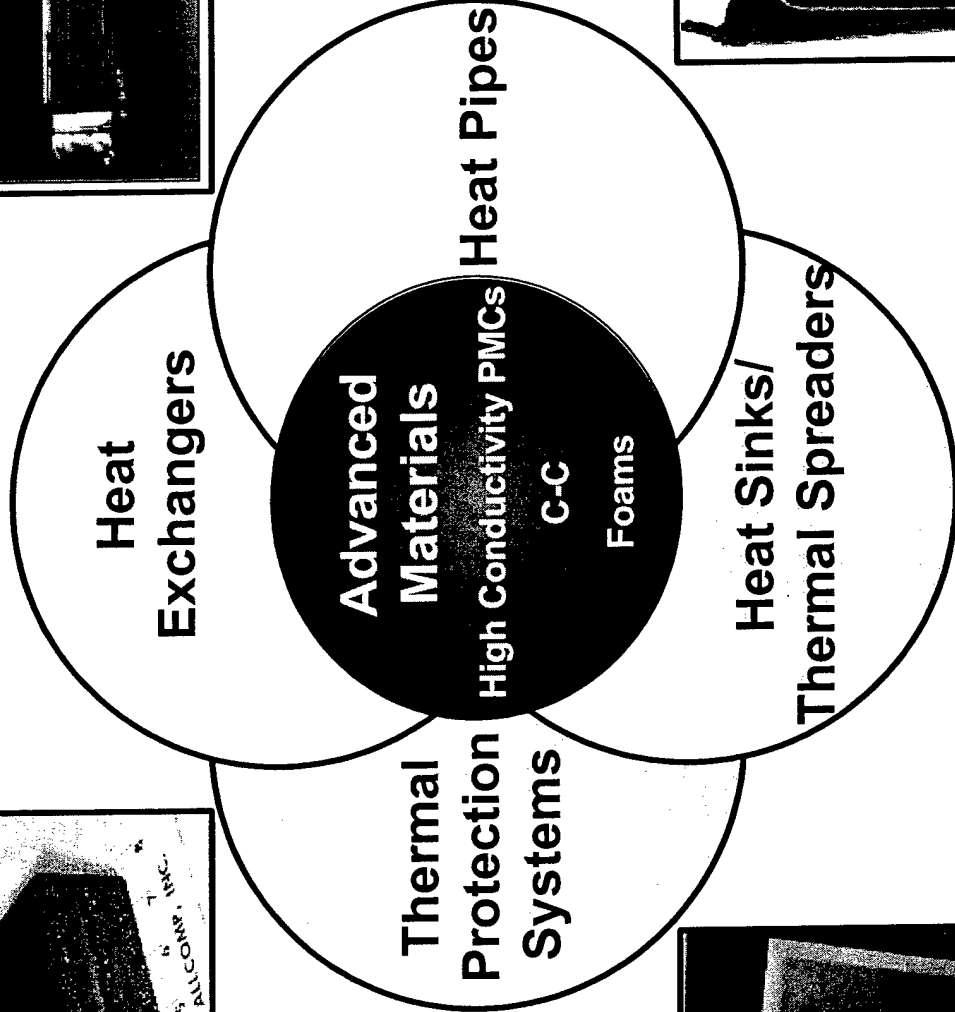
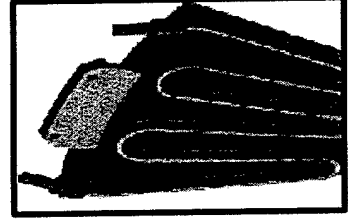
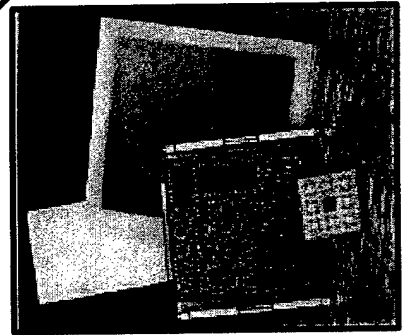
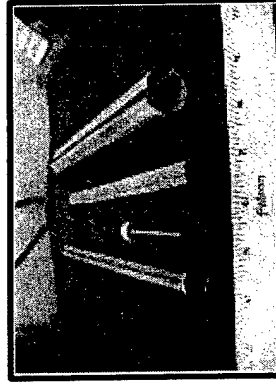
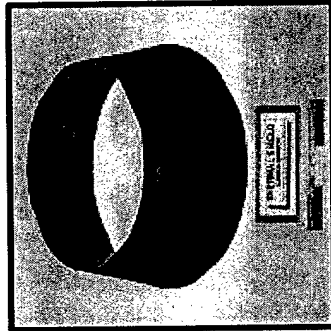
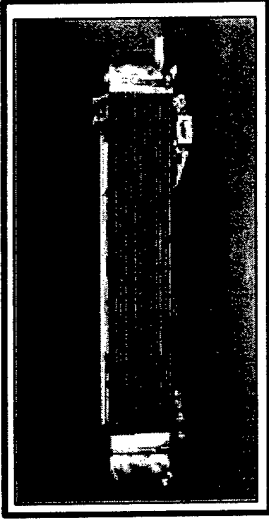
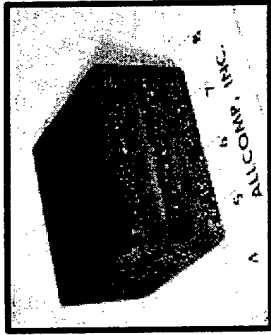
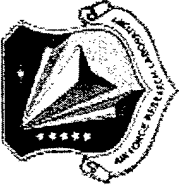
Less costly Logistics will always be an issue. Operational cost far outweigh any other phase of the Acquisition Lifecycle.



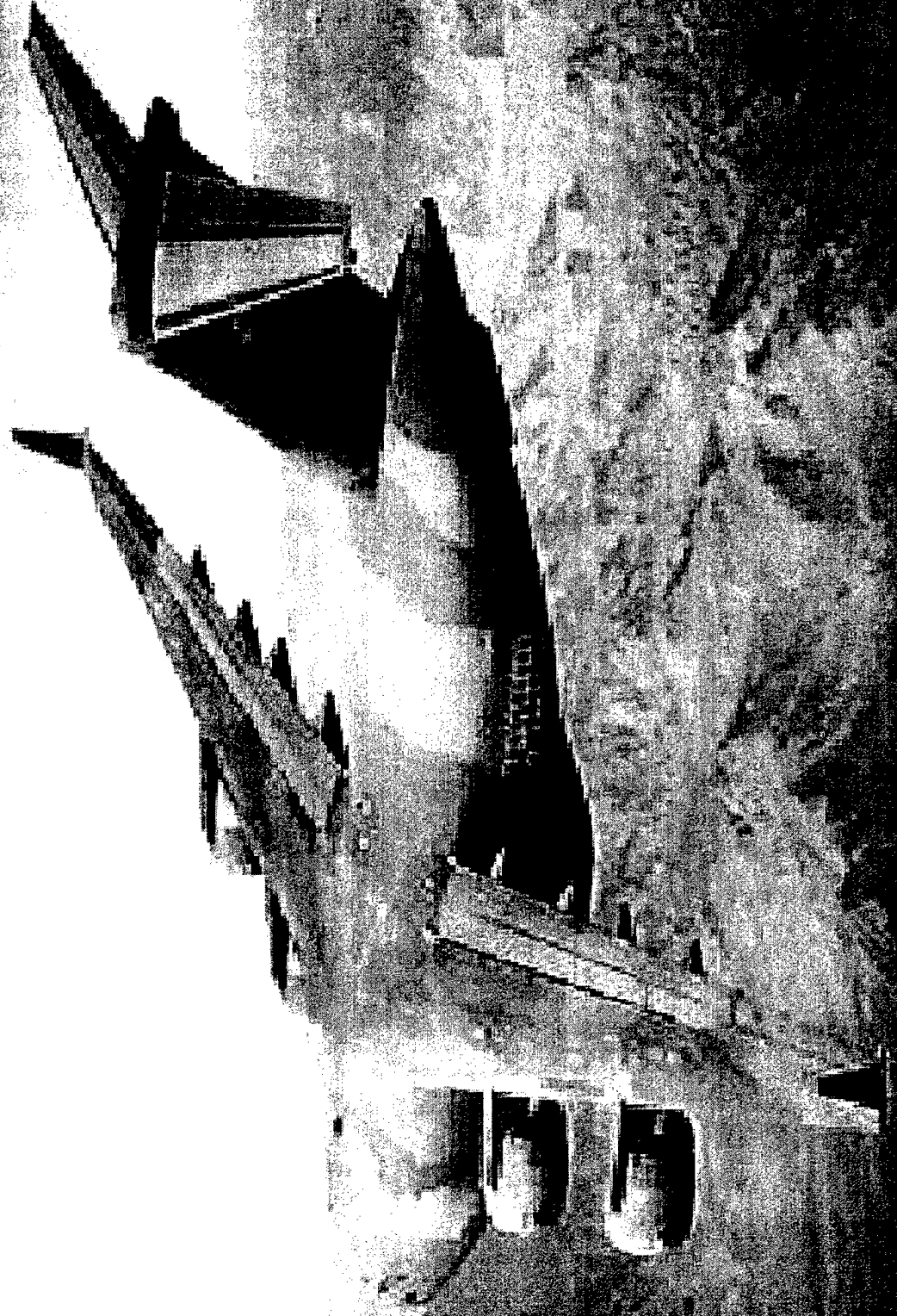
Considering lifecycle cost and lower operational temperatures, advanced materials can/will deliver lower logistical costs.

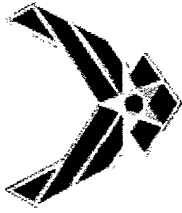


# Thermal Management Applications

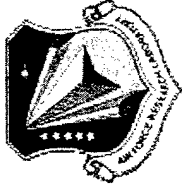


# Thermal Management for Aircraft Applications

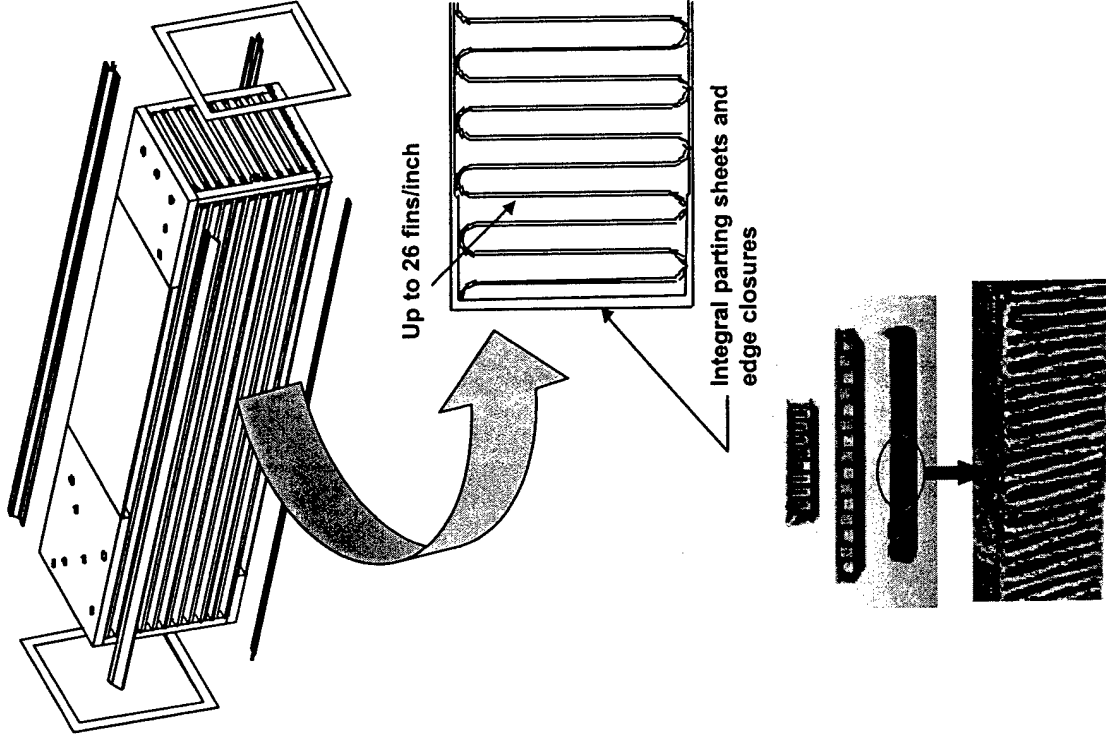


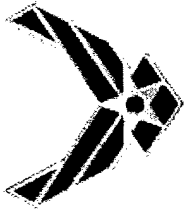


# Past Effort: C-C Heat Exchanger

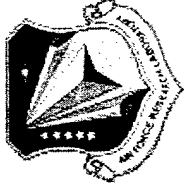


- Program initiated July 1996 in AFRL/VA with tech support from AFRL/MLBC.
- Objective: Development/fabrication/demonstration of affordable lightweight, C-C F/A-18E/F primary heat exchanger with 6000 hour service life goal
- Design of C-C HX Core completed with better predicted results than metallic designs
- Methods to form thin-wall, high density fins per inch successfully developed
- Two designs resulted assembled using a BNi-5; Ni-19Cr-10Si (liquidus 2075°F) braze
  - Integral - layers fabricated using CVD C-C processing
  - Conventional - layers fabricated by brazing component
- Oxidation protection needs further work
- Impetus for contracts looking at one-step C-C processing and oxidation protection

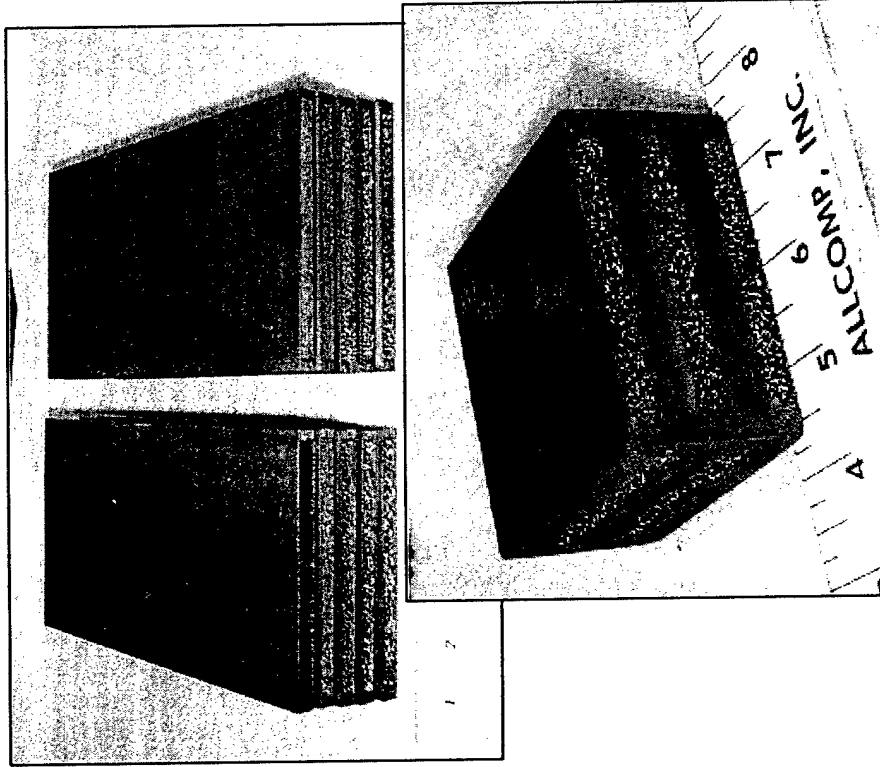




# Current Program: Carbon Foam Heat Exchanger



## Next Generation Heat Exchanger - Carbon Foam

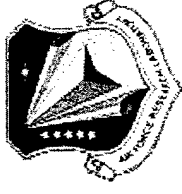


- Develop extremely light-weight, high conductivity composite V-22 heat exchangers
- Design and fabricate full size heat exchanger to decrease volume/increase cooling capacity
- Provide extended life, lightweight, corrosion-resistant, very efficient Environmental Control System
- Extends time between failure by at least 2X
- Extend range due to 70% weight reduction and
- Increase heat exchanger efficiency by 25%
- Increase heat transfer coefficient, h by 5X

Coordination with Navy  
Advanced Concept

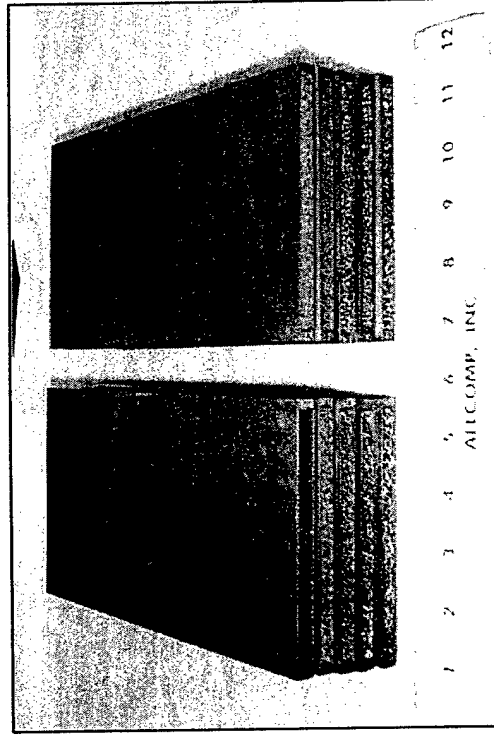


# Future Program: Carbon Foam Primary Heat Exchanger



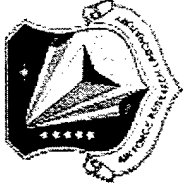
## Next Generation Advanced Heat Exchanger - Carbon Foam

- Build from previous efforts in
  - Carbon foam (Hi-K, graphitic)
  - Carbon foam heat exchanger
  - Oxidation protection (temps greater than NAVY SBIR)
- Design and fabricate full size heat exchanger (JSF???)
  - Provide extended life, lightweight, corrosion-resistant, very efficient Environmental Control System
  - Extends time between failure by at least 2X
  - Extend range due to 70% weight reduction and
  - Increase heat exchanger efficiency by 25%
  - Increase heat transfer coefficient, h by 5X





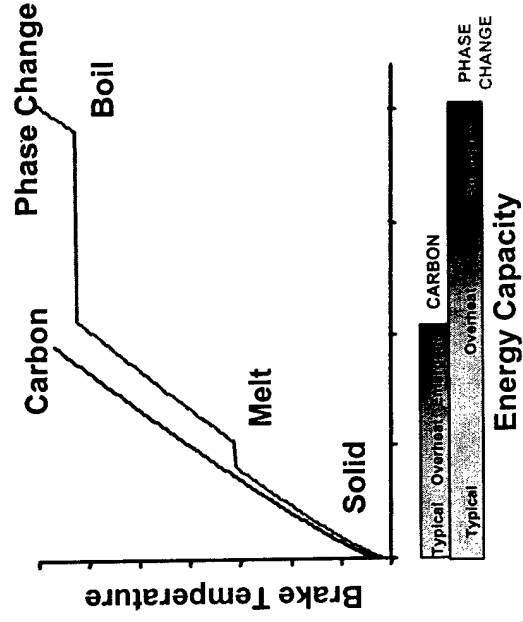
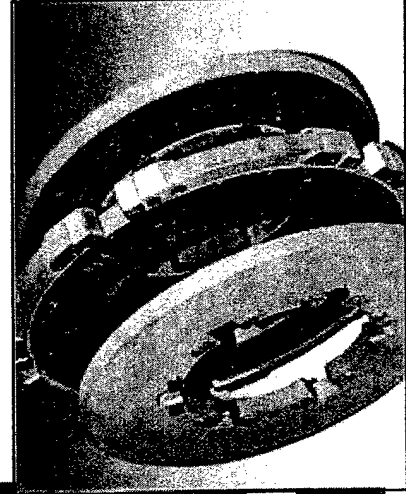
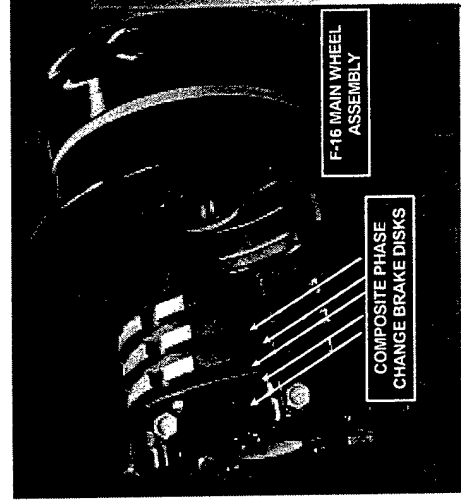
# Current Program: Phase Change Thermal Management



## Next Generation Aircraft Brake - Phase Change Brakes (PCB)

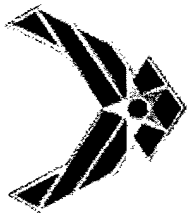
Current operating aircraft brake systems utilize the mass of the brake disks, either steel or carbon/carbon composites, to absorb the heat associated with braking the aircraft. The new concept takes advantage of phase-change (i.e. melting and/or vaporization) of high heat capacity materials to provide at least a

- 30% increased heat absorption capability without increasing weight or volume.
- 30% weight and volume reduction without changing the total heat absorption.

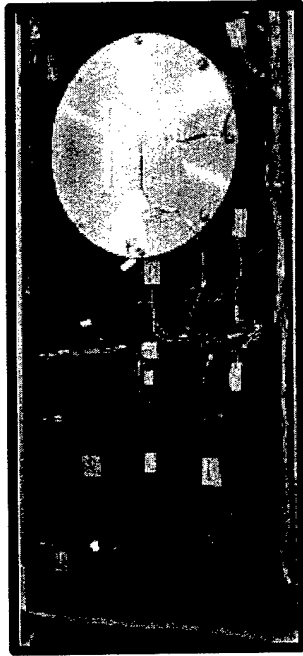
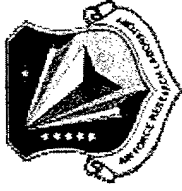




**Thermal Management for  
Space Applications**

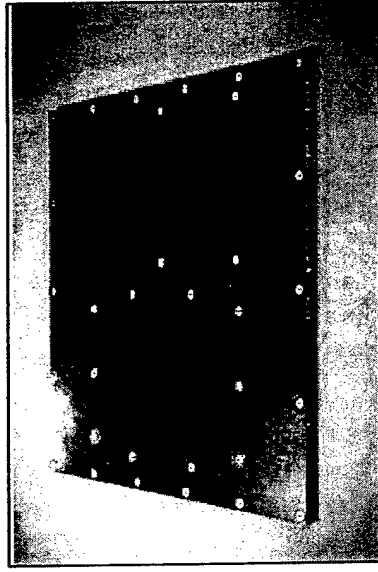
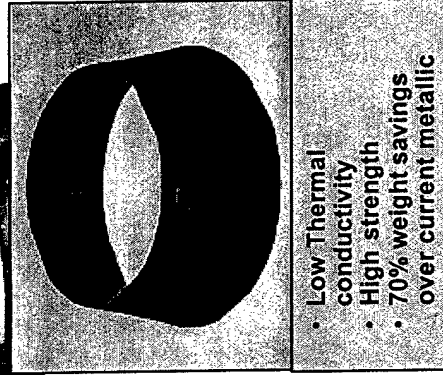
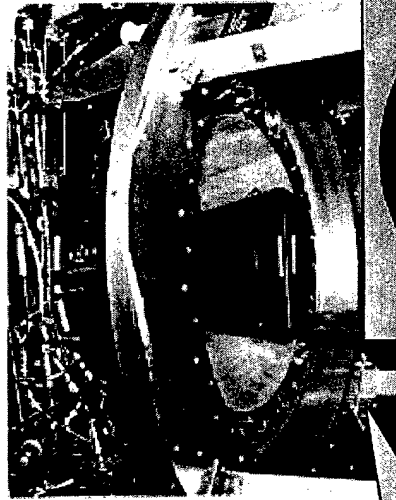


# Thermal Management for Space Structures



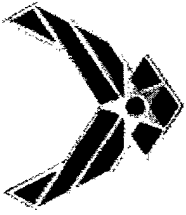
## Light Weight Dimensionally Stable Structures

- Demonstrated C-C technology for spacecraft applications
  - Optical bench
  - Thermal doublers
  - Heat sinks
  - Engine shield
- Demonstrated equivalent or better properties than (M55J/K1100)/CE
  - In-Plane thermal conductivity equivalent
  - 3X improvement in through-the-thickness panel conductance
  - Mechanical characteristics equivalent
- Transitioned to
  - MGS
  - Titan's Wideband Instrumentation SubSystem
  - Multifunctional Structure experiment on Deep Space 1 spacecraft

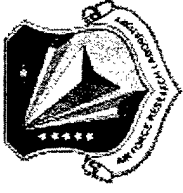


## C-C Spacecraft Radiators Partnership

- Low density
  - Decreased launch cost
  - Increased payload
- High thermal conductivity
  - Reduced module temperature
  - Increased module density
- High stiffness
  - Decreased deflections
- Same Thermal Performance as Aluminum radiator with heat pipes
  - Flying on Earth Orbiter 1
  - Collaborative effort: AF/Navy/NASA/Industry

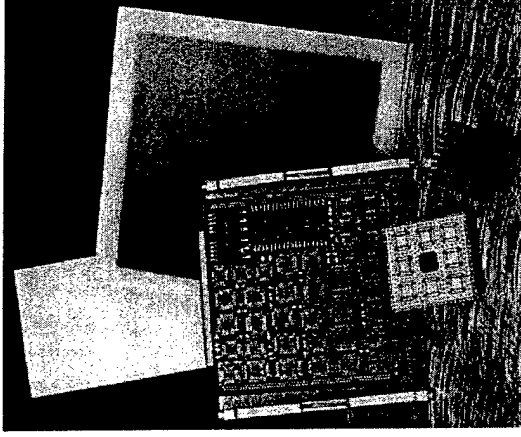


# Thermal Management for Space Structures



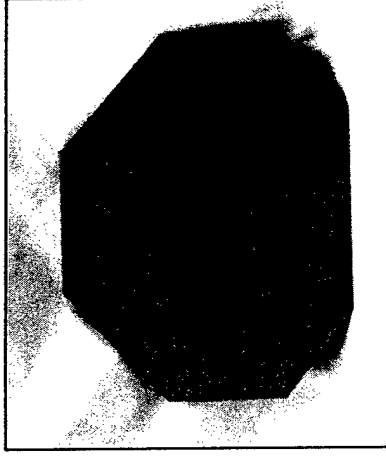
## Thermal Structural Materials Solutions for Space

- Reduced Weight
  - Weight savings (~50%)
    - Aluminum: 6 lbs
    - K1100/CE (PMC): 3.3 lbs
- Maintain/improve thermal performance
- Maintain structural performance
- Minimize hardware costs
- Radiator fins flown on STEX spacecraft.
- Battery panel flown on Mars '98 Orbiter.
- Thermal structural panel flown on STRV-1/d.
- Transitioned technology to Stardust



## Carbon-Carbon Thermal Planes for Electronics

- 30% lighter weight than Al
- Low thermal expansion
  - Reduced solder fatigue
  - Increased lifetime
- High thermal conductivity
  - Reduced board temperature
  - Increased module density
- High stiffness
  - Reduced board deflections
  - Increased board density

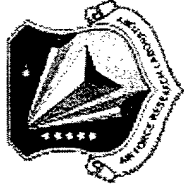


## Economical Carbon-Carbon for Spacecraft Thermal Doublers

- High thermal conductivity
  - Reduced module temperature
  - Increased module density
- Low density
  - Decreased launch cost
  - Increased payload
- Low modulus
  - Compliant with surrounding materials

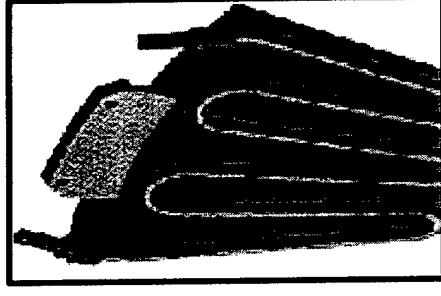


# Organic Matrix Composite Heat Pipes



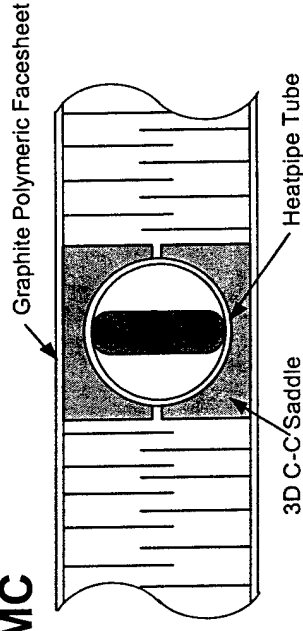
## Why OMCs?

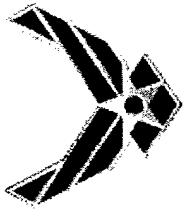
- The trend towards OMC structures for weight, stiffness and dimensional stability has driven the need to have composite radiators
- Aluminum heatpipes cannot be readily embedded in composite panels due to CTE mismatch issues
- The use of OMC reduces component weight (i.e. up to 10-20%)
- A CTE compatible heatpipe radiator would allow the incorporation of high thermal conductive materials, resulting in thermal efficient designs.



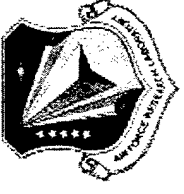
## Technical challenges of OMC heat pipes:

- Non permeable –  $2 \times 10^{-10}$  scc/sec He
- CTE match of hybrid OMC material and interface joint material – ? CTE – 0 to 1 ppm/K
- Integration of thermal efficient heat pipes with OMC skins and honeycomb core components
  - Fewer heat pipes per radiator possible
  - Less weight
  - Less complex design and fabrication processes

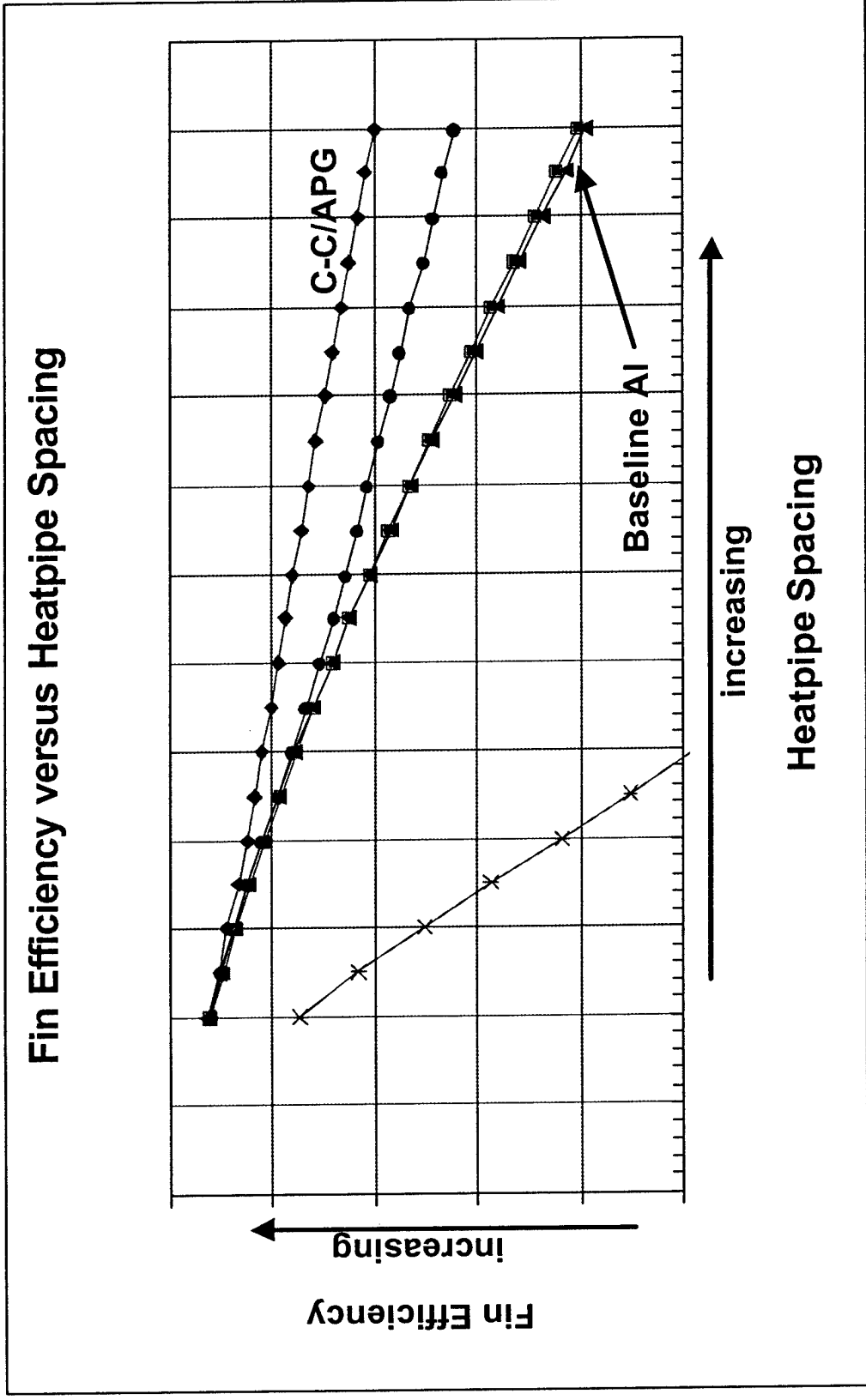




# Organic Matrix Composite Heat Pipes

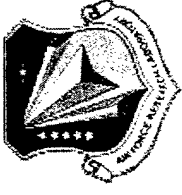


## OMC Heat Pipes



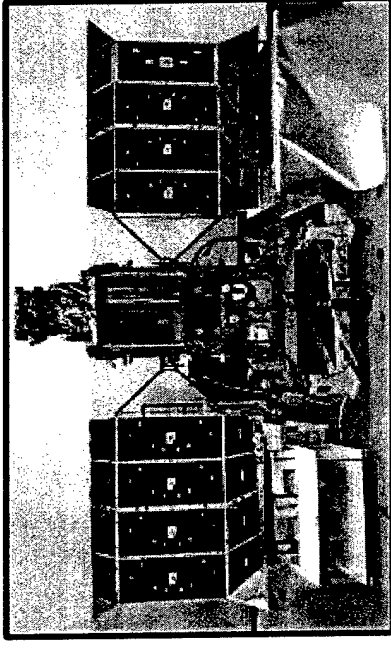


# Current Programs: OMC Heat Pipes/Radiators



## Problem

- Aluminum heat pipes cannot be readily embedded in composite panels due to CTE mismatch issues
- Aluminum radiator panels are incompatible with composite bus structures
- Aluminum doublers add unnecessary weight

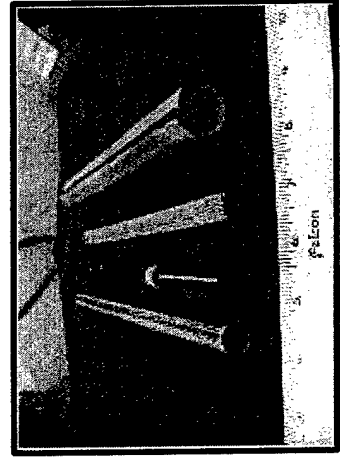


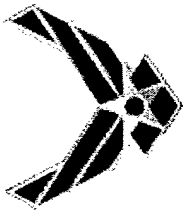
## Objective

- Develop affordable processing techniques for producing a non-permeable carbon-carbon heat pipes
- Develop techniques to integrate OMC heat pipes into the radiator
- Eliminate Al doublers

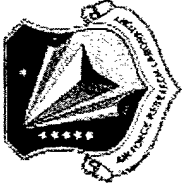
## Benefits

- All composite bus
- Lower weight
- Lower fabrication costs
- Greater thermal efficiency



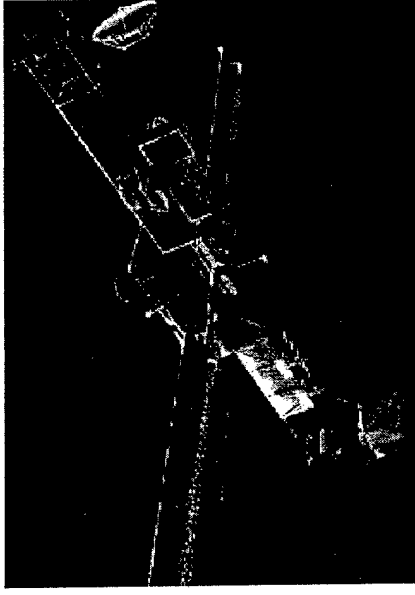


# Future Programs: OMC Heat Pipes/Radiators



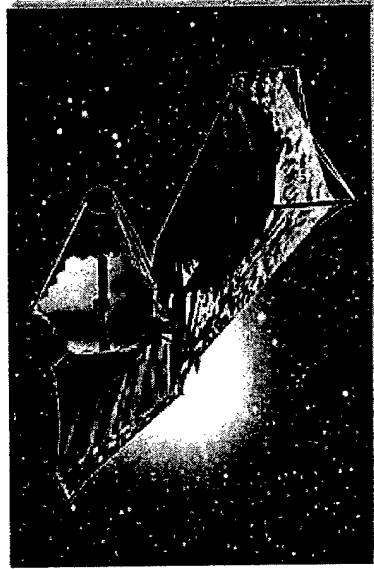
## Problem

- Aluminum heat pipes cannot be readily embedded in composite panels due to CTE mismatch issues
- Aluminum radiator panels are incompatible with composite bus structures
- Aluminum doublers add unnecessary weight



## Objective/Approach

### Next Generation Technologies (??)

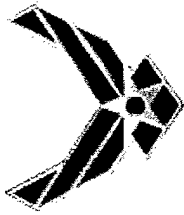


## Benefits

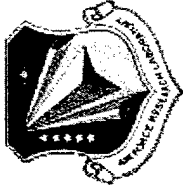
- All composite bus
- Lower weight
- Lower fabrication costs
- Greater thermal efficiency



Beyond  
current tech

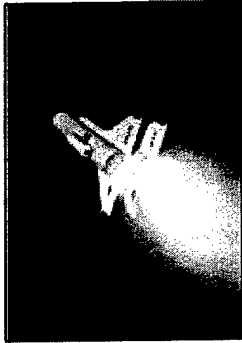


# Military Space Plane



## AF SOV Gen 2

- Launch-On-Demand: 8 Hrs
- Military Ops Tempo
- Reduce Launch Cost: 100x
- Flexible Launch and Recovery



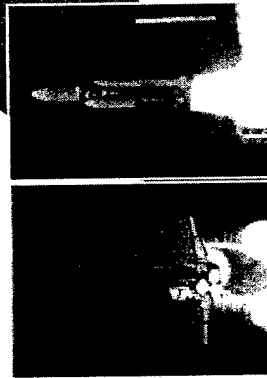
## AF SOV

- Launch-On-Demand: 1 day
- Flexible Payload Options
- Reduce Launch Cost: 10x
- Recall After Launch



## AF EELV

- Reduce Launch Cost: 2x
- Launch-On-Schedule
- Reconfigure Vehicle for Payload
- No Recall After Launch



## BASELINE Shuttle / ELVs

Near Term

2000

2008

Mid Term

2016

Far Term

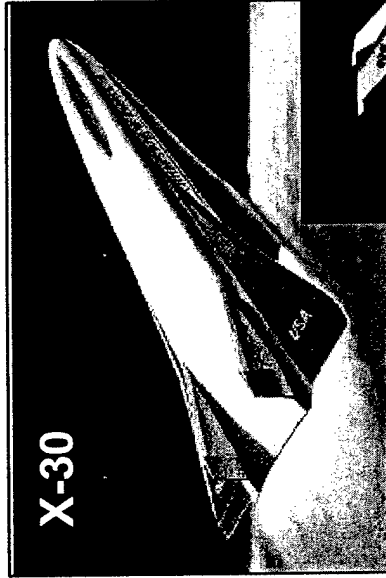
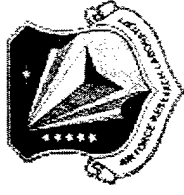
2025

## Attributes:

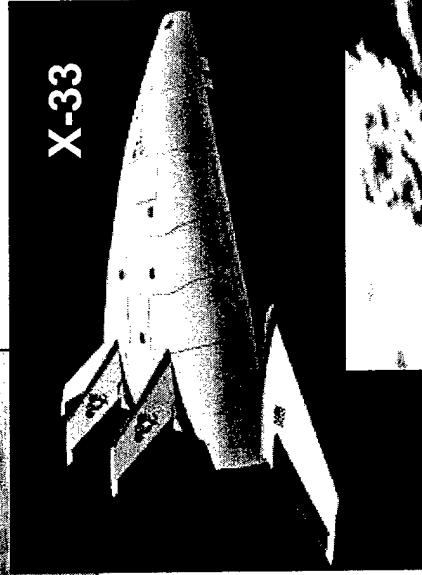
- Responsive and Affordable Delivery of Mission Assets To, Through and From Low Earth Orbit
- Multi-Mission Capable With Inter-changeable Payloads
- Rapid Turn Time and Alert Hold Capability
- Launch and Recovery from U.S. Bases
- Nearly All Weather Operations
- Autonomous Operation Design
- Primary Structure: 500 sorties (overhaul @ 250)
- Engine Life: 250 sorties (overhaul @ 100)
- Remove & replace main engine: 4 hrs
- Maintenance man hours per sortie: 50



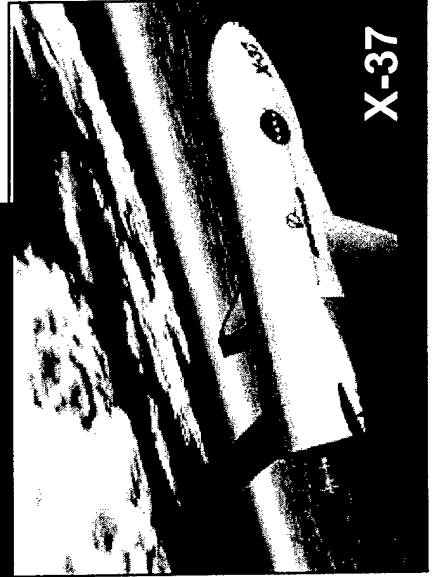
# X-Vehicles LE TPS



- TPS (<1500) – Titanium Matrix Composite
- TPS (1500-3000F) – C-C and C-C/SiC
- TPS (>3000) – Active Cooling (C/SiC and C-C w/MoRe heatpipes, heat exchangers)



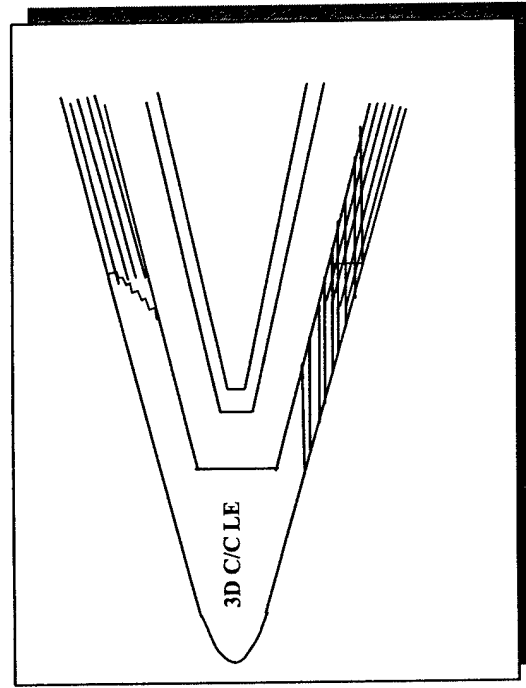
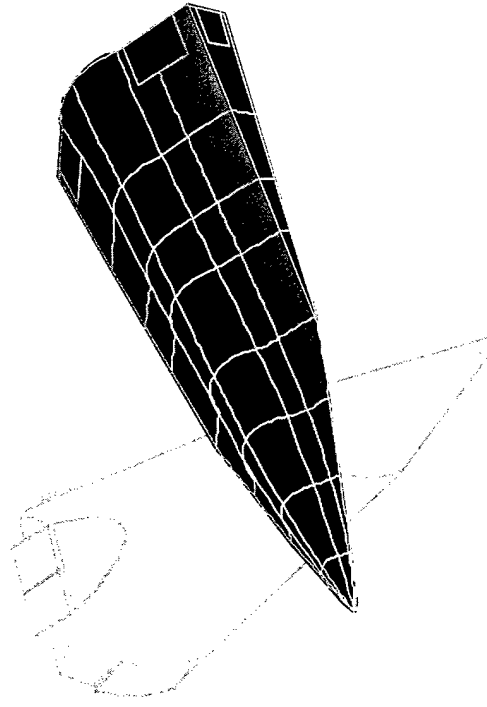
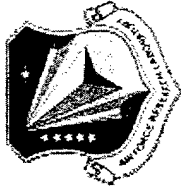
- Nose Cap – C-C
- Leading Edges – C-C
- Other – metals, tiles, blankets,



- Nose Cap – TUFII/AETB tiles
- Leading Edges – TUFII/AETB tiles



# Current Programs: Thermal Protection Materials



## OBJECTIVE

- Develop low cost, advanced TPM for the CAV (Common Aero Vehicle)

## APPROACH

- Modified CC aeroshell: thermally efficient, structural, low cost
- Insulation layer: lightweight, thin section
- Integral stackup: aeroshell + insulation + structure
- Triaxial braiding: thin wall CC aeroshell
- Leading edge to heatshield transitions
- Cold wall ablator (CWA) overlay: low CC aeroshell recession
- Integrated CC leading edge: high bending resistance
- Modified CC processing: cost reduction

## BENEFITS

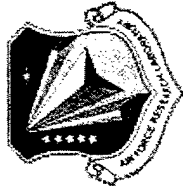
- Thermal efficiency = minimal areal weight & thickness
- Mechanical properties degradation ? 15% of allowables
- Cost reduction over current material systems of 45%

## CUSTOMERS

- CAV; SOV/SMV/Launch Vehicle technology transfers

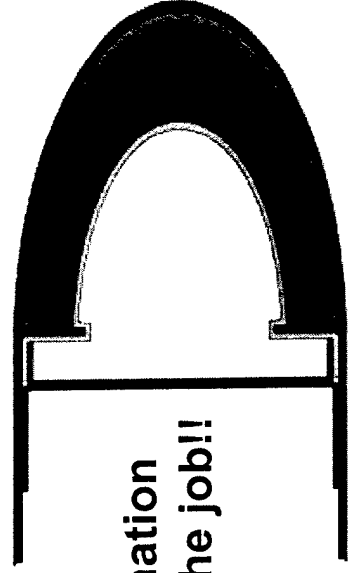


# Next Generation Leading Edge TPS Concept



## Rainbow Solution

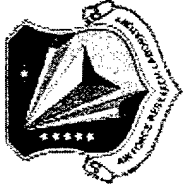
- “Think out of the Box” design philosophy
- Thermal management solution for thermal protection
- A hybrid concept
- Structurally integrated approach – not parasitic
- Novel combination of materials
  - C-C
  - Ceramics
  - Metals
  - Foams
  - Aerogels
  - Phase Change Materials
- Focus is on
  - Reliability/Durability/Supportability
  - Cost/Manufacturability
- One ongoing effort with Boeing, and one SBIR to be awarded on Jan 2003



The right combination  
of materials for the job!!



# Thermal Management Summary



**AFRL/ML actively engaged in thermal management research and transition**

- Identified the area as a key technology solution to address Air Force needs
  - Successful technology transitions demonstrated
- Integrated well with other organizations
- Broad spectrum of R&D programs and applications
- Excellent potential for transition (military & commercial)
  - Working closely with DoD, customers and industry
  - Focus is on near and mid-term applications
  - Future Work:
    - Nanomaterials for enhanced multifunctionality
    - Dimensional control, performance enhancement
    - Carbon Foam applications: heat exchangers and radiator panels
    - Novel thermal protection applications

# **FABRICATION TECHNIQUES FOR MAKING AN EFFICIENT MICRO-HEAT EXCHANGER**

**P. Kwon**

**Department of Mechanical Engineering  
Michigan State University  
East Lansing, Michigan**

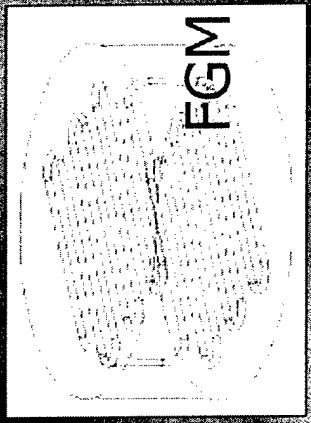
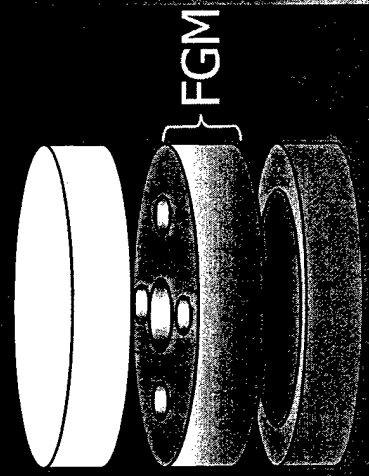
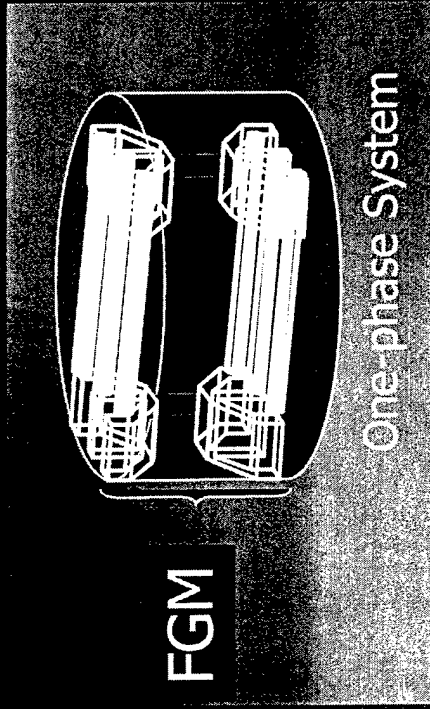
11/14/2002

Air Force Workshop on Multifunctional  
Materials

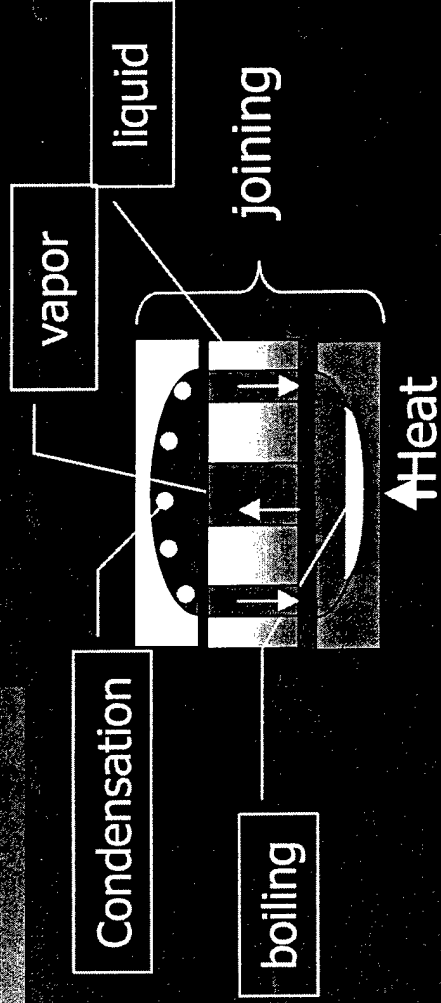
# Methods to remove heat

- Heat spreaders
  - ✦ One of the most common methods
  - ✦ Dissipates heat to the environment by forcing air through pin arrays or fins or cooling naturally.
  - ✦ Materials with high thermal conductivities and heat capacities. (diamond, silicon nitride, molybdenum etc.)
- Cooling fluids circulating in closed channels
  - ✦ "Microchannels" (100 to 300 microns in diameter)
  - ✦ Stringent requirements
  - ✦ Miniaturization
  - ✦ Fluids – One-phase and Two-phase System

# Possible Designs



One-phase System



Two-phase System

Air Force Workshop on Multifunctional Materials

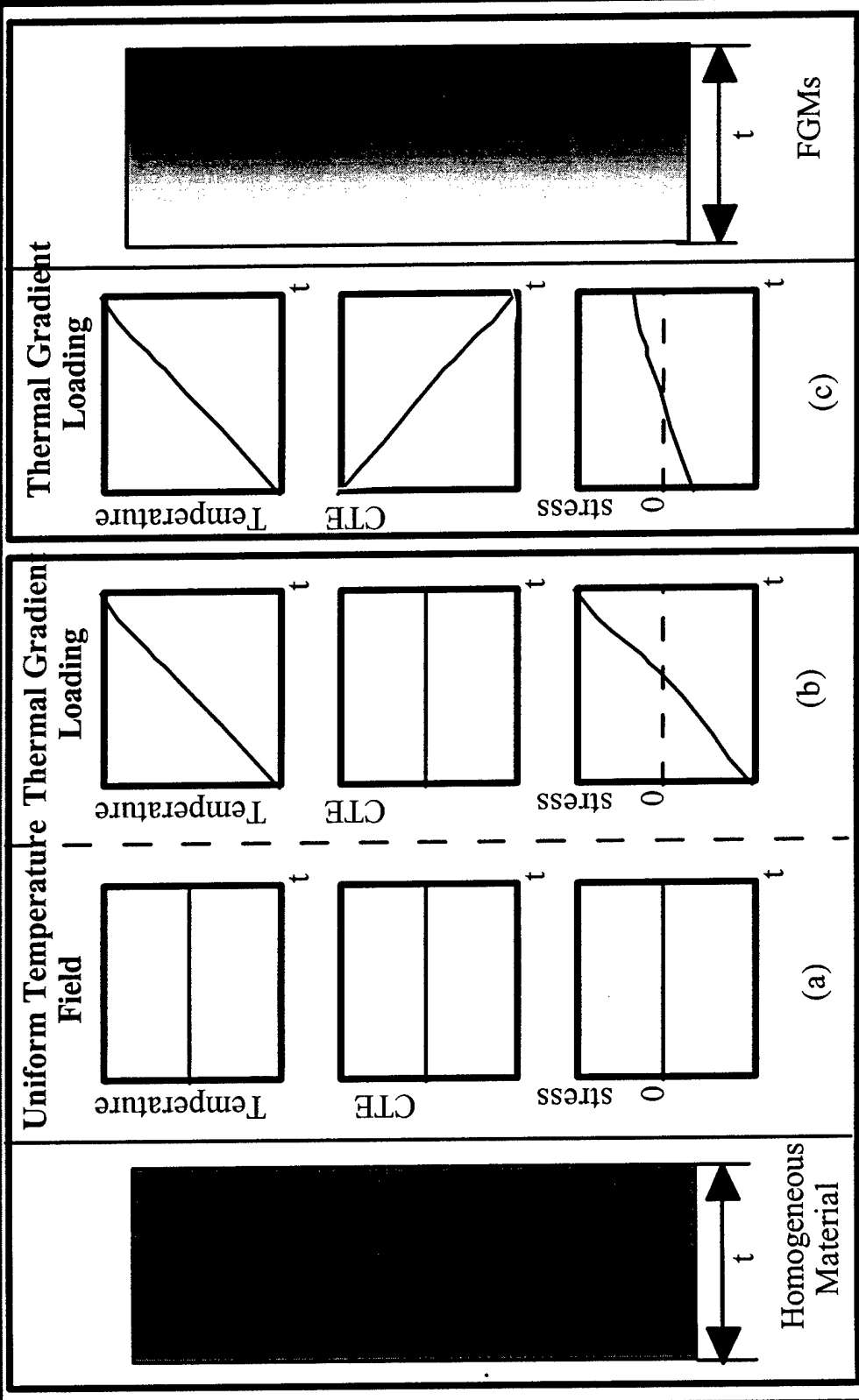
11/14/2002

# OBJECTIVES

- Multifunctional – Structure + Thermal Management
- Processing Issues
  - ↳ Functionally Gradient Medium (FGM) with minimum residual stress
  - ↳ Introduction of channels and
  - ↳ Joining techniques
- Process in general
  - ↳ More Flexible: Powder Processing
  - ↳ More Complex: Process techniques & model
- Applications: Electronic Cooling, Cutting Tool, Turbine Engine etc.



# Micromechanical Design



# Effective Properties

- “Homogeneous” Materials
- Fiber Composites:

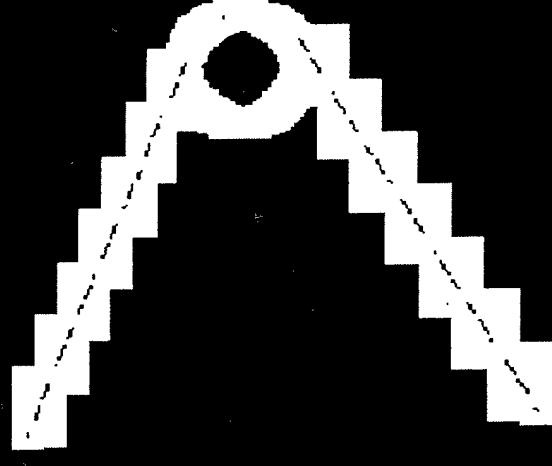
- ✦ Rule and Inverse Rule of Mixture

- Particulate Composites:

- ✦ Single Ellipsoidal Inclusion [Eshelby; 1957, 1961, 1962]

- ✦ Many Ellipsoidal Inclusions MT [Mori & Tanaka; 1973],

- GSC [Christensen & Lo; 1979], DS [Norris; 1985] & Many Others



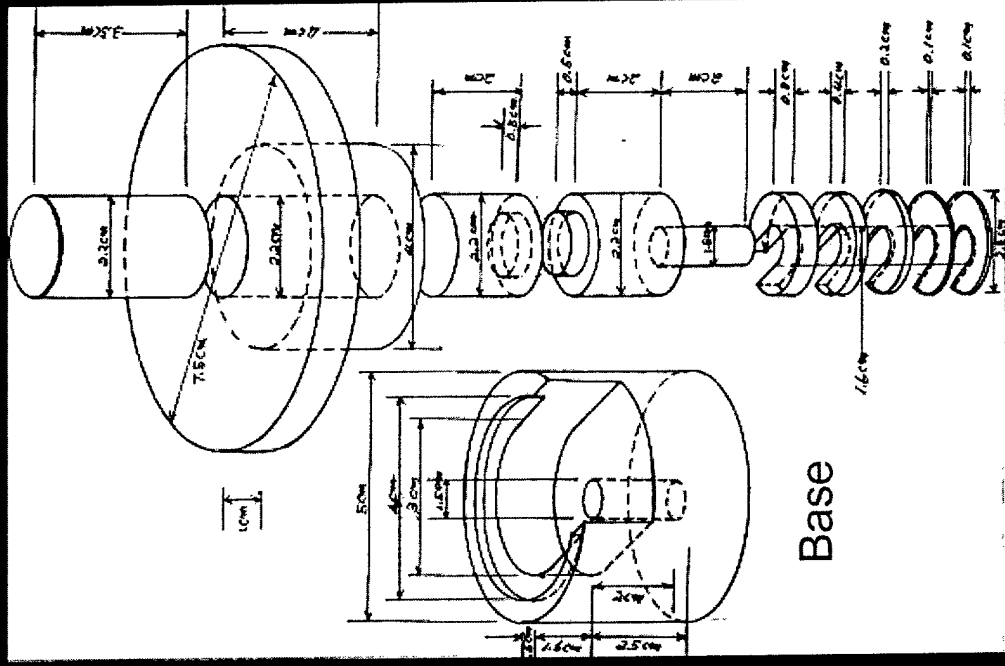
Eshelby's Problem

Mori-Tanaka Model

# Fabrication Techniques

- **Micro-texturing**
  - ↳ Multi-layers – Each layer of macroscopically homogeneous mixed powders
- **Micro-configuring**
  - ↳ Internal Geometry - Fugitive phase
  - ↳ Surface Geometry – Fugitive phase & Machining partially sintered ceramics
- **Joining Techniques**
  - ↳ Fully Sintered Ceramics (FSC)
  - ↳ Partially Sintered Ceramics (PSC)
  - ↳ Compacted Ceramic Powder (CCP)

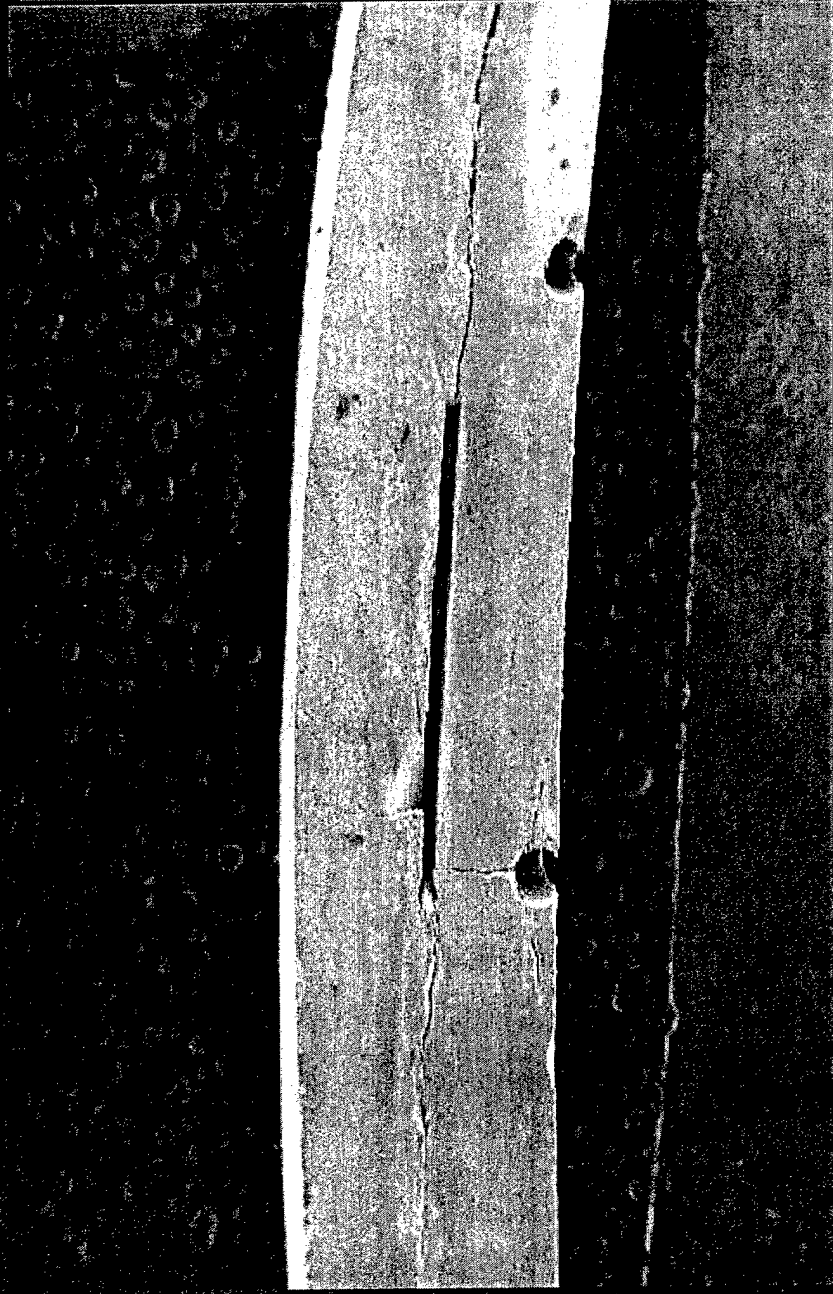
# Multilayer Powder Compaction



Air Force Workshop on Multifunctional Materials

11/14/2002

# Residual Stress Effect on FGM



Alumina

Zirconia

Air Force Workshop on Multifunctional  
Materials

11/14/2002

# Approach

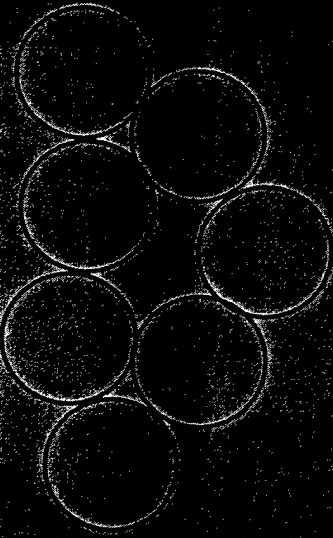
- Develop a powder processing protocol
  - Minimize process-induced residual stress in FGMs
  - The intertwined functionality existing among powder characteristics, processing conditions and corresponding shrinkage and densification behaviors.
- Plans to develop Process Model
  - Development of Compaction Model
    - Yield Surface
    - Flow rule
  - Development of Sintering Model

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Materials

# Powder Characteristics

Narrow size distribution (NSD) powders



High Shrinkage

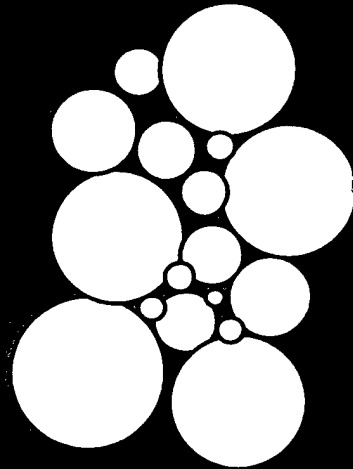
low CTE material

high CTE material

Bi-material



Low Shrinkage



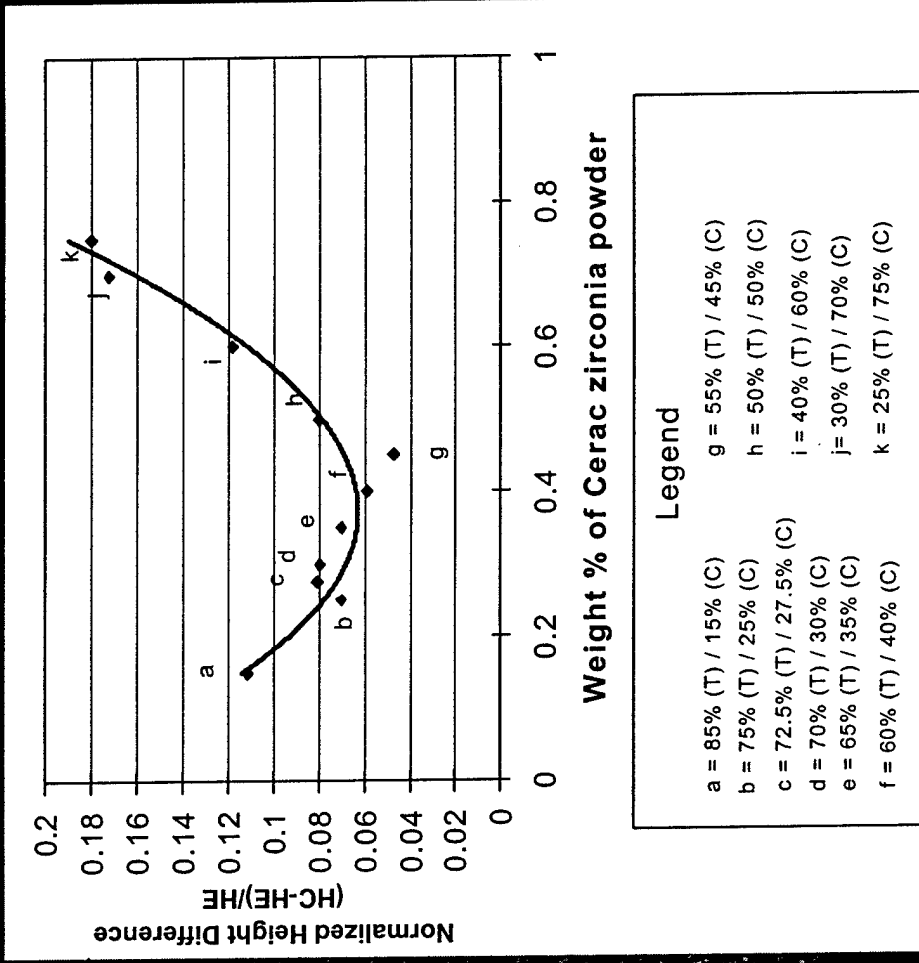
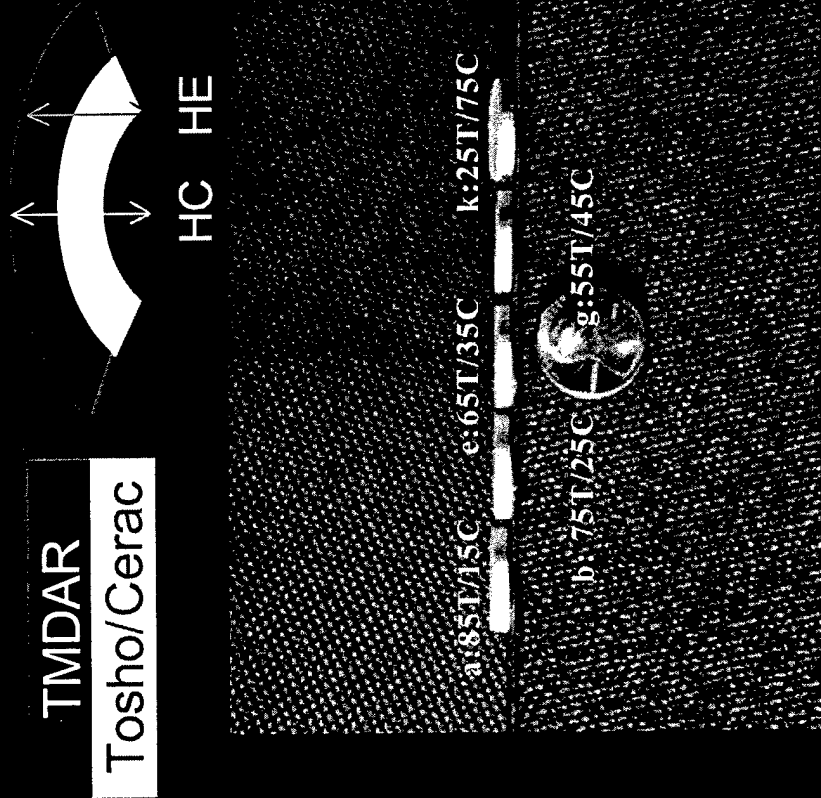
Wide size distribution (WSD) powders

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# Controlling Residual Stress

T C

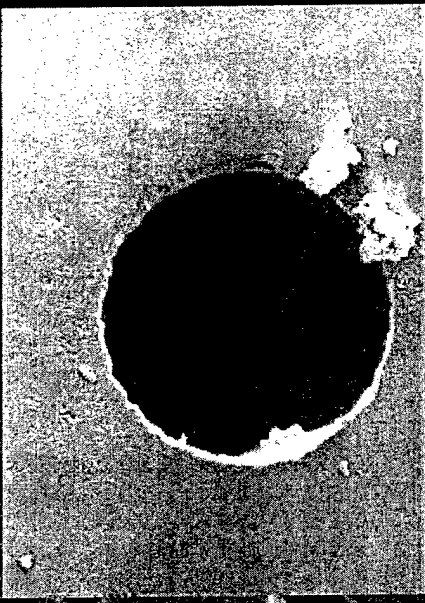
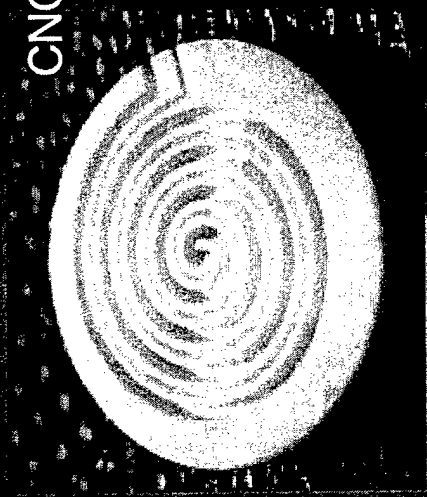


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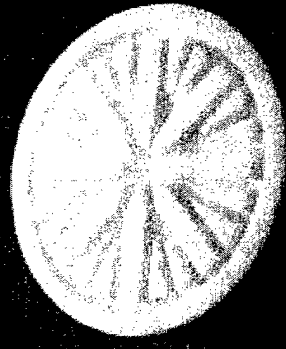
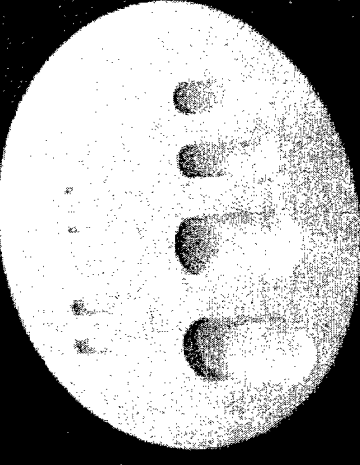
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# Internal & External Channels

CNC-Machined on PSC, Sinter & Join



CNC-Machined on PSC, Sinter & Join



Fugitive Phases: Various Polymers & Graphite

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Materials

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# Powders Used

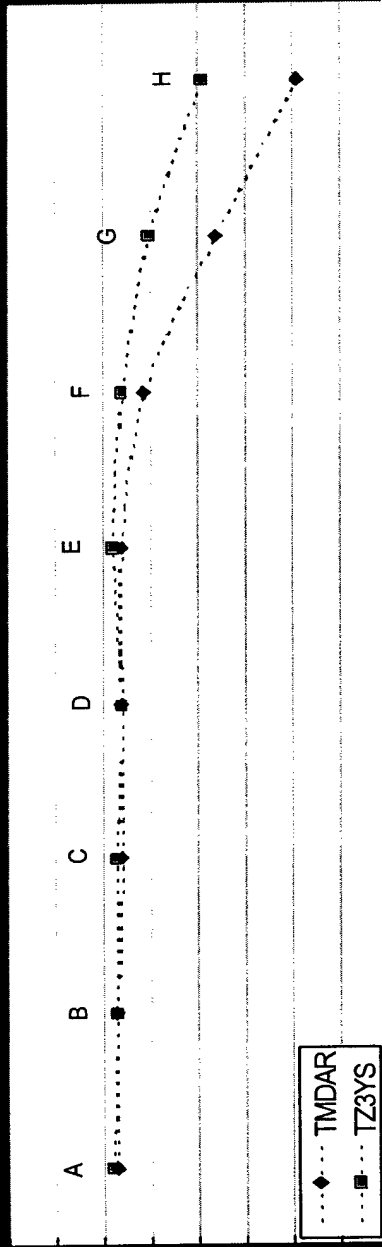
| Materials | Manufacturer | Powder Name | Average Particle Size (micron) |
|-----------|--------------|-------------|--------------------------------|
| Alumina   | Tamai        | TMDAR       | 0.2                            |
| FSZ       | Tosoh        | TZ-8YS      | 0.58                           |
| PSZ       | Tosoh        | TZ-3YS      | 0.6                            |
|           | CERAC        |             | 1.23                           |
|           | Sumitomo     | OZC-3YC     | 0.9                            |

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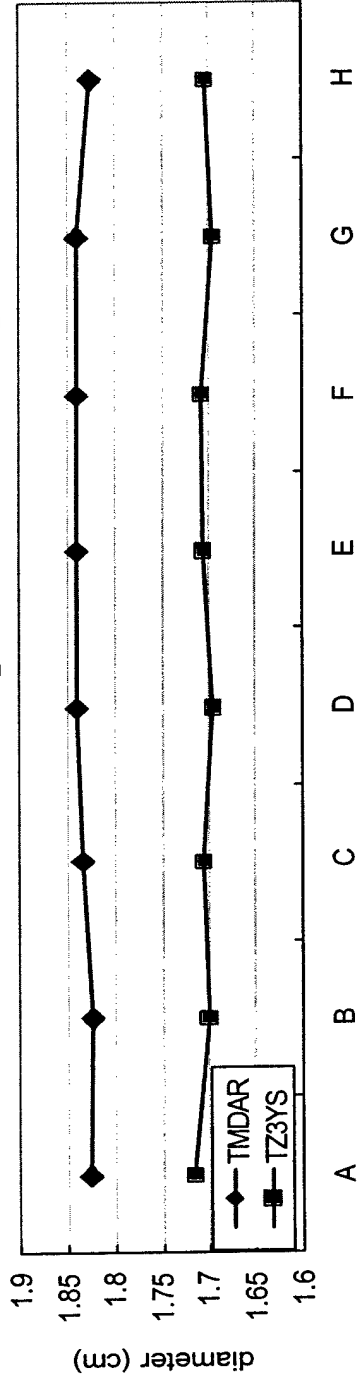
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# Dimensional Changes

Dimensional Shrinkage after Final Sintering



Diameter Shrinkage after Final Sintering



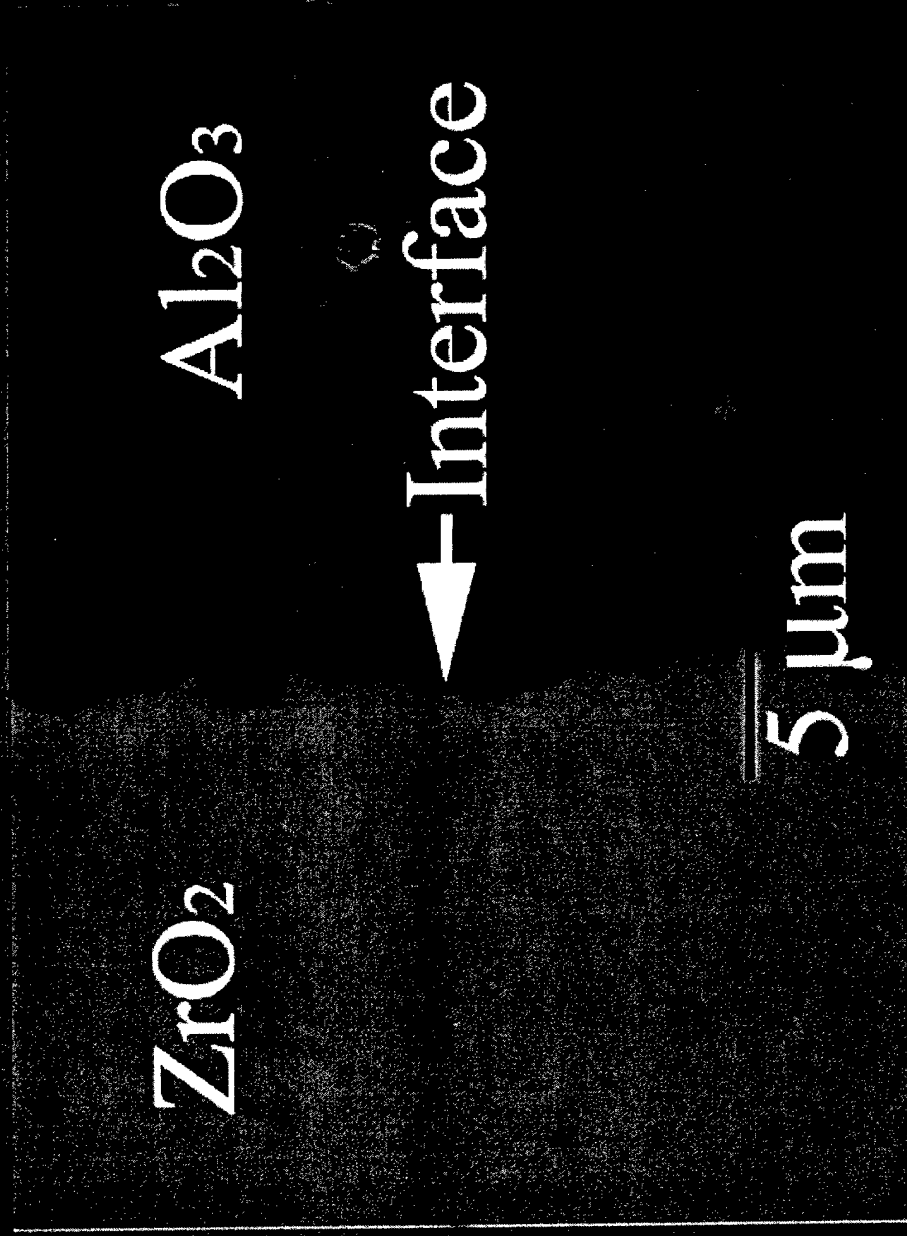
sample label

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Materials

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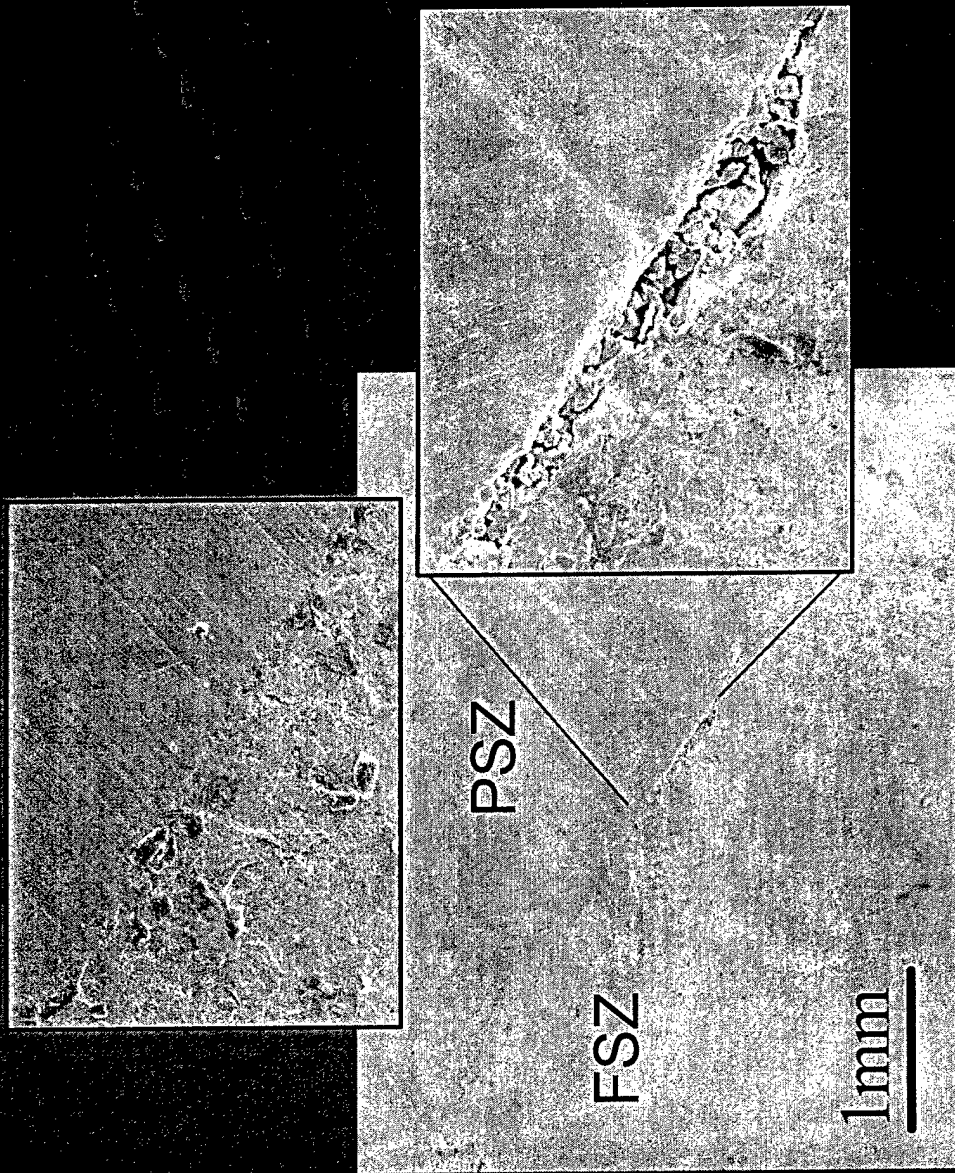
# Joining with Silica film



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# Joining without Silica Film



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# Summary of Processing

## Internal Channels

- Powder Mixing
- Compaction
- Fugitive Phase
- Pre-sintering (1000°C for 3hrs)
- Sintering
- Polishing and Spin-coating
- Joining

## Surface Channels

- Powder Mixing
- Compaction
- Pre-sintering (1000°C for 3hrs)
- CNC-Machining
- Sintering
- Polishing and Spin-coating
- Joining

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Materials

# **3-D WOVEN COMPOSITE STRUCTURES WITH INTEGRATED FIBER OPTIC SENSORS**

**Dr. Alexander Bogdanovich**

**Vice President, Research & Development  
3TEX, Inc.**

**109 MacKenan Drive, Cary, NC 27511**

**Phone: 919-481-2500 ext. 113**

**E-mail: [bogdanovicha@3tex.com](mailto:bogdanovicha@3tex.com)**

**Presented at the 1st Air Force Workshop on**

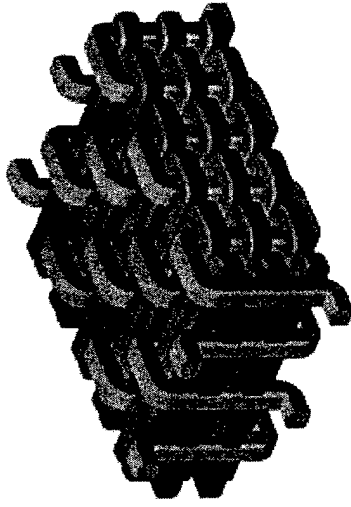
**“Multifunctional Aerospace Materials”**

**October 23-23, 2002, Purdue University, W. Lafayette, IN**



**IN SITU EVALUATION OF 3-D WOVEN COMPOSITE STRUCTURAL  
PERFORMANCE USING FIBER OPTIC SENSORS  
AFOSR STTR PHASE I and PHASE II (to start in November 2002)**

**Awarded to 3TEX, Inc.**



- **The concept of this novel technology:**

To use three orthogonal reinforcement elements (yarns placed in warp, weft and Z directions) of a 3-D woven fabric preform as natural carriers of integrated optical fibers and sensor systems associated with them.

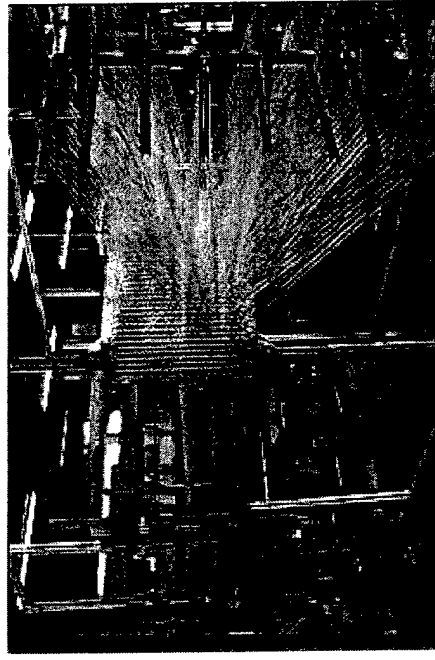
- **Objective:**

In-situ strain monitoring of composite structures at any location within the structure and in any of the three orthogonal directions by means of fiber optic sensor systems integrated in the 3-D reinforcement elements.

- **Concept validation:**

Use of automated 3-D weaving machines for manufacturing fabric preforms and VARTM composite processing technology for producing composite panels and bonded joints with integrated EFPI sensors in all three directions.

Schematic of 3-D orthogonal woven preform

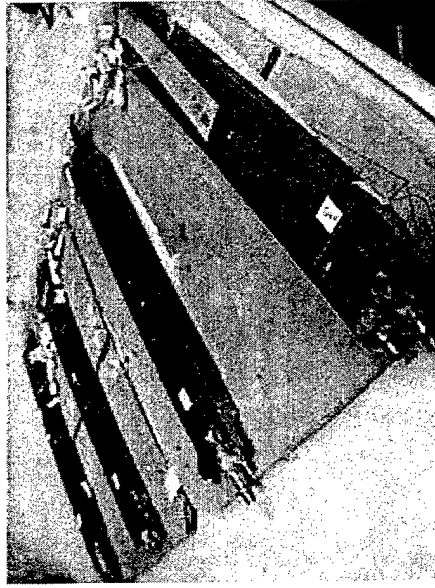


Industrial 3-D weaving machine (3TEX)



# EFPI SENSOR INSTRUMENTED CARBON/EPOXY SPECIMENS USED FOR THE CONCEPT VALIDATION

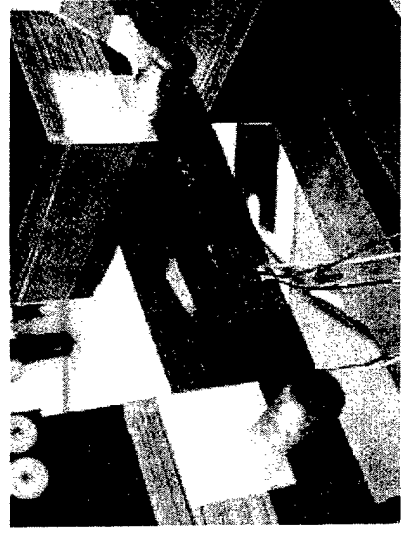
Instrumented 3-D weave flexure specimens



4-point bending test of beam specimen



4-point bending test of beam with drilled hole

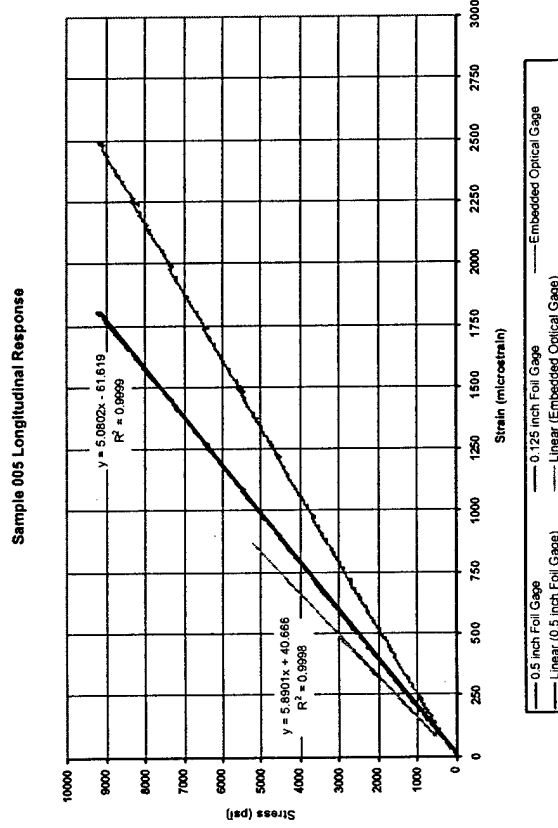


Sensor location in lap joint simulation specimens



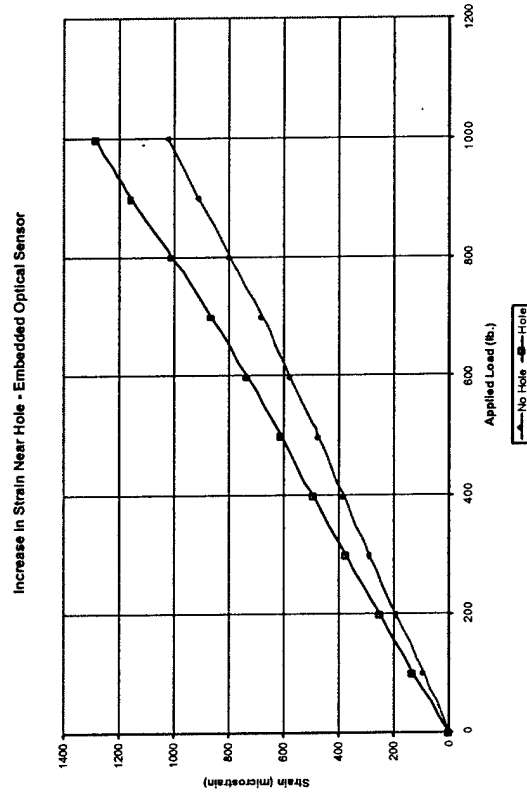
# SOME RESULTS OF THE CONCEPT VALIDATION

4-point flexure test longitudinal strain data from EFPI sensor and foil gages



A smaller foil gage shows strain (-----) more characteristic for a resin pocket.  
 A larger strain gage (-----) covers resin pocket and some of the yarn area next to the specimen surface.  
 The EFPI sensor shows strain (-----) within yarn adjacent to the specimen surface.

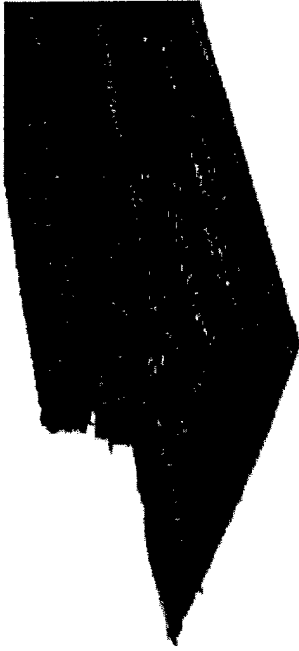
Strain concentration near hole captured by EFPI sensors in 4-point flexure test

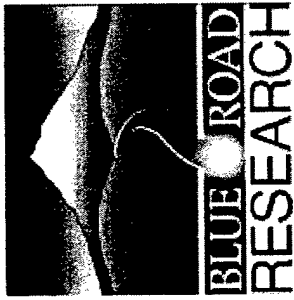


A through-thickness hole was drilled near integrated EFPI longitudinal strain sensor. Strain recorded by the sensor in the presence of hole (-----) is significantly higher than the strain at the same location in the absence of hole (-----).

# ANTICIPATED BENEFITS FOR DESIGN AND APPLICATIONS

- Embedding fiber optic sensors into 3-D weave composites in the zones of anticipated high stress/strain gradients and simulating in-service loading conditions will provide invaluable information for
  - optimizing 3-D fiber architecture in the preform for each specific type of loading conditions
  - selecting most suitable fiber and resin combinations for composite structures
  - optimizing thickness and other geometric parameters of the structure
  - combining experimental and theoretical tools for structural analysis and design
  - significantly increasing reliability of design, thus reducing cost of inspection, repair and maintenance.





**In-Situ Evaluation of Composite Structural  
Performance in Presence of High  
Stress/Strain Gradients Using  
Multi-axis Fiber Grating Strain Sensors**

---

Eric Udd  
Stephen Kreger  
376 NE 219<sup>th</sup> Avenue  
Gresham, Oregon 97030

503-667-7772 (P)  
503-667-7880 (F)

[www.bluerr.com](http://www.bluerr.com)

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## **Strain Measurement Interior to Composite Parts- Background/Partnerships**

---

- First quantitative measurements of multi-dimensional strain interior to composite parts
- Blue Road Research partnered with U of DL, interest from Boeing (aircraft, spacecraft) and Thiokol (rocket motors)
- Synergistic with funded research from NASA (multi-axis strain measurement), health monitoring for composite cryo tanks and rocket motors (AFRL/WPAFB and AFRL/Edwards AFB)



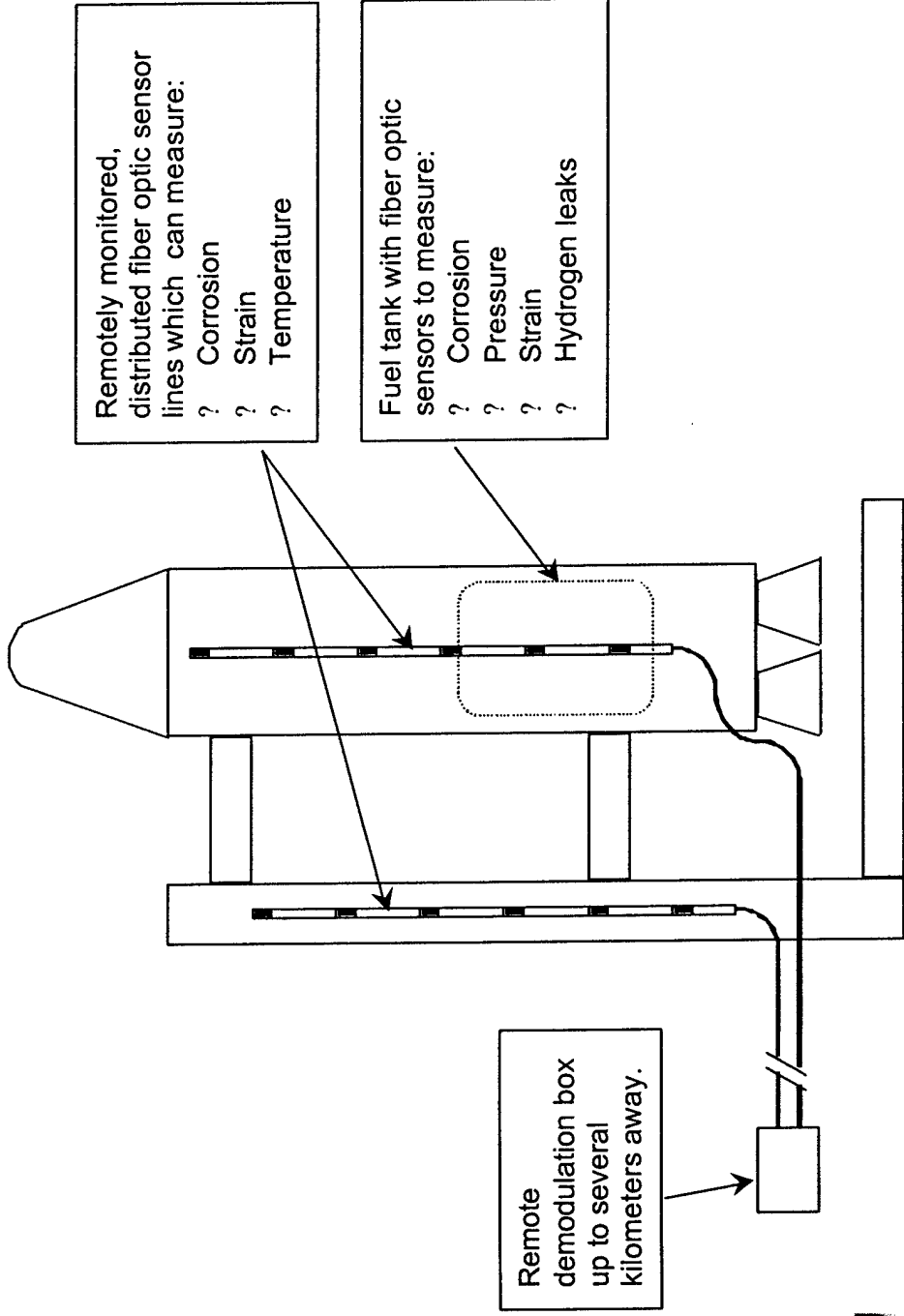
## **Strain Measurement Interior to Composite Parts- Relevancy**

---

- Multi-dimensional strain measurement using fiber gratings interior to complex composite parts
- Electrical alternatives are bulky and not compatible with conductive materials
- Embed multi-axis fiber grating and obtain quantitative measurements of transverse strain and strain gradients
- Applies to aircraft and launch vehicle composite parts

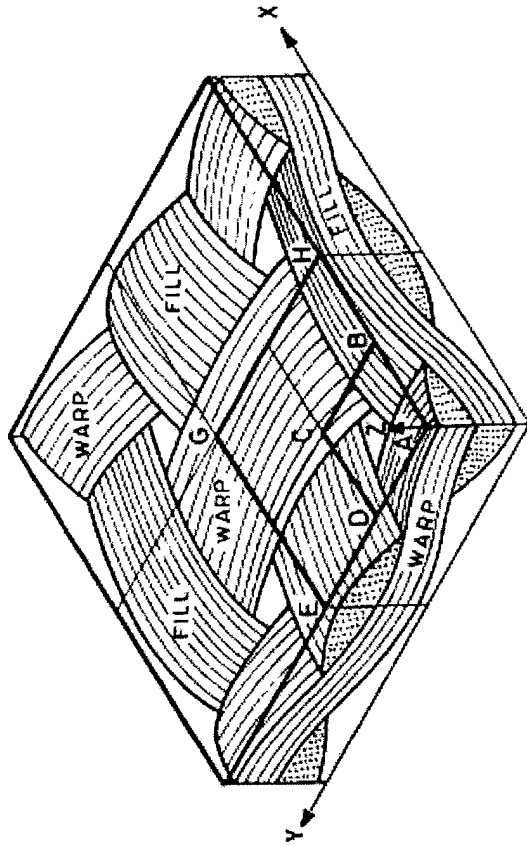
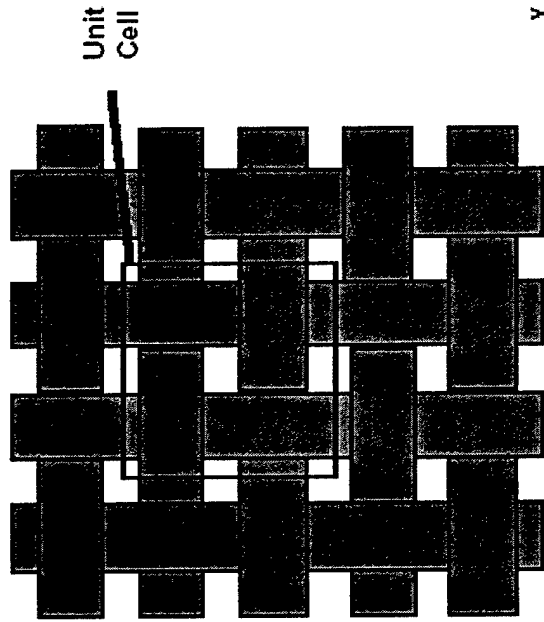
# *Distributed Sensors in Space Vehicles*

---



# Schematic of the Microstructure and Unit Cell of Plain Weave Fabrics

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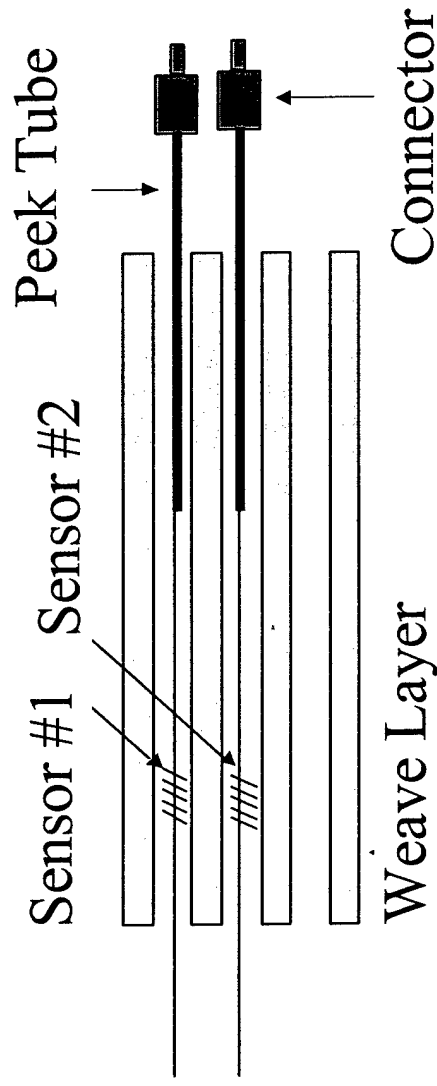




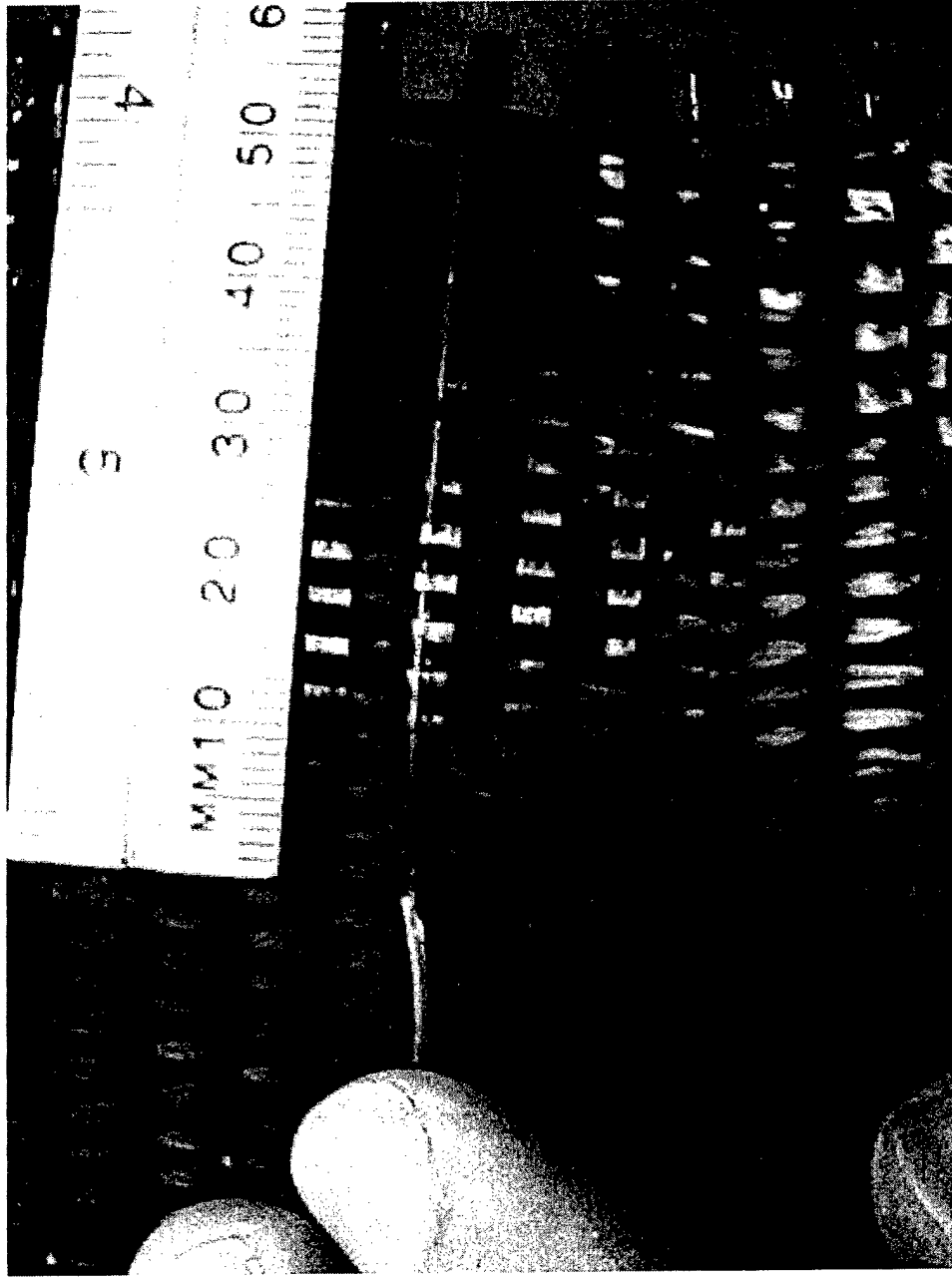
## Initial Experiment

---

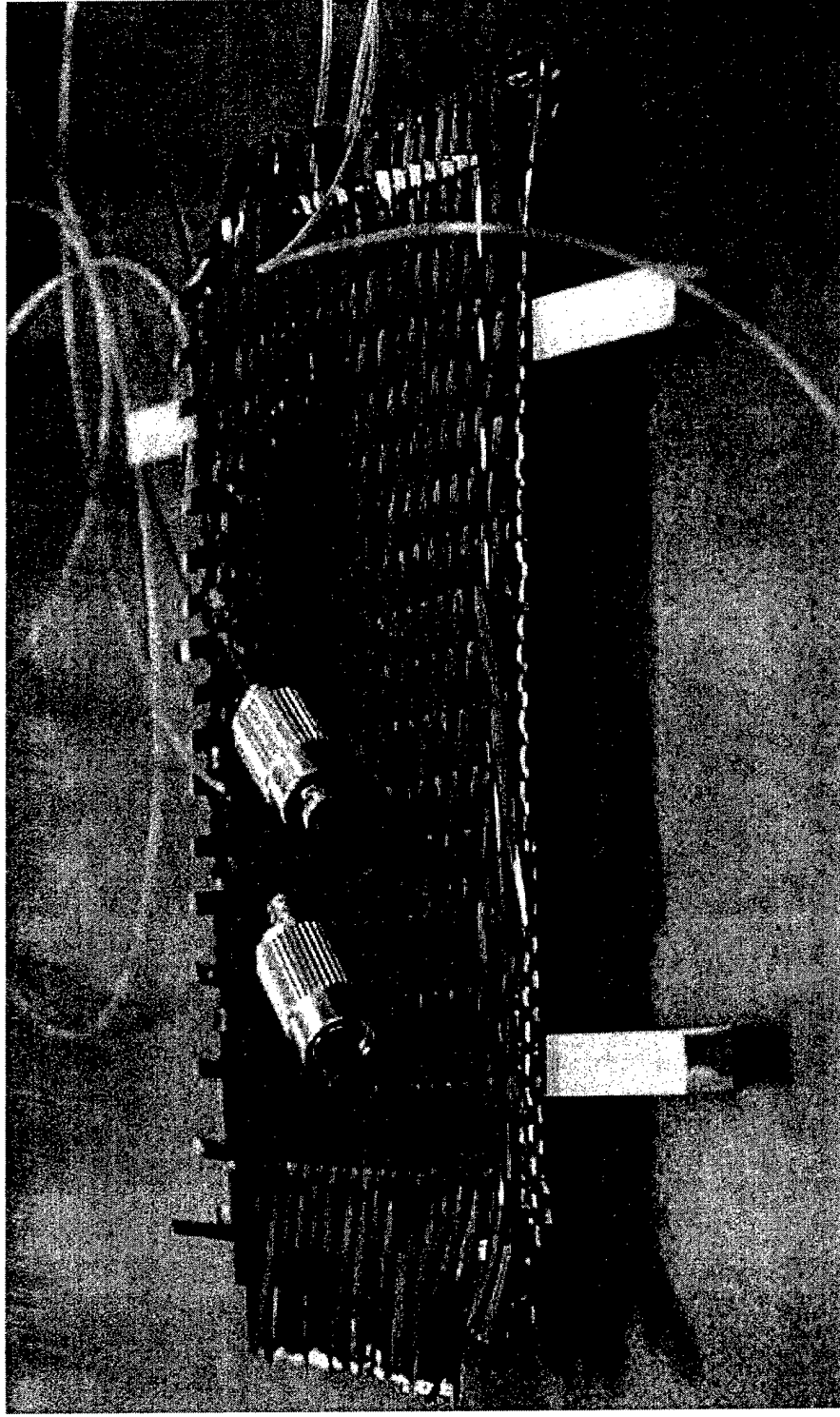
- A biaxial weave structure was used to support the fabrication of a small composite coupon for testing
- Multi-axis fiber gratings were placed in the four-layer coupon between the first and second layers and between the second and third layer



# Placement of Sensor

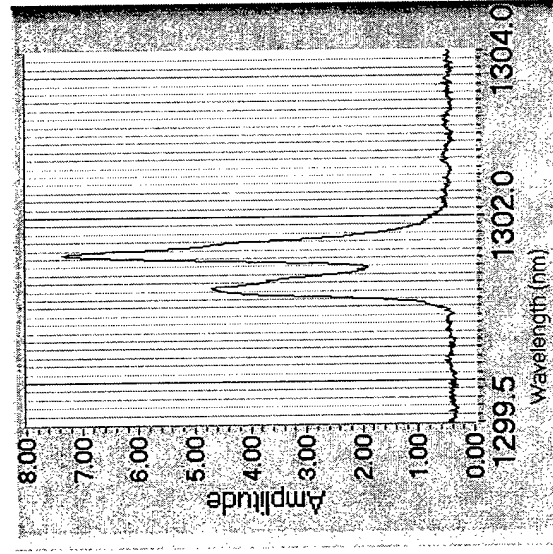


# Finished Composite Test Specimen

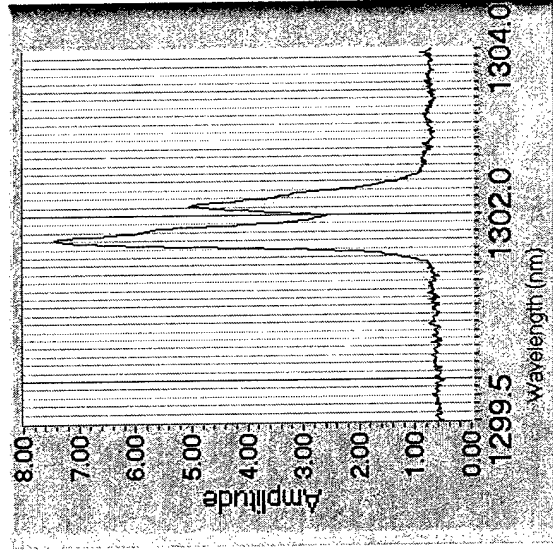


# Monitoring Sensor #2 During the Cure Cycle: Increasing Temperature to Peak Temperature

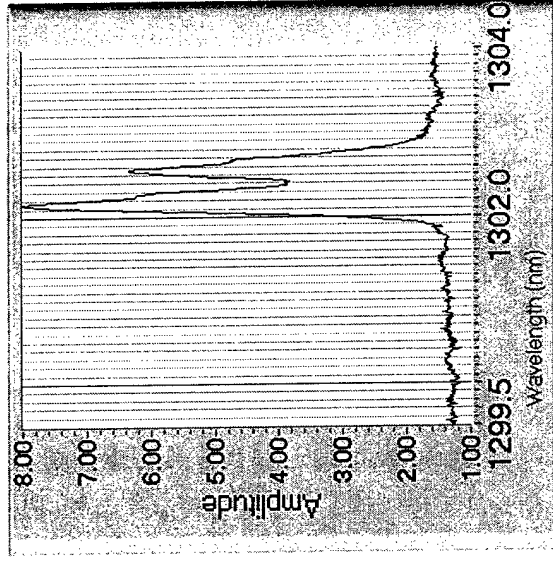
---



0 min.



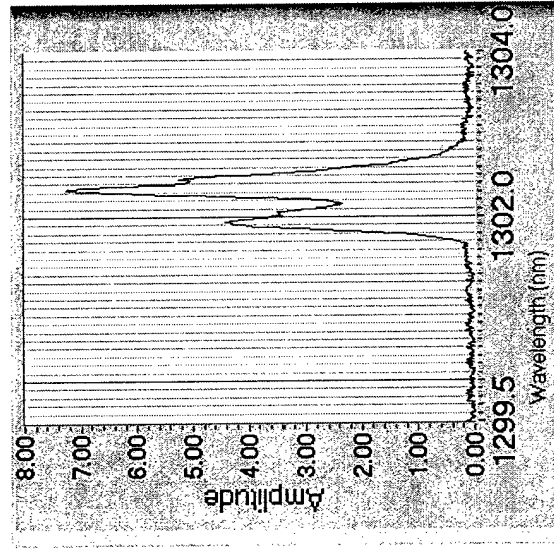
44 min.



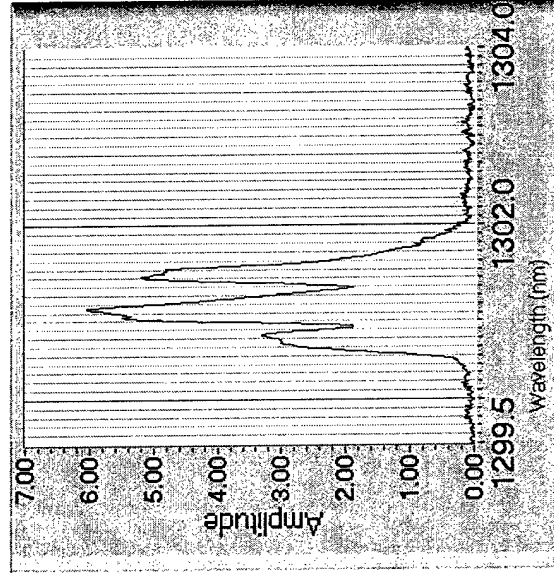
95 min.

# Monitoring Sensor #2 During the Cure Cycle: After Cross Linking/Cure and Cool Down

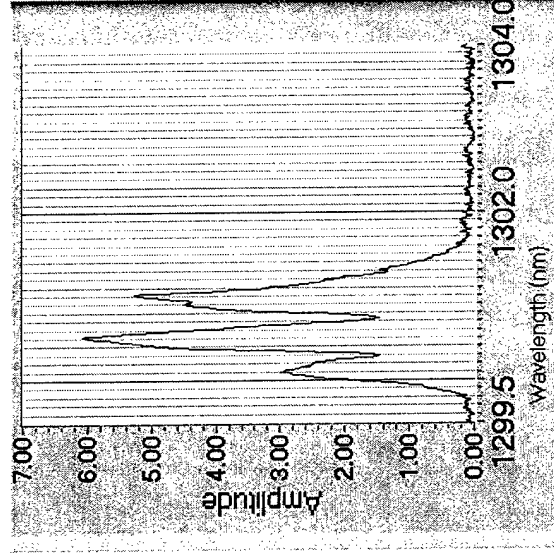
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115 min.



160 min.



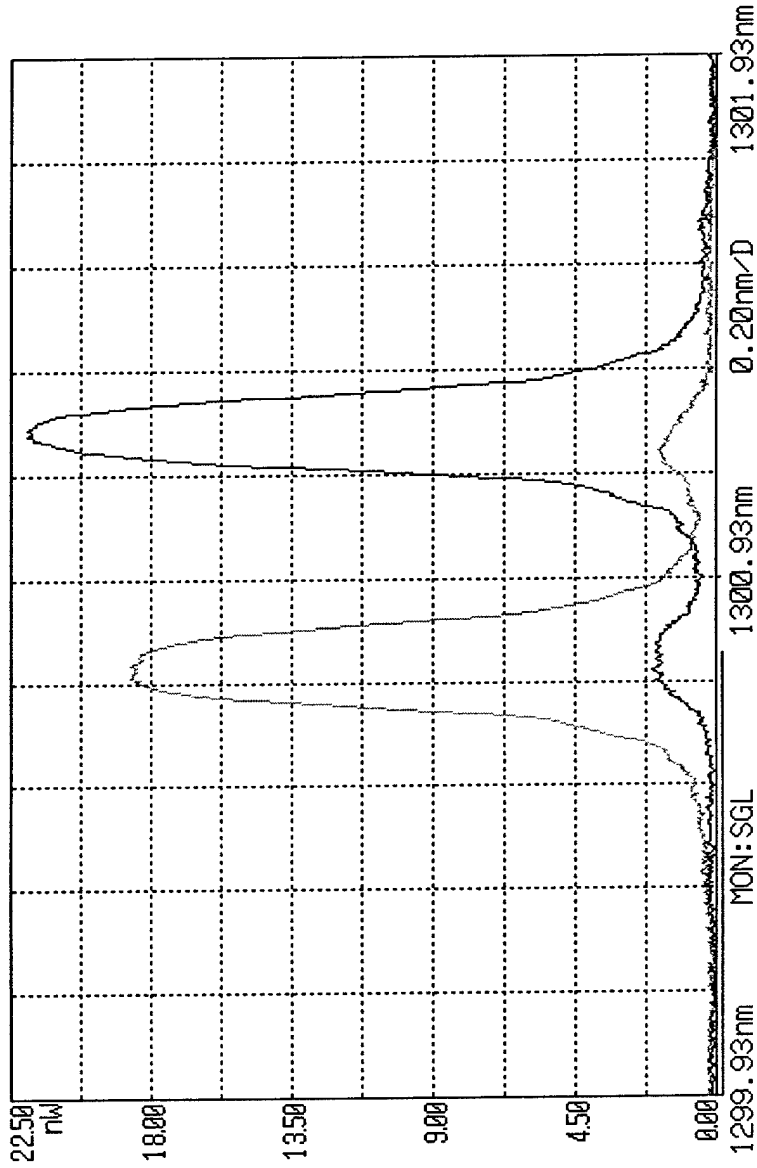
200 min.

# Polarization Extinction

2001 Aug 22 14:41

A:WRITE /DSP  
B:FIX /BLK  
C:FIX /DSE

V V1 V2 V2/V1  
2.25nm/D RES:0.05nm SENS:NORM HLD AUG: 1 SMPL: 501



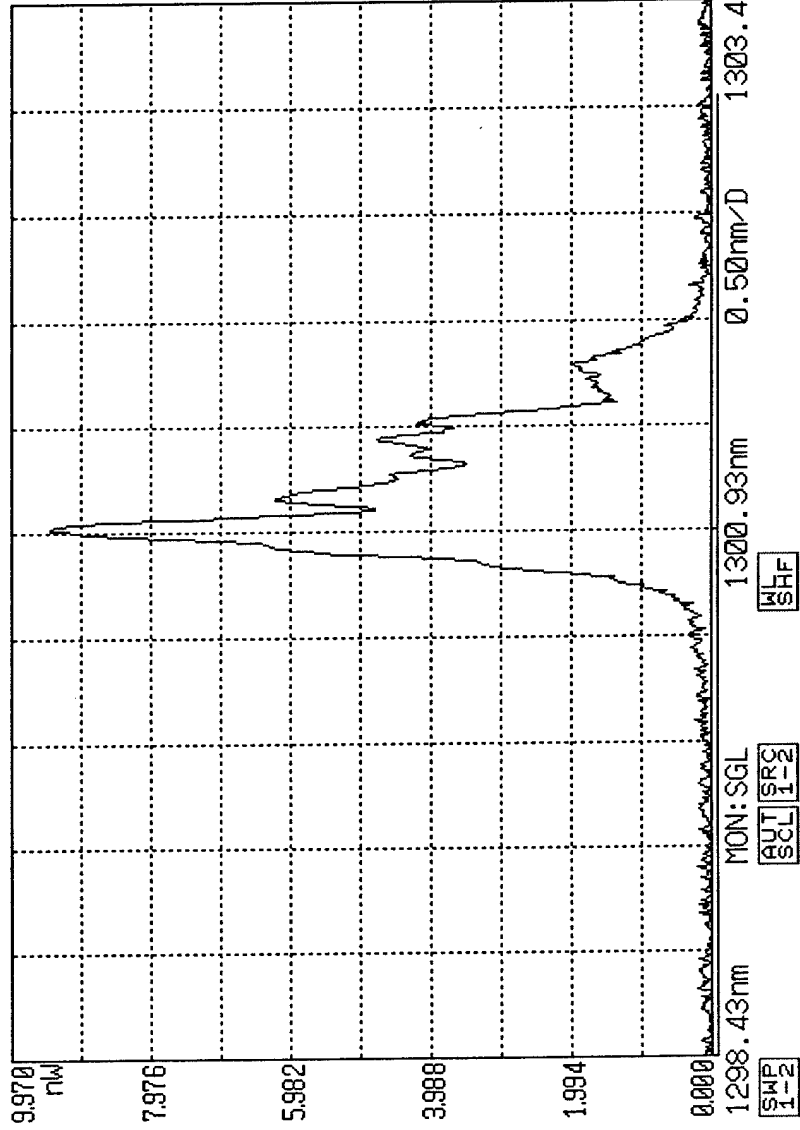
BLUE ROAD  
RESEARCH

# Sensor #1: Shorter Wavelength

2001 Aug 22 09:32

A:WRITE /DSP  
B:FIX /BLK  
**CHK** /BLK

V1 V2 V2/V1  
0.997nm/D RES:0.05nm SENS:NORM HLD AUG: 1 SMPL: 501



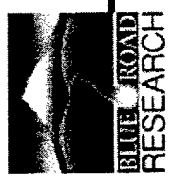
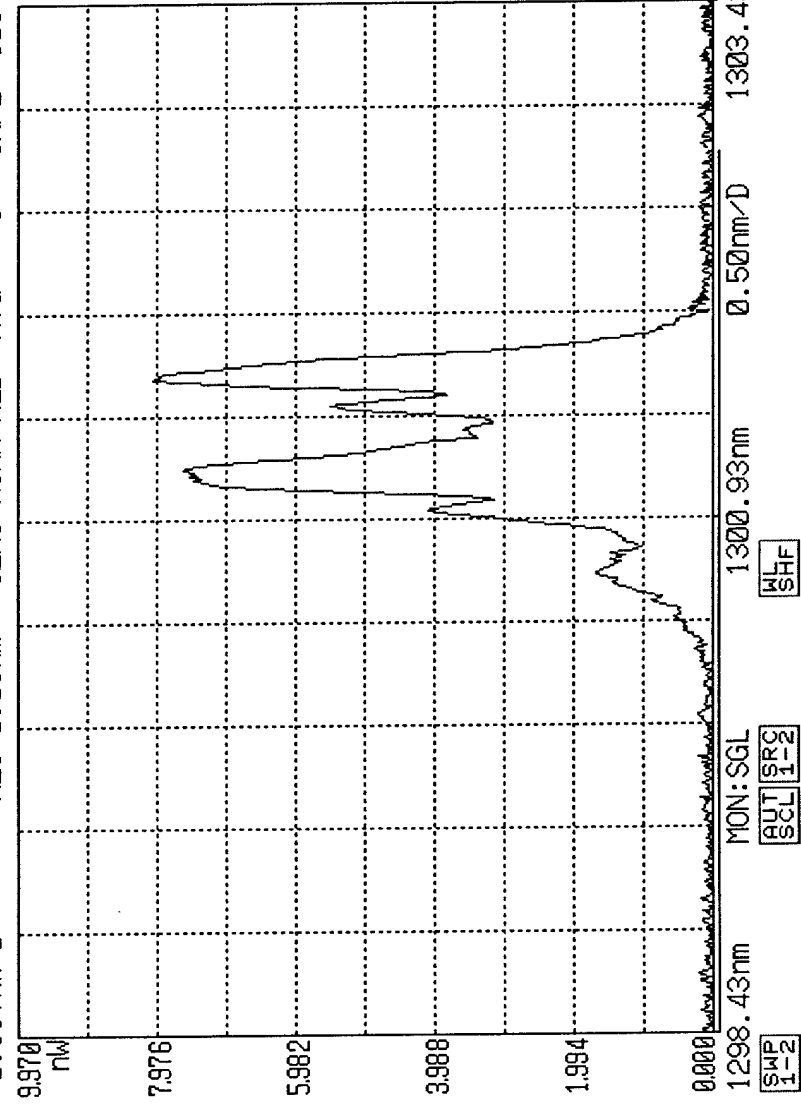
BLUE ROAD  
RESEARCH

# Sensor #1: Longer Wavelength

2001 Aug 22 09:39

A:WRITE /DSP  
B:FIX /BLK  
**C:FIX /BLK**

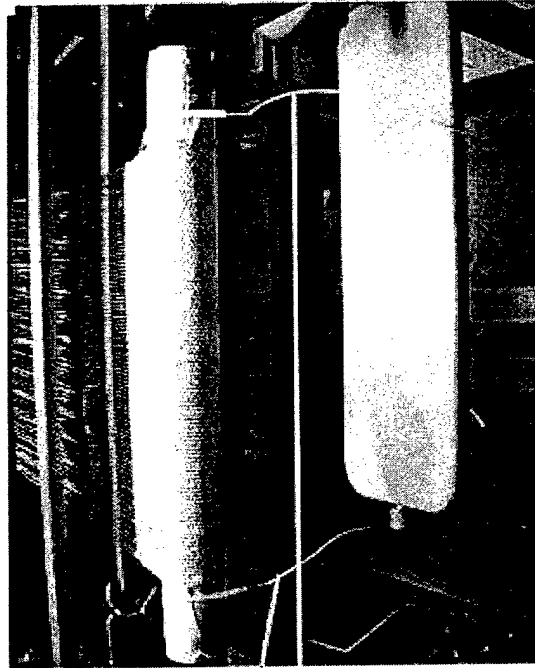
V1 V2 V2/V1  
0.997nm/D RES:0.05nm SENS:NORM HLD AUG: 1 SMPL: 501



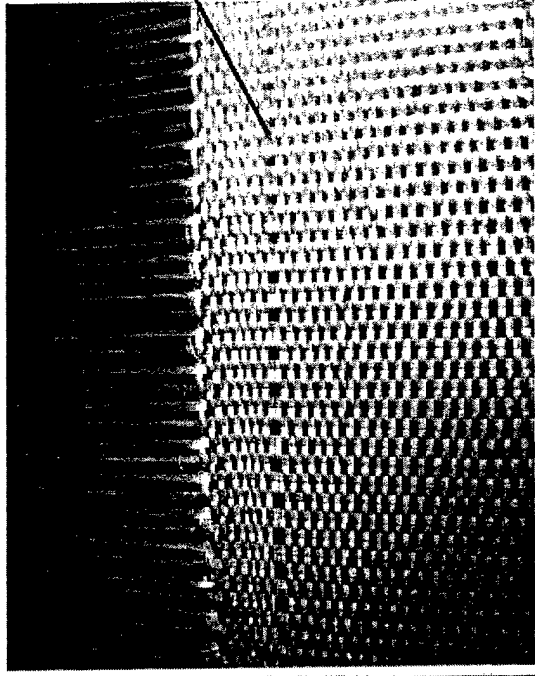
BLUE ROAD  
RESEARCH

# Fabrication of Smart Fabrics

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Connector-  
cables



Fiber Optics

# Single and Dual Axis Grating Sensors in E-glass/ Vinylester and E-glass/ Epoxy Composites

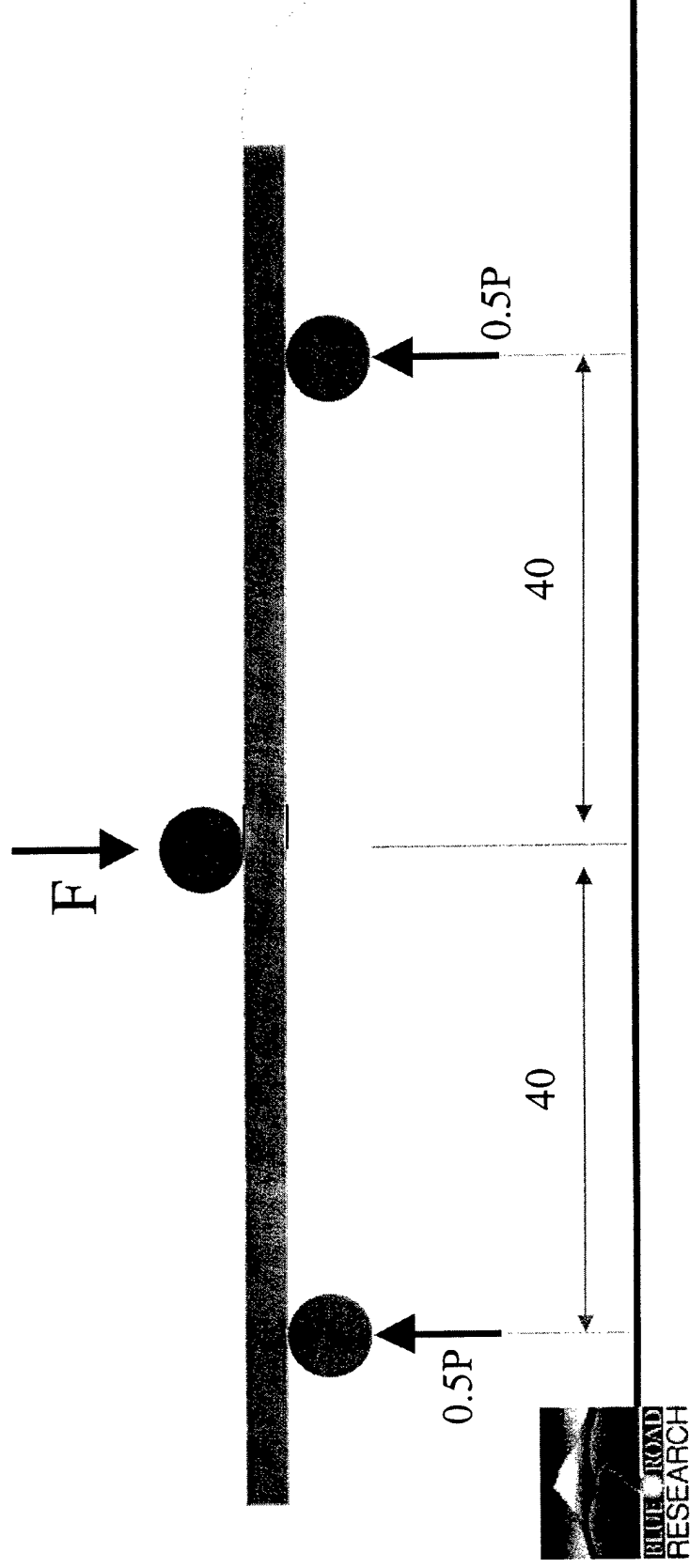
---

- Several panels were manufactured with single and multi-axis Bragg gratings using the Vacuum-Assisted Resin Transfer Molding (VARTM) process
- The response of the sensors in different stages of the VARTM process was recorded

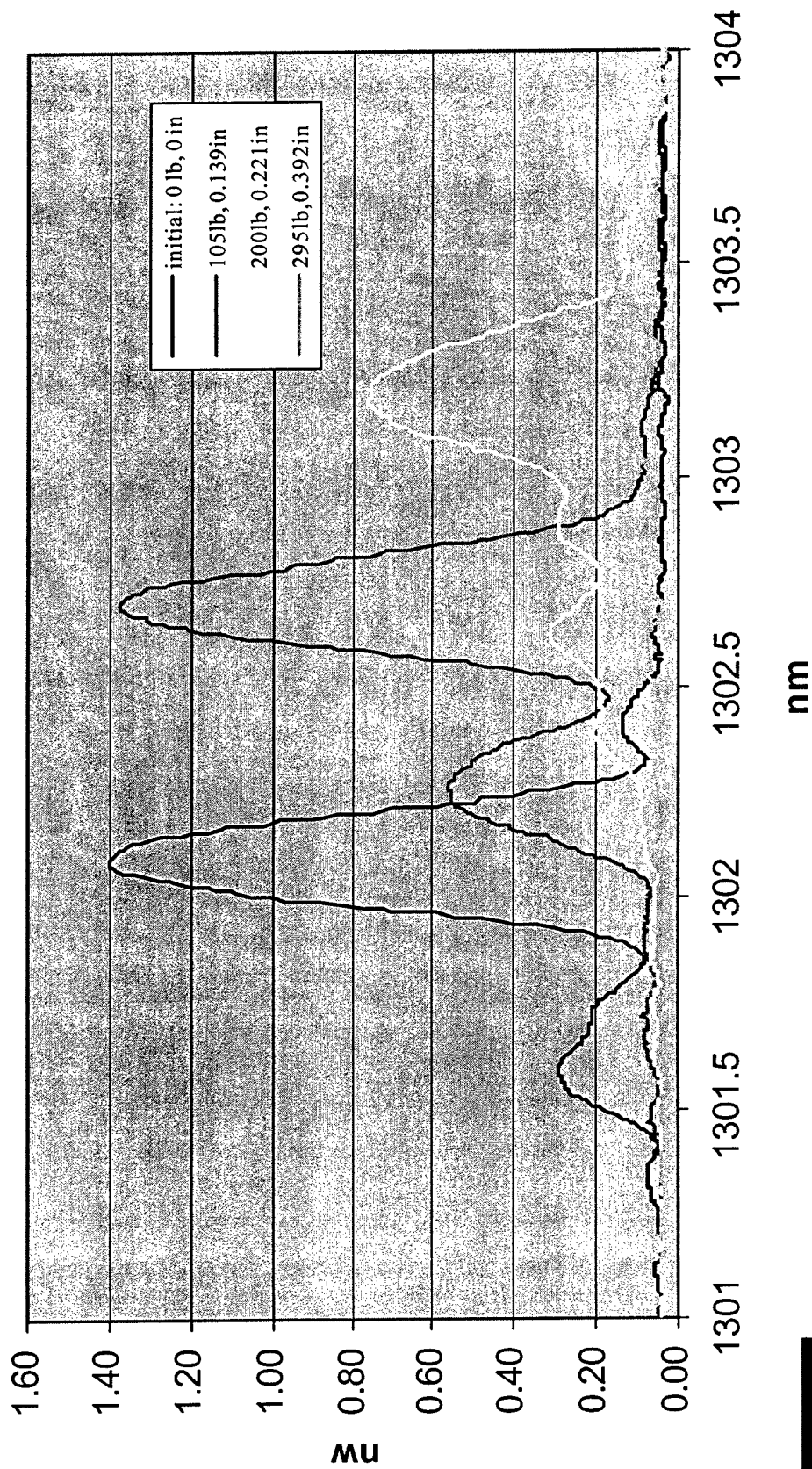
## Mechanical Test Setup – Three Point Bend Test

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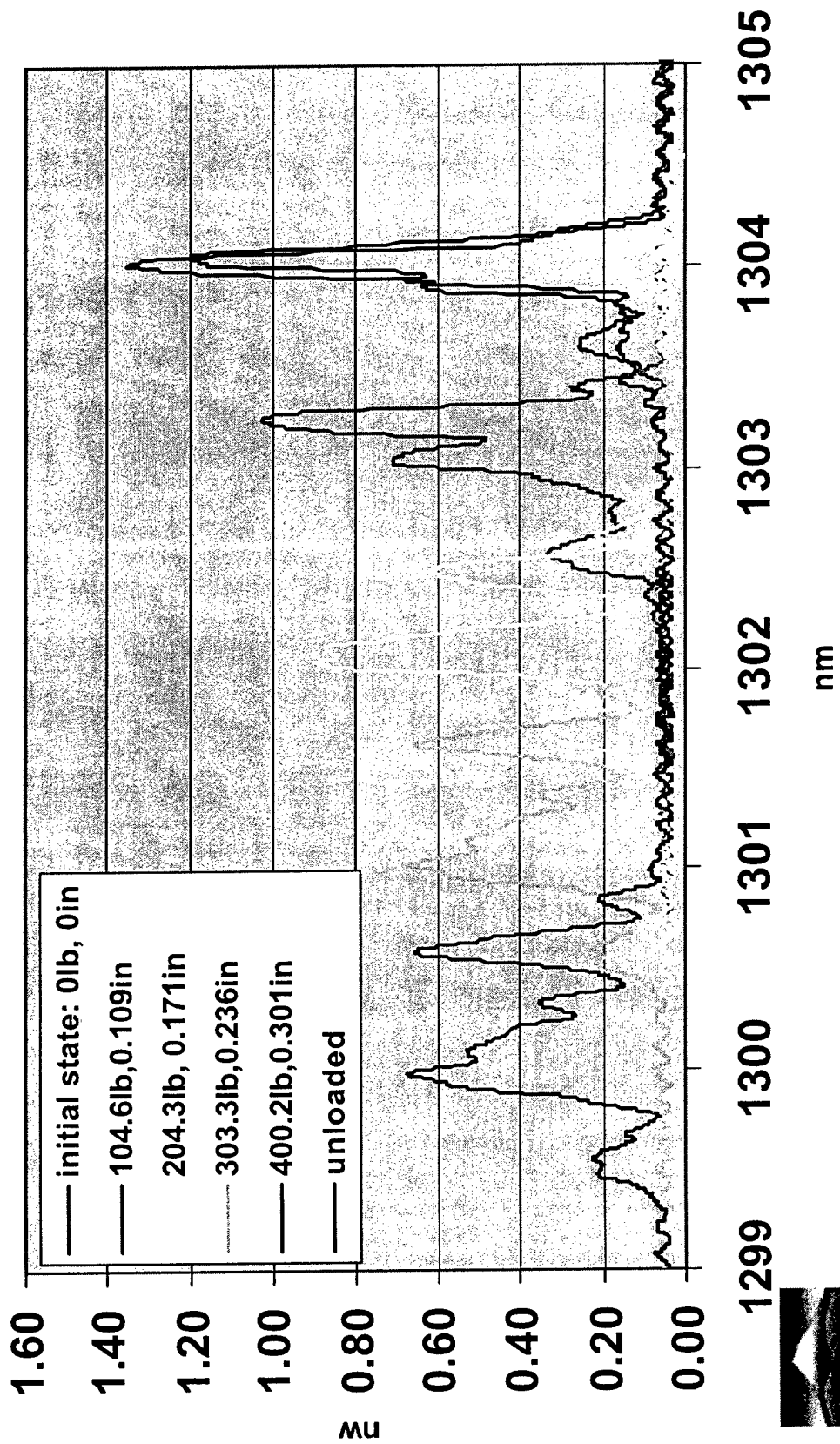
- The specimens containing dual axis sensors were loaded by three point bending.
- The grating portion of the dual axis grating sensor was put beneath the load head.



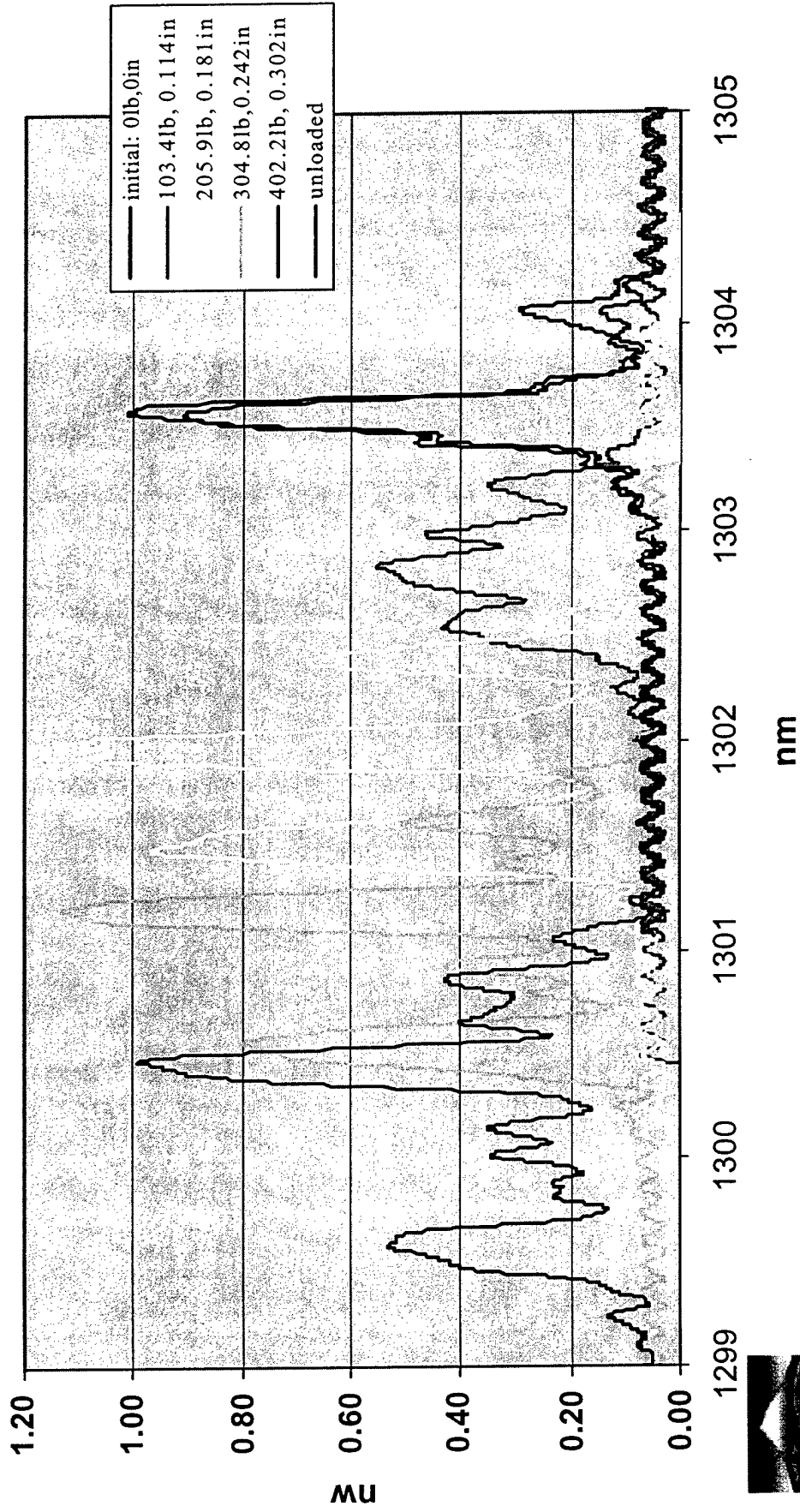
# Dual Axis FBG Sensor in E-glass/vinylester Composites Strained in Tension, Right Peak



# Dual axis Grating Sensor in E-glass/epoxy Composites Strained in Compression, Right Peak



# Dual Axis FBG Sensor in Glass/epoxy Composites Strained in Compression, Left Peak

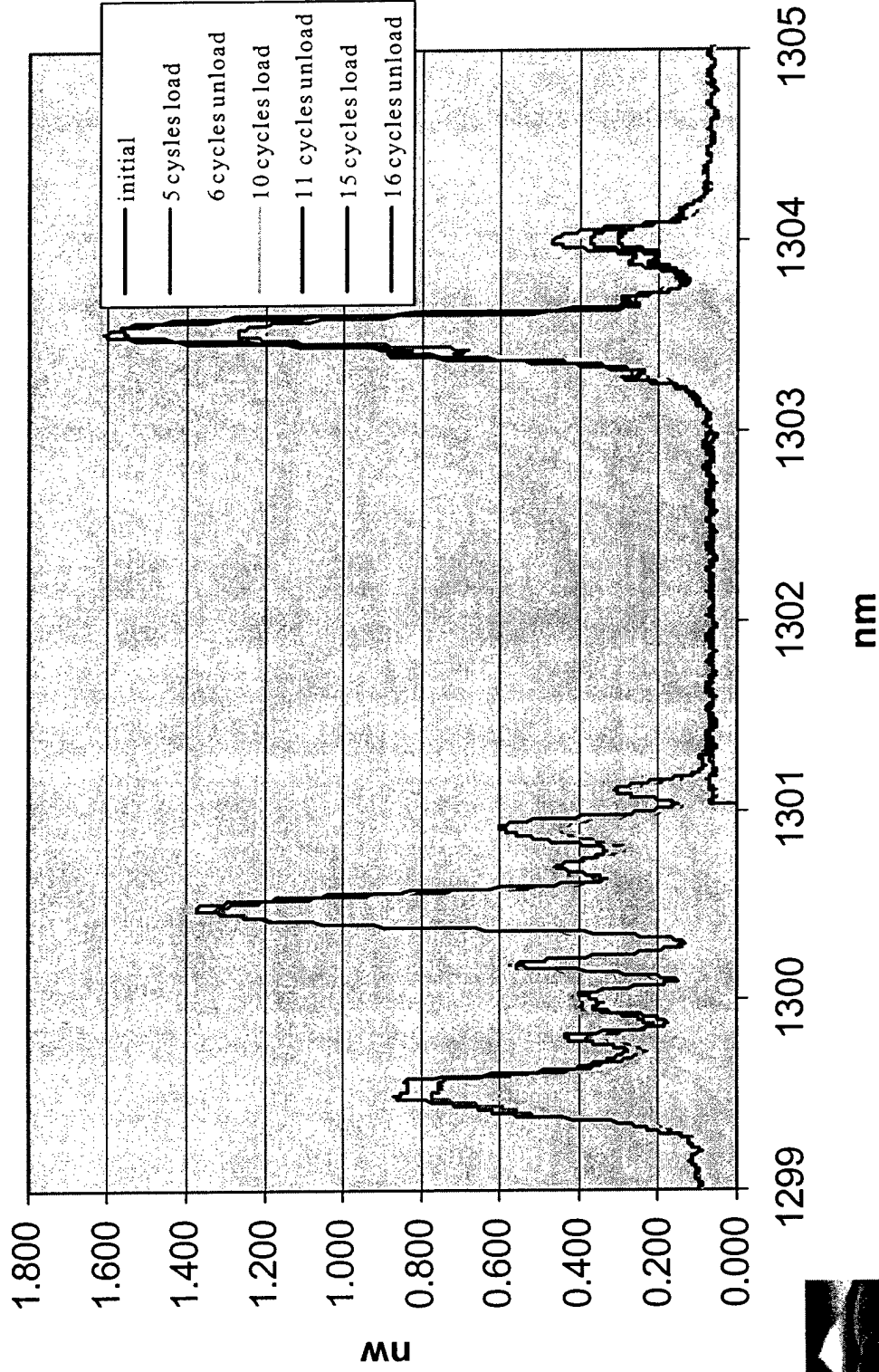


## Repeatability and Drop Test

---

- Repeatability of the dual axis FBG sensor embedded in textile composites was evaluated using a loading-unloading cycle test.
- The results demonstrated that the signal from the dual axis FBG sensor is repeatable.
- A drop weight impact test was performed, only a small permanent deformation (strain) was formed by the impact

# Dual axis FBG sensor in glass/epoxy composites under cyclic compressive loading-unloading (0lb-400lb), left peak

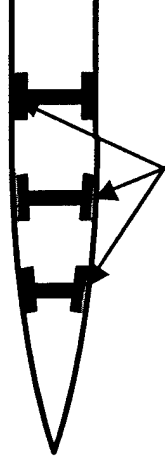
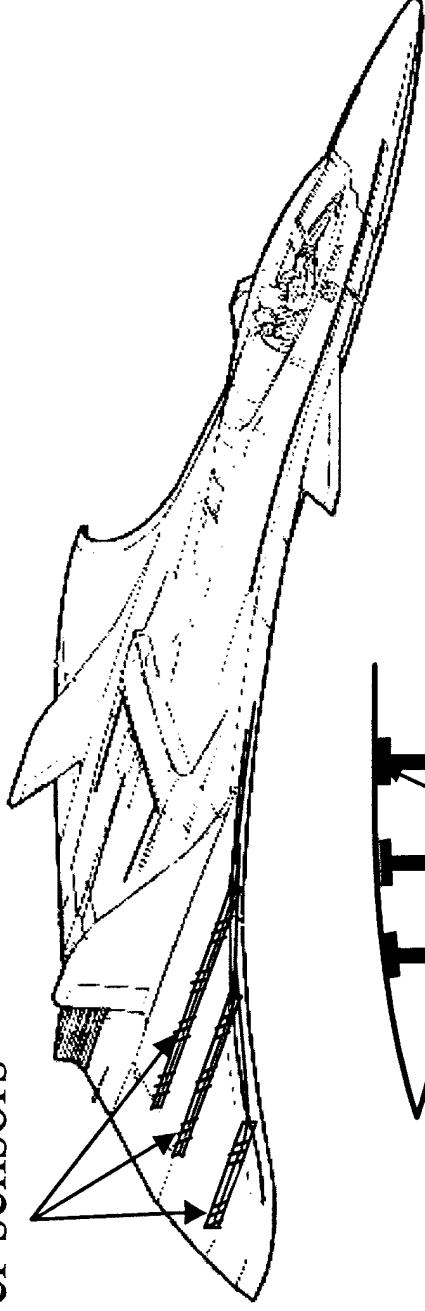


# Bonded Joint Health Monitoring System

---

Distributed

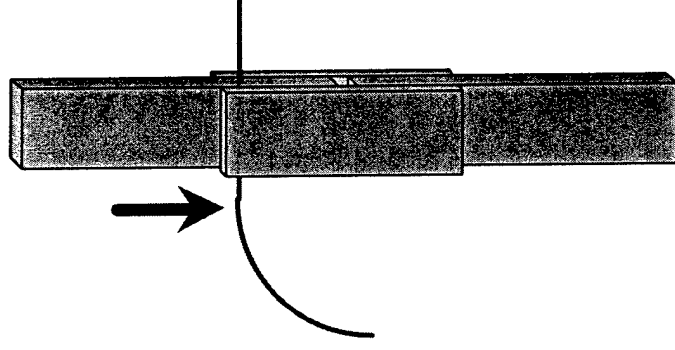
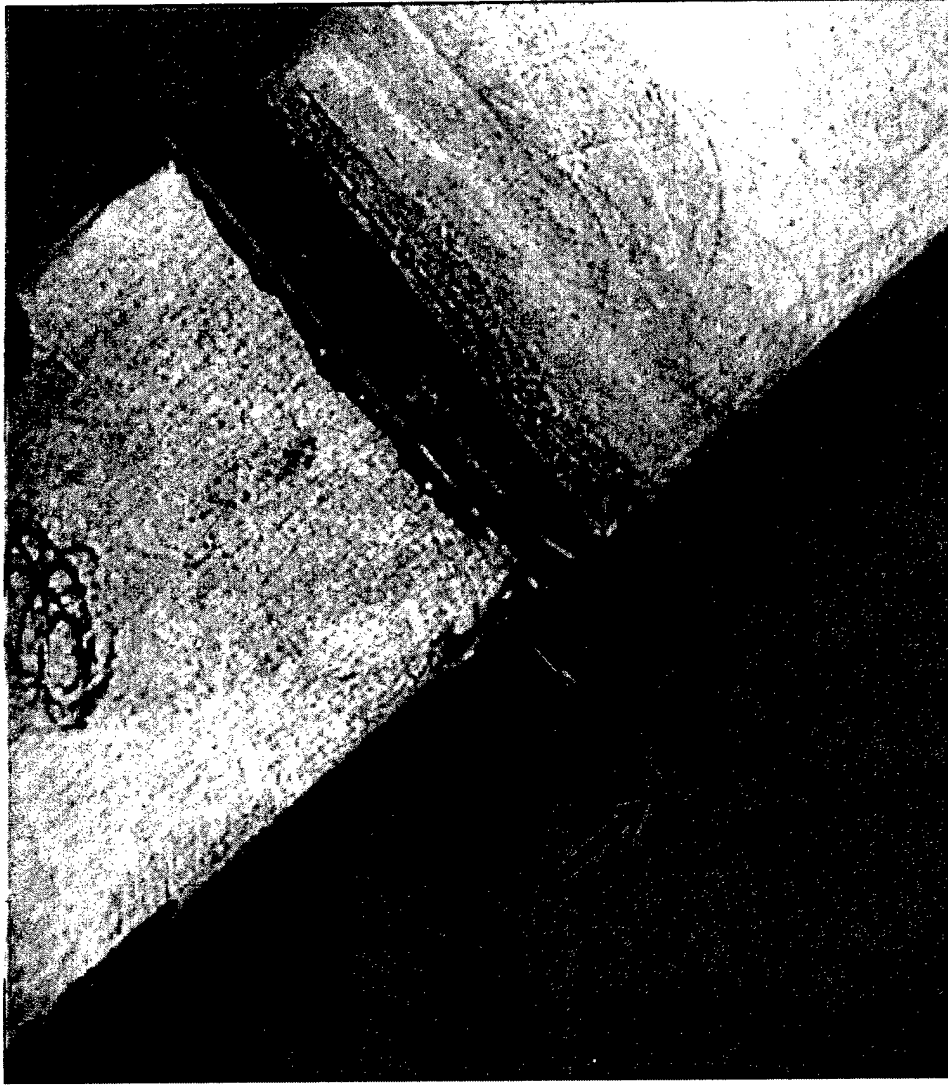
Fiber sensors



Bonded joints

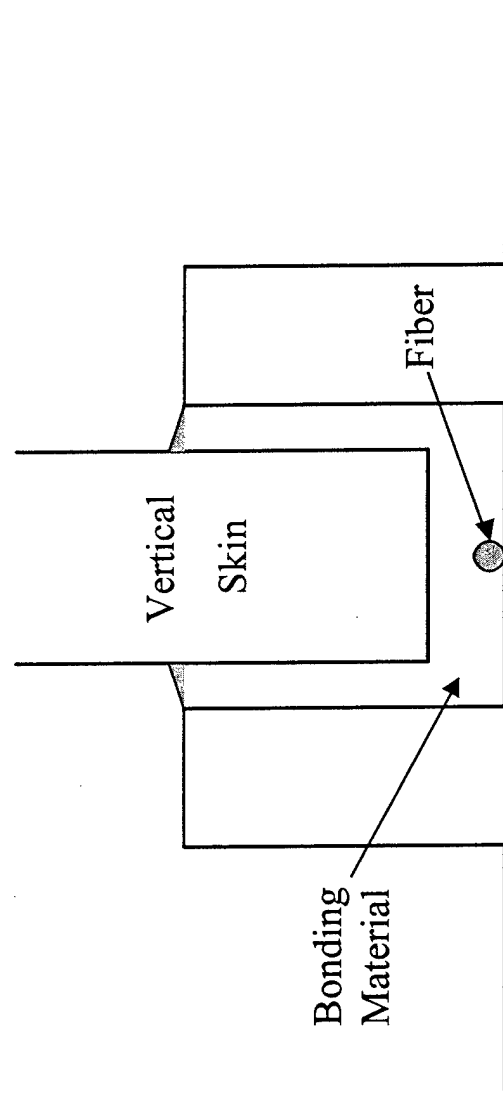
# Joint Instrumented for Shear

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# Pi-Channel Multi-Axis Strain Monitoring

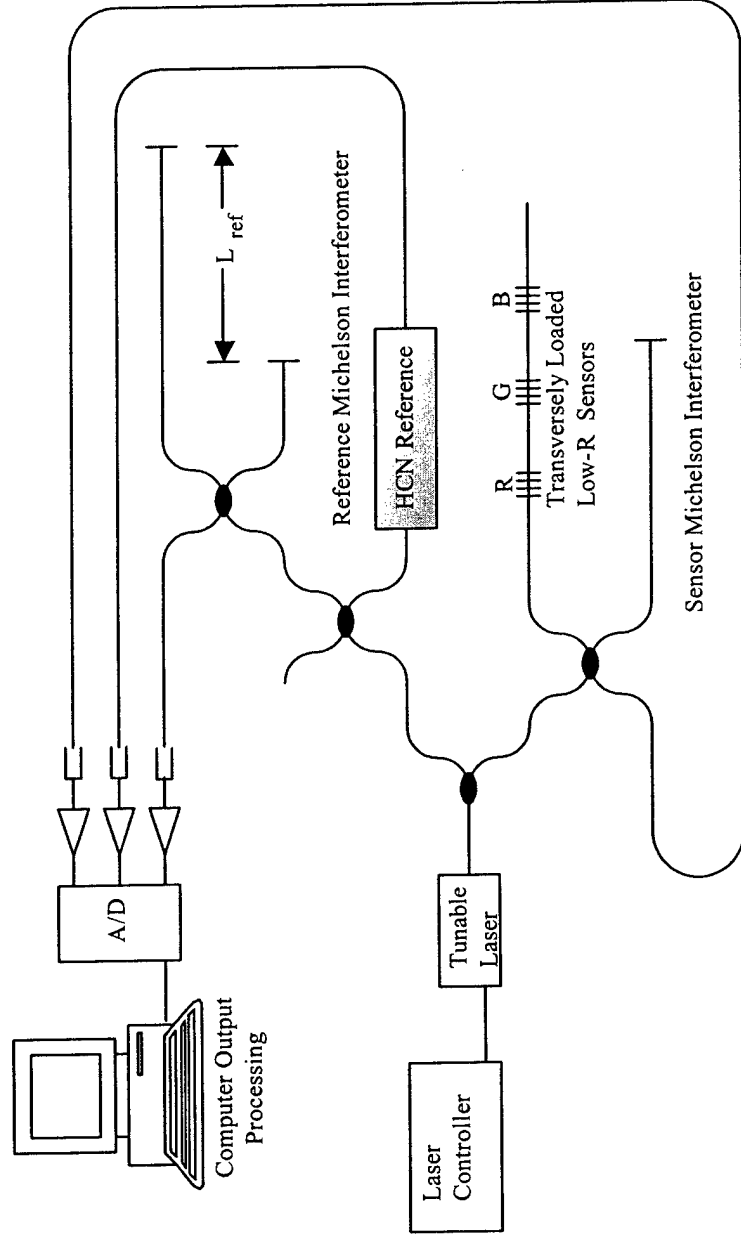
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Bottom Skin Pi-Channel

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# High Density Fiber Grating Strain Sensor System



# Composite Structures Summary

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- Simultaneous measurement of axial and transverse strains
- Measurement of sub-grating strain distributions for “simple” conditions in weave structures
- Useful for structural monitoring during part formation and subsequent loading

# Composite Structures Systems Development

---

- Demonstrate static ground testing.
- Compare baseline loaded and unloaded strain signatures with current readings to detect structural damage.
- Evolve monitoring equipment to dynamic, low-power, rugged, compact system for in-flight monitoring.

# Ongoing Improvements in System Capability

---

- Develop theory and modeling tools to better link multi-axis strain measurements to structural behavior.
- Use WDM and interferometric techniques to multiplex hundreds of sensors on single line.
- Develop algorithms to translate complicated multiple peak structures into highly spatially resolved multi-axis strain measurement.



# **FAST SELF COOLING MECHANISMS**

Roger J. Morgan and Sai Lau

Texas A&M University

**AFOSR WORKSHOP ON  
MULTIFUNCTIONAL AEROSPACE  
MATERIALS**

24<sup>th</sup> OCTOBER 2002

# THEME

- “OUT OF THE BOX”
  - SURFACE COOLING CONCEPTS
  - THERMAL ABLATION RESISTANT STRUCTURES
  
- GOALS
  - RAPID TEMPERATURE - TIME COOLING
    - LIMIT IR-TIME SIGNATURES
  
  - ENHANCED THERMAL RESISTANT STRUCTURES-  
PROCESSIBLE COATINGS AND STRUCTURES

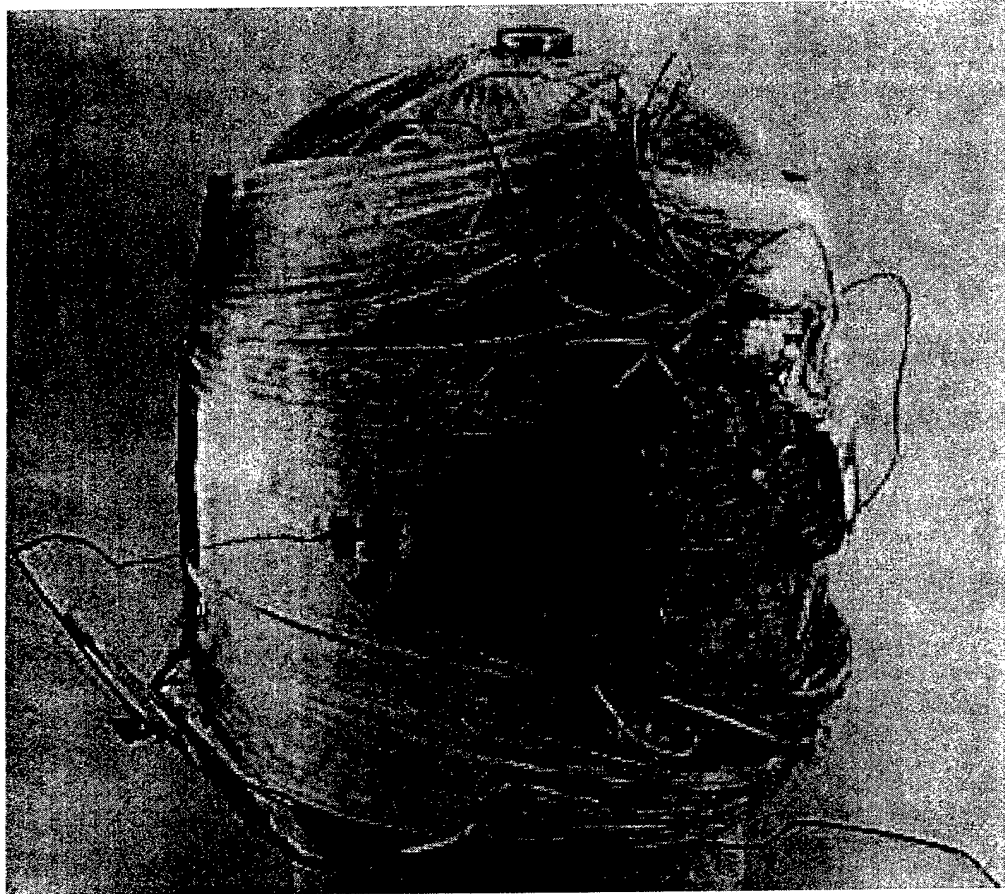
# **SUBJECT MATTER**

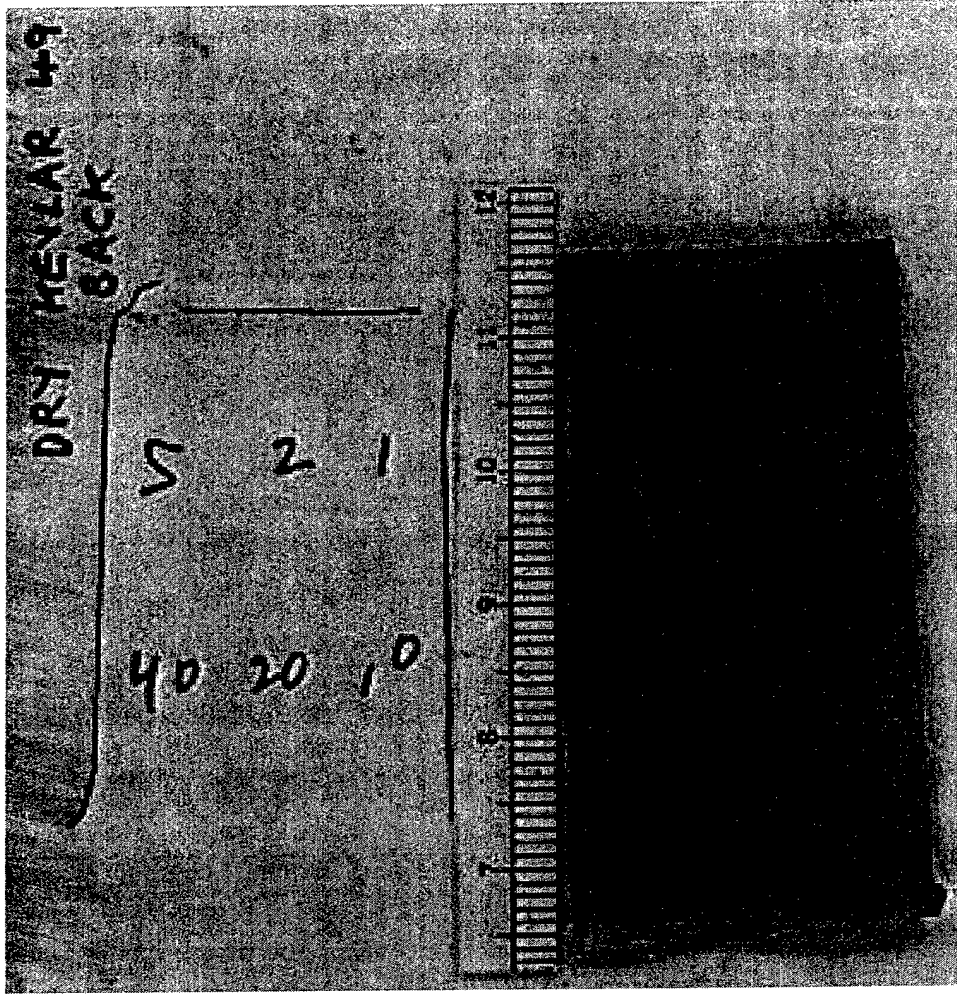
- HISTORY
  - LASER HARDENING MECHANISMS
    - HIGH MOISTURE BEARING FIBERS (FIBER -S)
    - TUNGSTEN CARBIDE, TANTALUM CARBIDE IN-SITU SERVICE ENVIRONMENT FORMATION
- SURFACE MOISTURE EVAPORATION
  - SKIN COOLING MECHANISM
  - MICROFLUIDICS
- THERMAL CONDUCTION - INTERNAL COOLING “PIPES”
- RAPID SUPER - THERMAL CONDUCTORS
- COATING SELF COOLING MECHANISMS (IN-SITU REPLENISHMENT)

Table 1  
Aromatic Polyamides That Were Developed  
for Commercial Fiber Production

| Chemical Name<br>(abbreviation)   | Chemical Structure | Trade Name<br>(company)                     |
|---|--------------------|---|
| poly( <i>m</i> -phenyleneisophthalamide)<br>(PmPI)  |                    | Nomex™(du Pont);<br>Conex™(Teijin)          |
| polybenzamide<br>(PBA)  |                    | PRD 49-1™*<br>(Du Pont)                     |
| poly( <i>p</i> -phenylene terephthalamide)<br>(PPTA)  |                    | Kevlar™(du Pont);<br>Twaron™<br>(Akzo N.V.) |
| polyterephthaloyl- <i>p</i> -aminobenzhydrazide<br>(PABH-T)   |                    | X-500™*<br>(Monsanto)                       |
| copolyterephthalamide of<br><i>p</i> -phenylenediamine and<br>3,4' diamino-diphenyl ether<br>(CPTA) |                    | HM-50™, Technora™<br>(Teijin)               |
| polyamidobenzimidazole<br>(PABI)  |                    | FVK™<br>(USSR)                              |

\*No longer commercially produced.





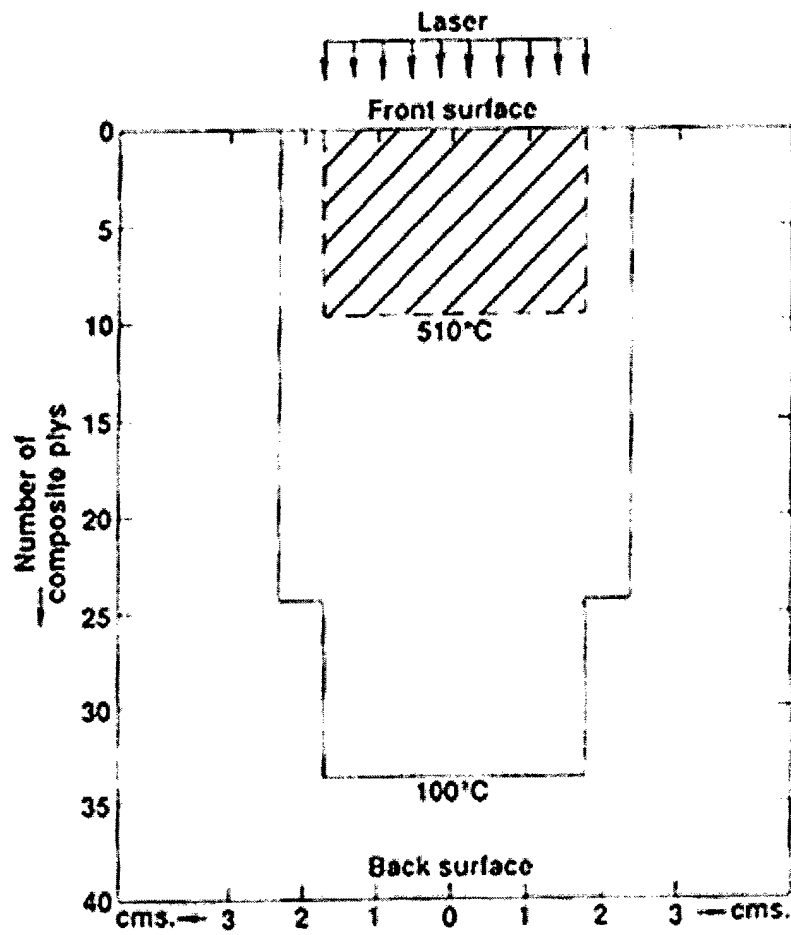
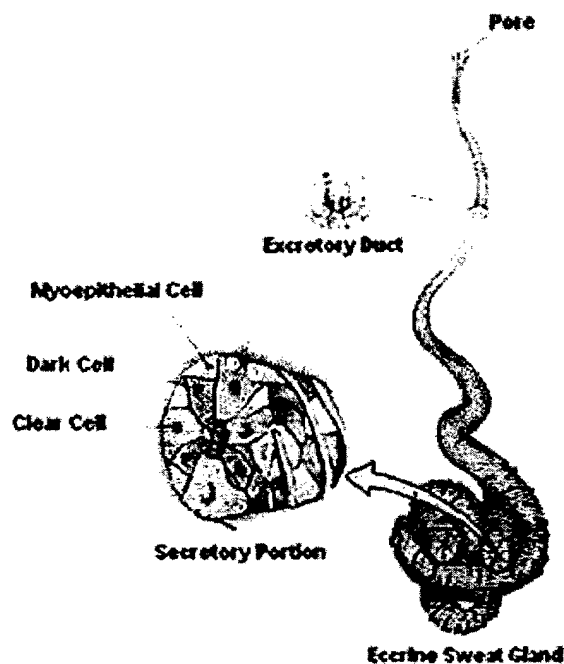


Figure 11. The 100°C and 510°C two-dimensional temperature contours in a 40 ply carbon fiber-epoxy composite after 10 s exposure to a 600 W/cm<sup>2</sup>, 3.5 beam diameter laser

# THE MECHANISM OF ECCRINE SWEAT EXPULSION

**Eccrine sweat glands** are simple coiled tubular glands located in the deep dermis or underlying hypodermis and are present throughout the body. Their primary function is evaporative cooling.



1. They develop as invaginations of the epithelium of the dermal ridge. They grow into the dermis with its deep aspect becoming the glandular portion of the sweat gland.
2. Eccrine sweat glands are simple coils of cuboidal epithelium containing two kinds of cells.
  - A. **Dark cells** produce sialo mucins.
  - B. **Clear cells** produce water and electrolytes.
3. The final production is hypotonic (99% water)
4. Adults produce between 0.5-10 liters/day.

# CONDUCTIVITY MODEL

## *ASSUMPTIONS:*

- The outer surface is heated instantaneously to 100 °C before cooling begins
- Inner surface temperature is maintained at 25 °C
- There is no cooling to atmosphere
- Water flow is semi-turbulent

## *GOVERNING EQUATION:*

(HEAT ADDED -HEAT CONDUCTED ACROSS THE MATERIAL)  
PER cm<sup>2</sup> PER s =

(HEAT INCREASE IN THE MATERIAL PER cm<sup>2</sup> PER s)

# EVAPORATION MODEL

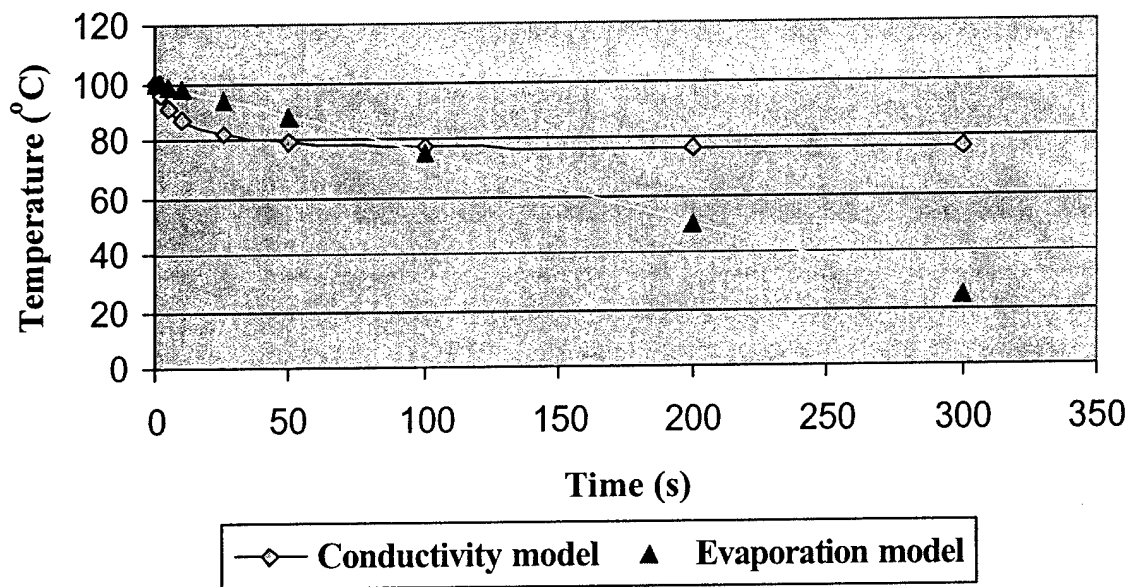
## *ASSUMPTIONS:*

- ? Pore openings cover 50% of surface area
- ? 0.2 kg. Of water evaporates per second per square cm. of surface area
- ? Material and water properties are considered at conditions prevailing at an altitude of approximately 60,000 ft.

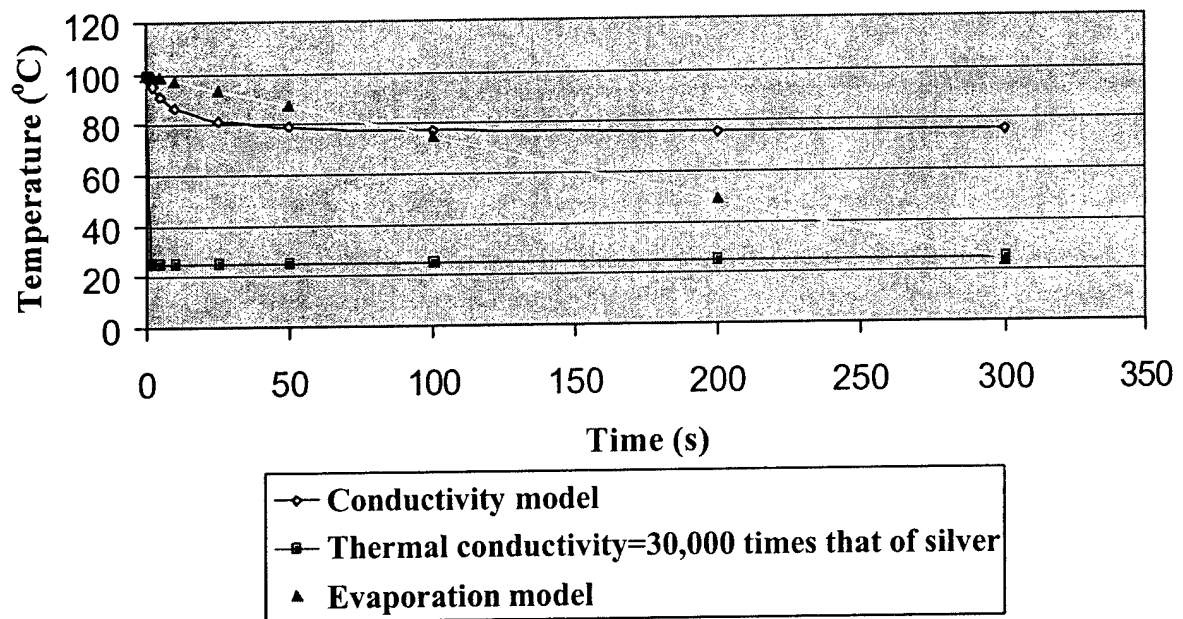
## *GOVERNING EQUATION:*

(HEAT ADDED - HEAT TAKEN AWAY BY EVAPORATION) PER  
cm<sup>2</sup> PER s =  
(HEAT INCREASE IN THE MATERIAL PER cm<sup>2</sup> PER s)

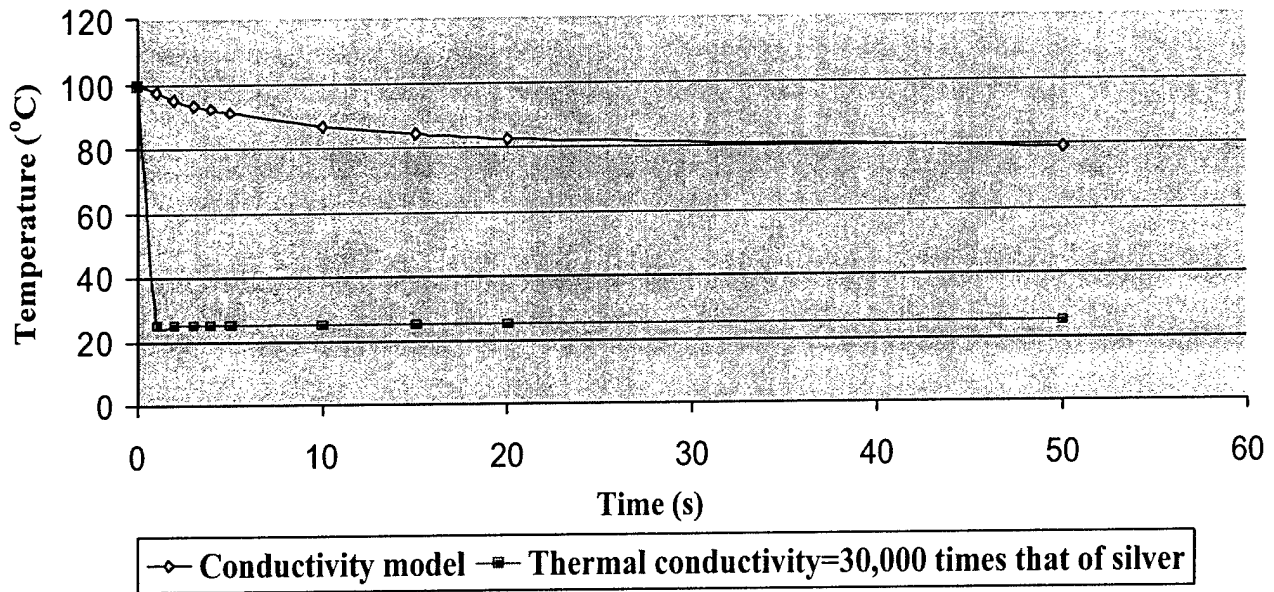
### Temperature vs Time



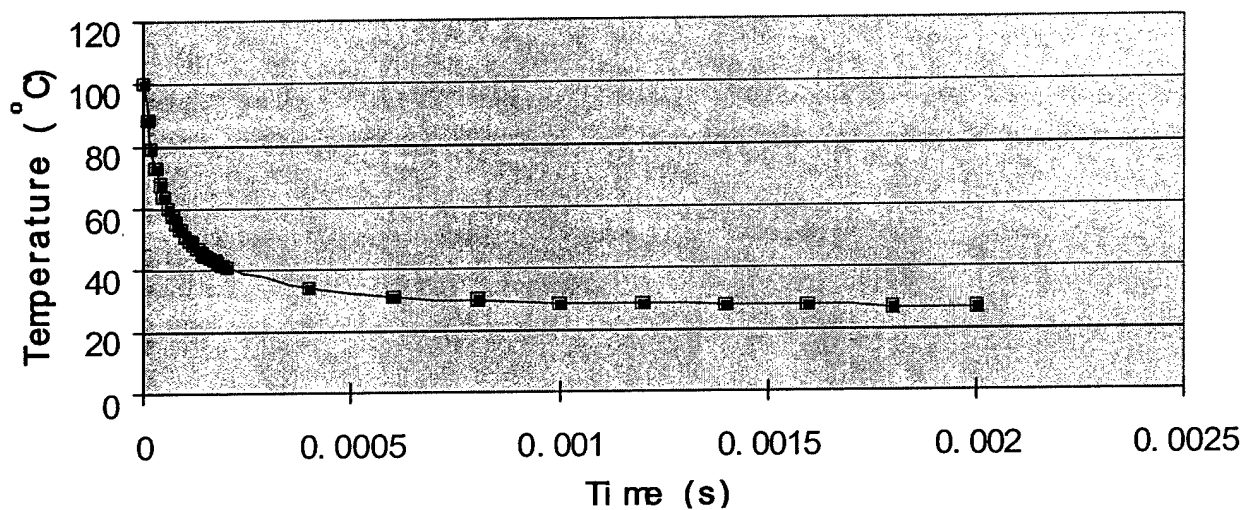
## Temperature vs Time for different methods of cooling



### Temperature vs Time



Temperature vs Time



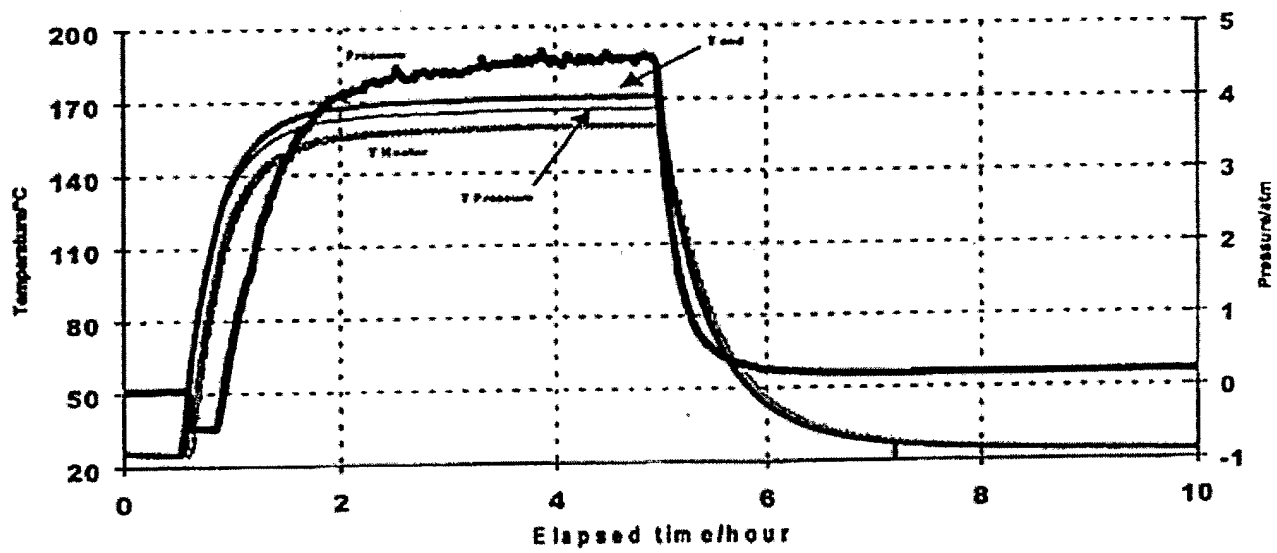
—■— Thermal conductivity=30,000 times that of silver

# **SUPER THERMAL CONDUCTOR**

- COPPER SEALED TUBE - 5  
MM D
- AIR 0.5 ATMOSPHERE
- 3 COATINGS - 0.1 MM  
THICK
  - OXIDES
  - CHROMATES
- UP TO  $3 \times 10$  THERMAL  
CONDUCTIVITY OF SILVER



Supertube with pressure transducer attached.



Pressure and temperature inside an operating Supertube.

# Graphitic Foam as Heat Carrier For Thermal Control in Phase Change Materials (PCM) Composite Systems

Khalid Lafdi

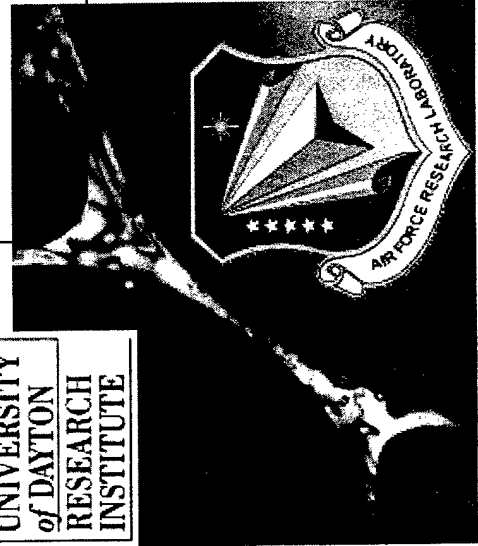
University of Dayton Research Institute  
300 College Park, Dayton OH. 45469-0168 USA

Materials & Manufacturing Directorate,  
AFRL/MLBC, WPAFB, OH 45433 USA

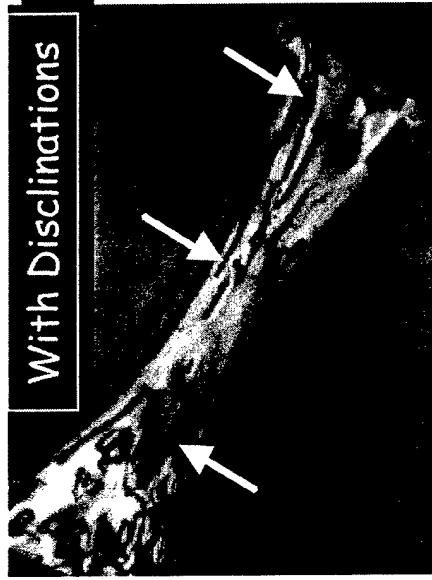
Khalid.lafdi@wpafb.af.mil

ITAR restricted

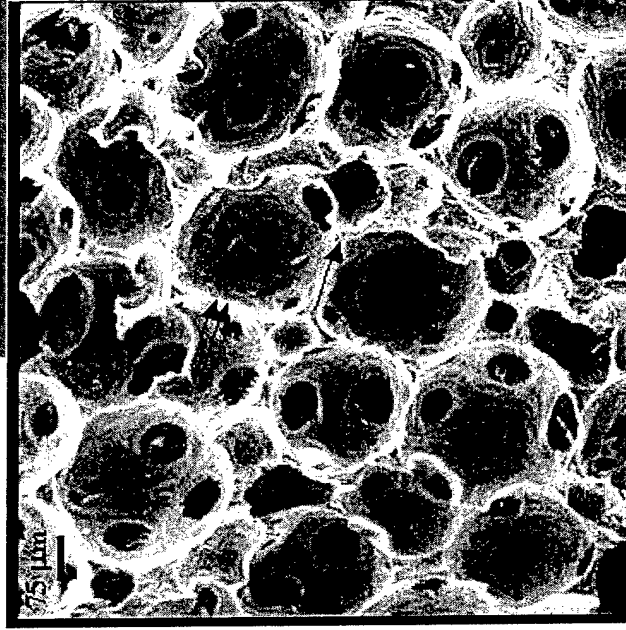
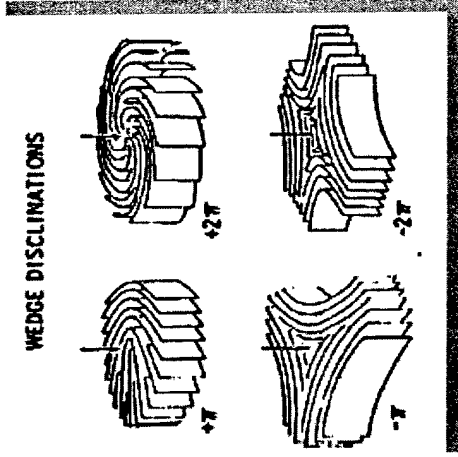
**UDRI**  
UNIVERSITY  
of DAYTON  
RESEARCH  
INSTITUTE



# Microscopy Characterization of Graphitic Foam

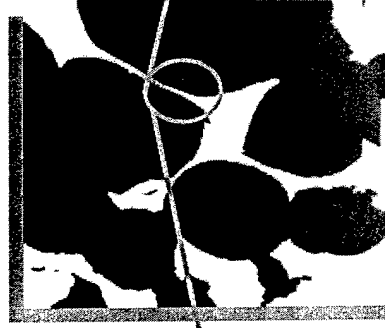


Ligaments

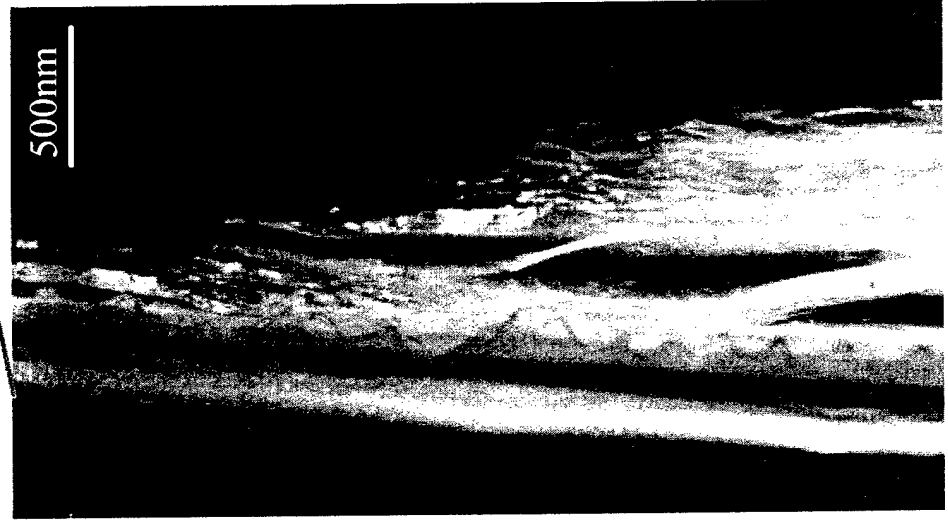


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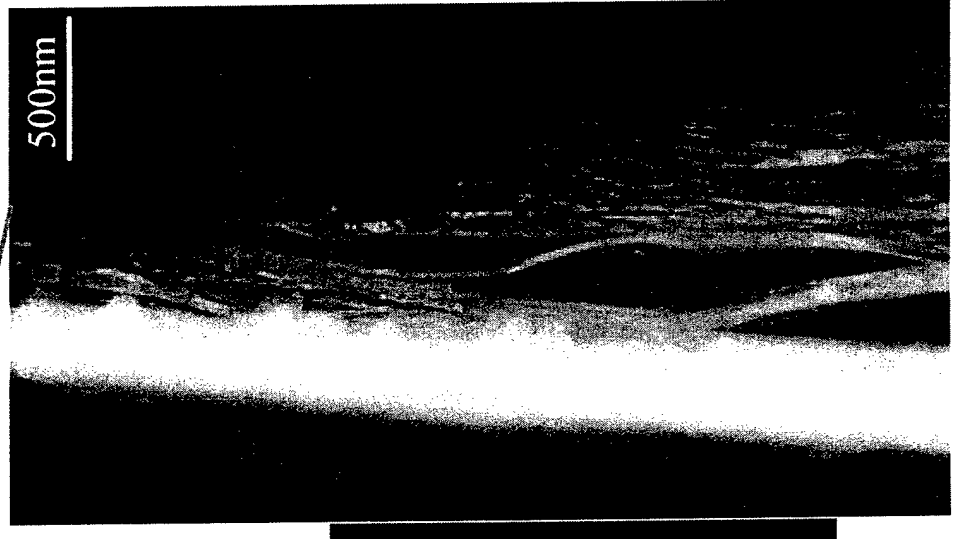
# TEM Characterization of Graphitic Foam



Dark Field

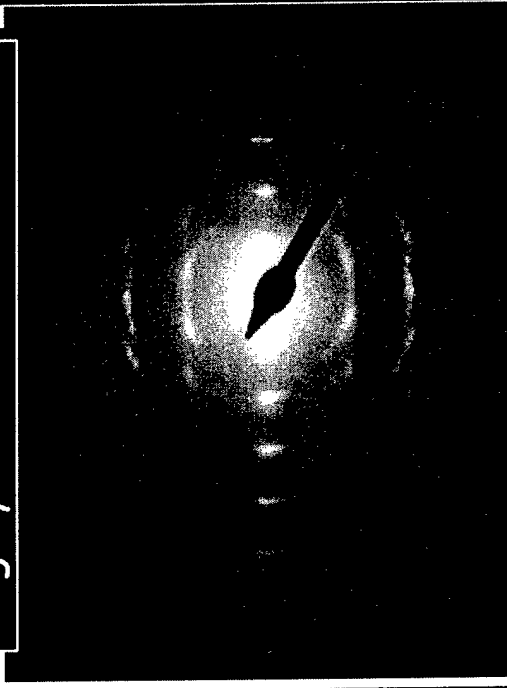


Bright Field



Ligament free of Disclinations

Highly Ordered Structure



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**Thermal Conductivity**

Local  $K = 250 - 750 \text{ w/m } ^\circ\text{C}$

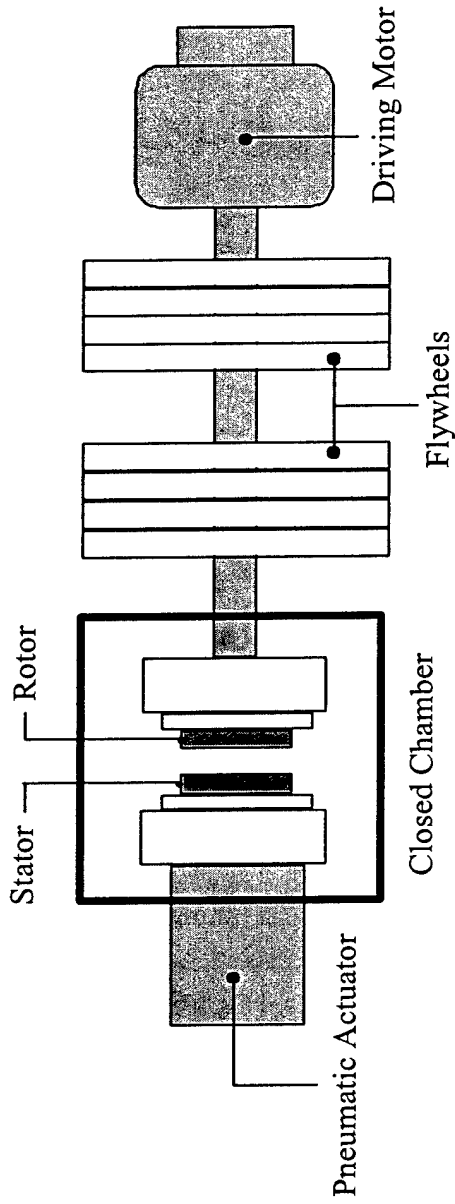
Bulk  $K = 50 - 200 \text{ w/m } ^\circ\text{C}$

Graphitized Foam:  
Ligament With Disclinations

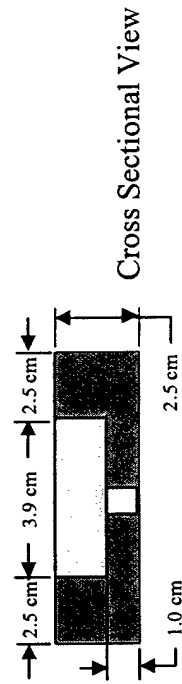
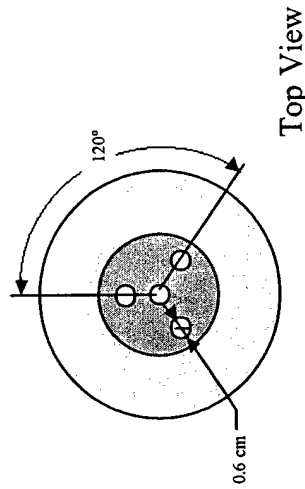
16mm



# Testing Conditions Using Sub-Scale Dynamometer



Schematic of the sub-scale dynamometer



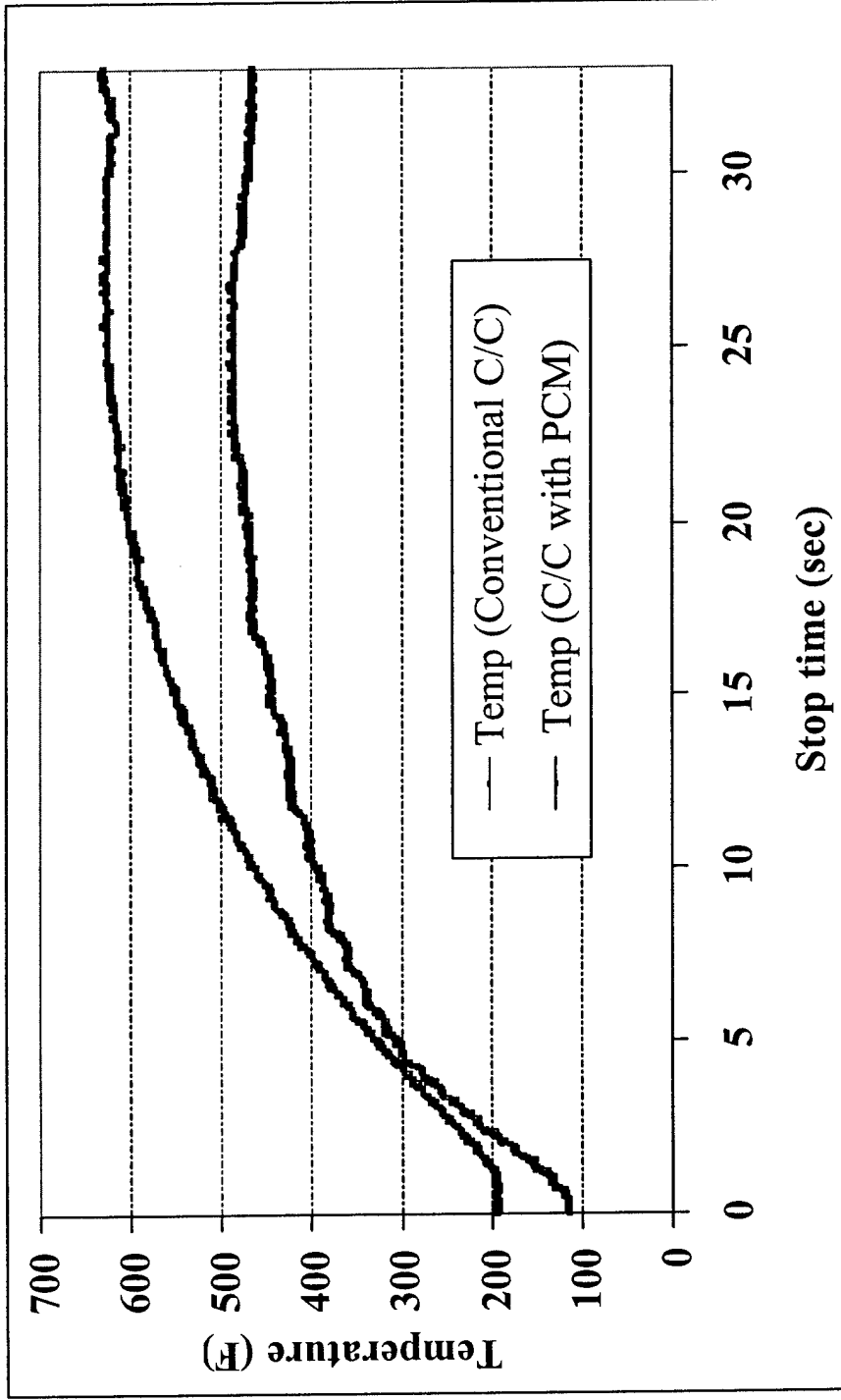
Dimensions of C-C composite brakes

| Test              | Number of stops             |
|-------------------|-----------------------------|
| Cold Taxi         | 100                         |
| Service Landing   | 100                         |
| Normal Landing    | 100                         |
| Taxi-Landing      | 50 (3 L.stps & 1 Taxi. stp) |
| Rejected take off | 5 stops                     |

Testing energy of the sub-scale dynamometer  
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# Temperature Profile at Landing condition

The thermocouple was located 5 mm from the sliding surface

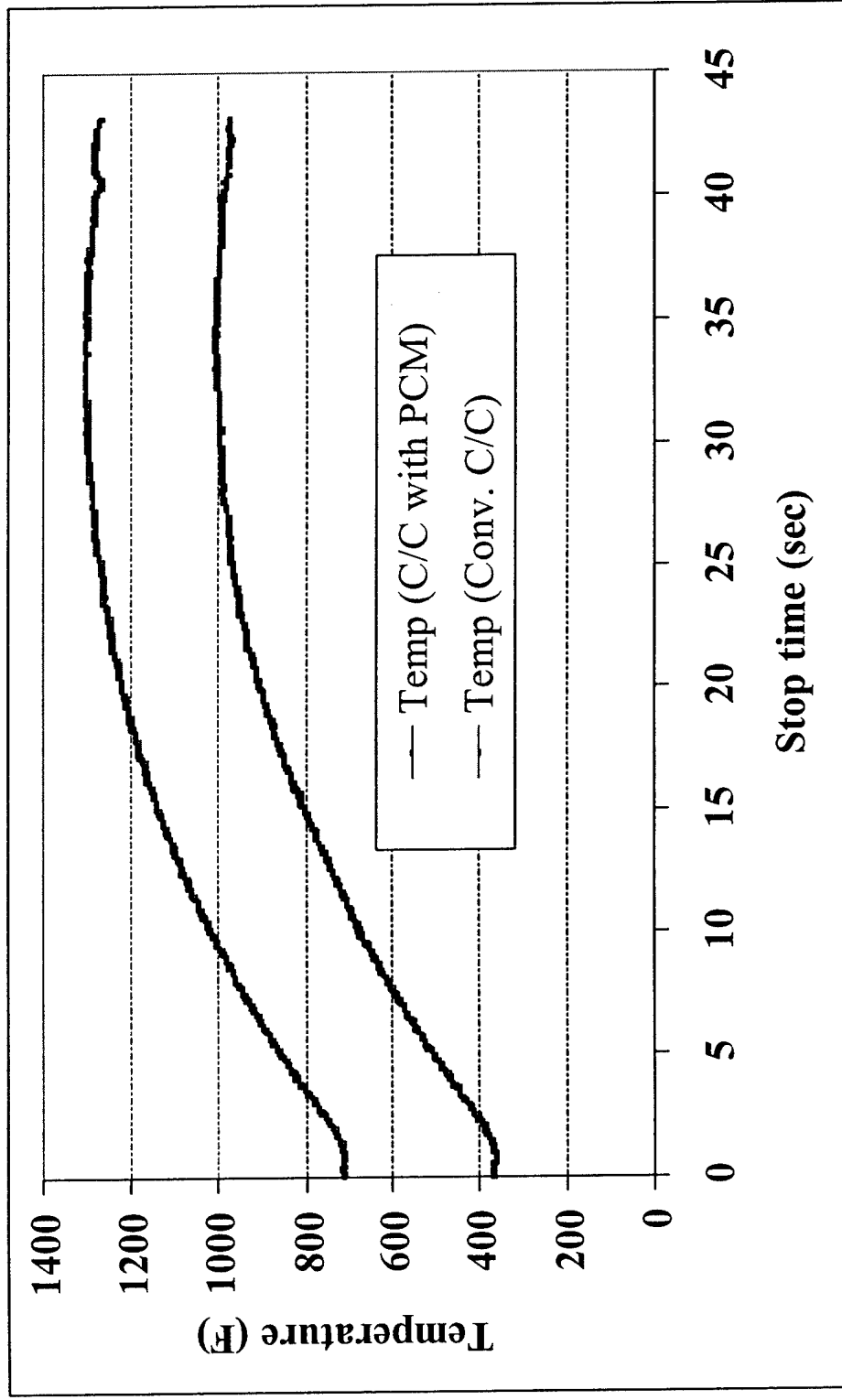


Temperature profile during normal landing Stop of conventional carbon-carbon composites and PCM-graphitic foam based composites.

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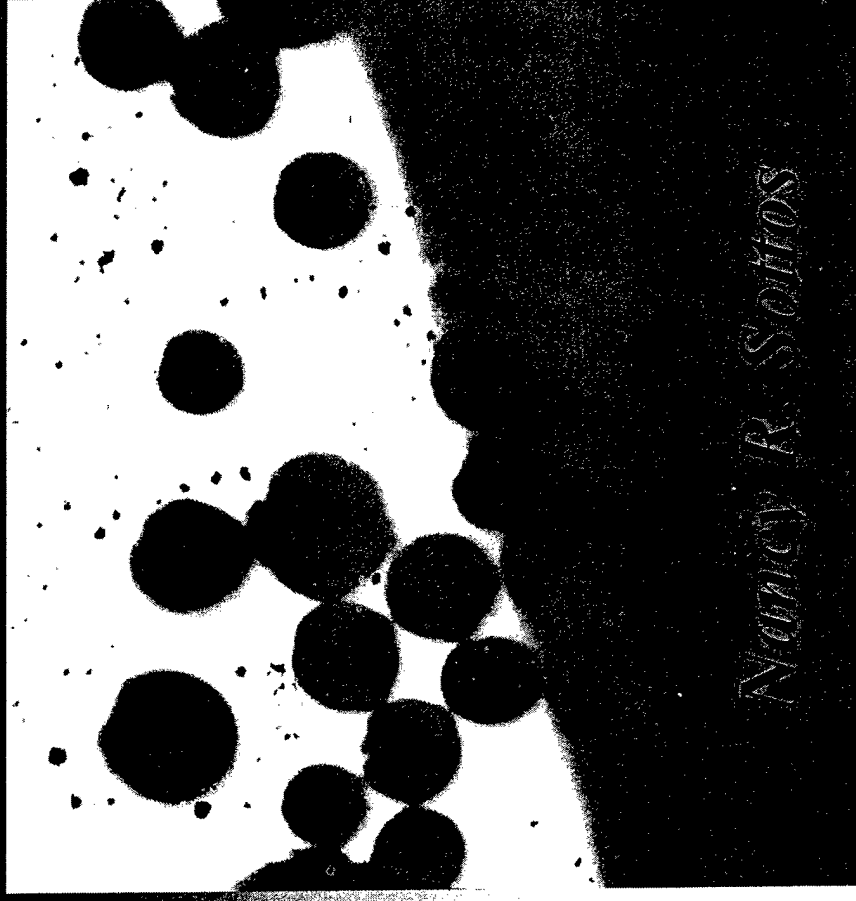
# Temperature Profile at Rejected Takeoff condition

The thermocouple was located 5 mm from the sliding surface



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# Autonomic Healing of Polymers and Composites



University of Illinois at Urbana-Champaign

**Beckman Institute** for Advanced Science and Technology



# Autonomic Healing Research Team



Faculty: Scott White, Nancy Sottos,  
Philippe Geubelle, Jeff  
Moore, Paul Braun,  
Jennifer Lewis

• Students: Eric Brown, Joe Rule, Daniel  
Therriault, Jeff Thompson,  
Mike Kessler\*, Suresh Sriram\*,  
Sabarivasan Viswanathan\*

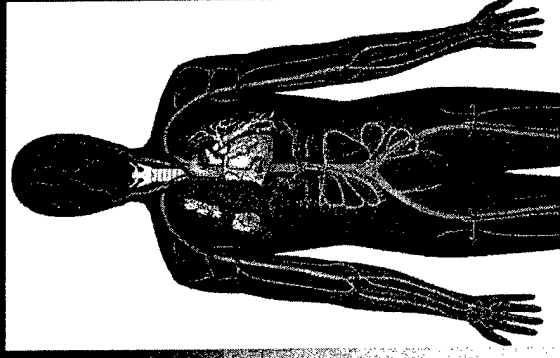
• Support: UIUC-CRI  
AFOSR  
Motorola  
Beckman Institute

[www.autonomic.uiuc.edu](http://www.autonomic.uiuc.edu)

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# Inspired by Biological Systems



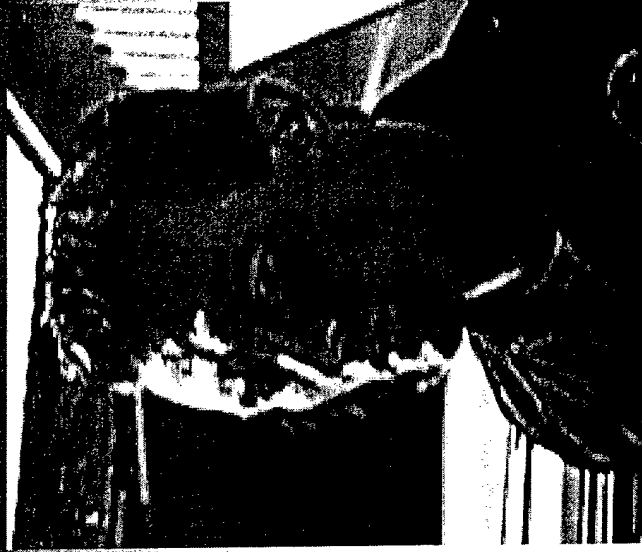
## Autonomy

The ability to function in an independent and automatic fashion

## Autonomic or Self-healing Functionality:

The ability to repair damage in an automatic and site specific fashion without manual intervention.

# Our Goal?



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# Motivation

Damage: Matrix cracking

## Structural Composites

- › Matrix Cracking
- › Interfacial debonding
- › Ply delamination

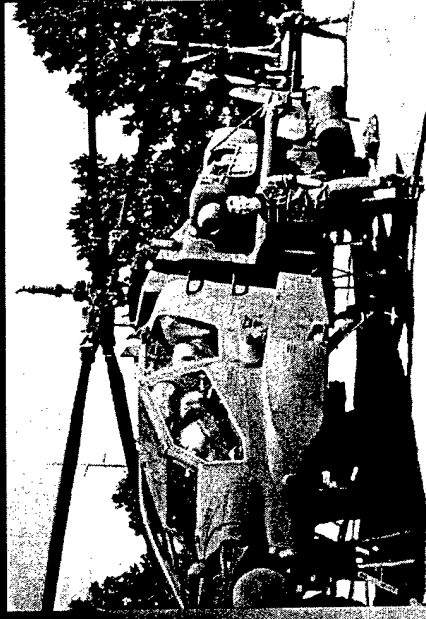
## Microelectronics

- › Interconnect fatigue
- › Polymer encapsulate failure

## Adhesives

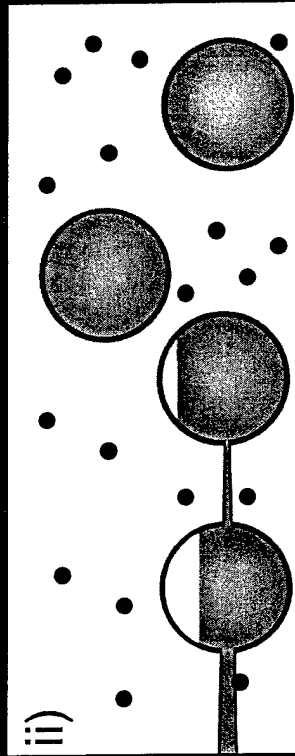
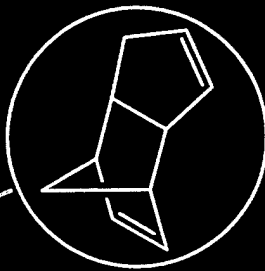
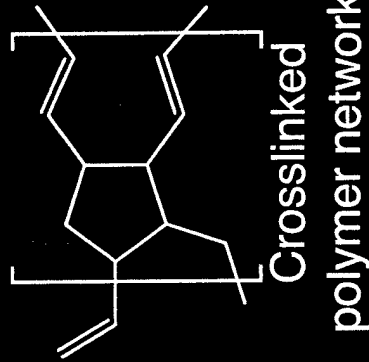
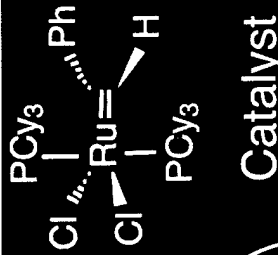
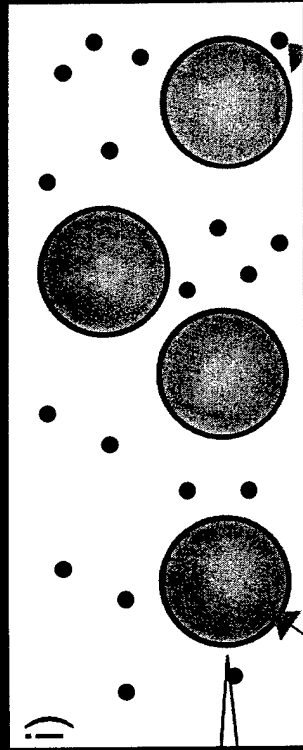
- › Microcracking

- Cracks are often deep in a structure where detection is costly and difficult
- Repair of cracks by external intervention is often impossible



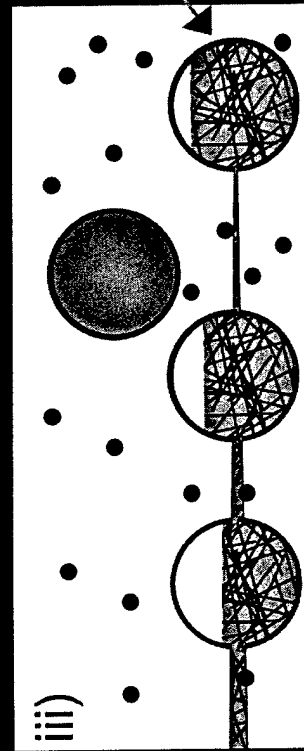
Cracking in cross-ply laminate  
Jennings (1990)

# Self-Healing Concept



polymer network

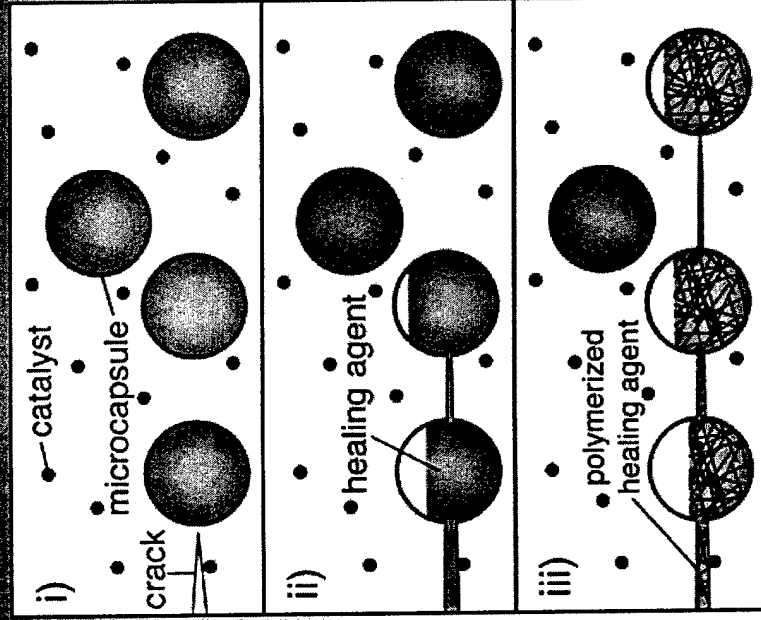
Healing Agent



# Self-Healing Materials

## Goals:

- 100% recovery of mechanical integrity
- Continuous healing over lifetime
- Seamless integration in material structure

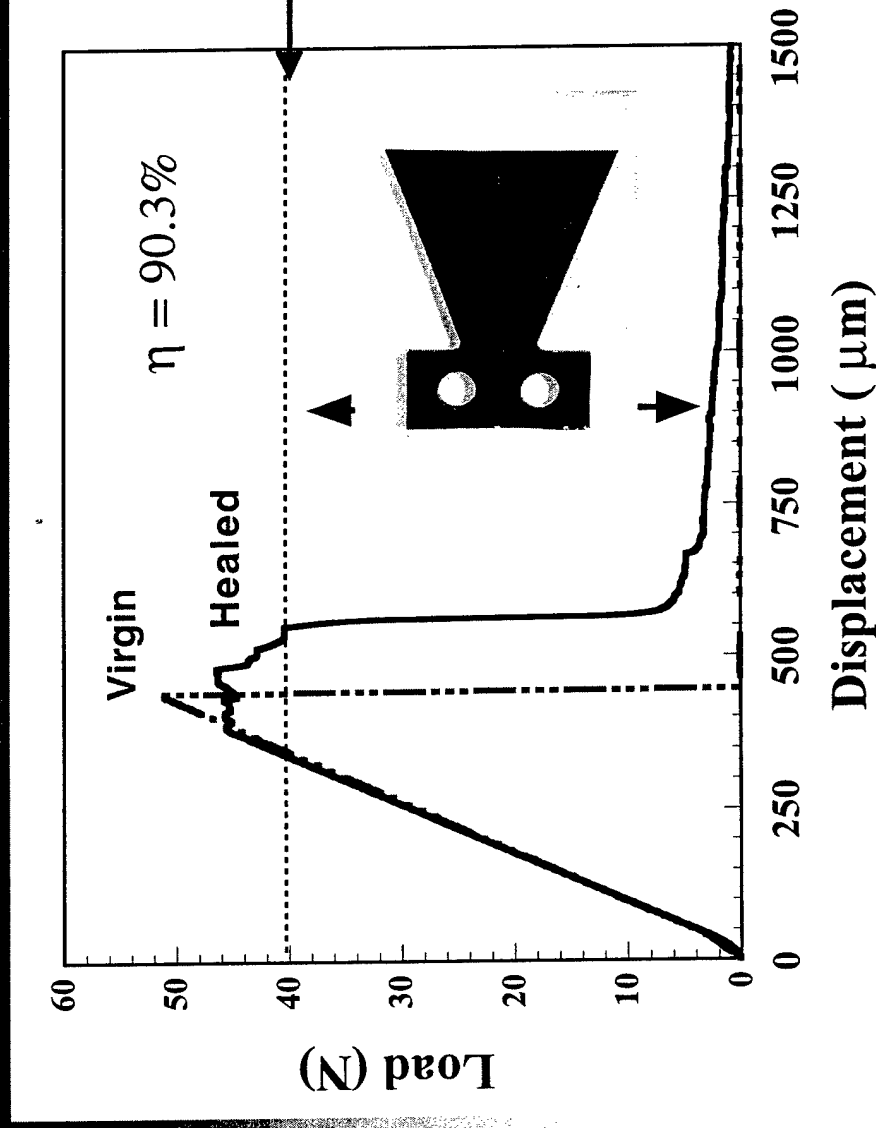


## Research Needs:

- Reactive materials development
- Environmental stability
- Mesoscale integration and fabrication
- Multiscale characterization
- Multiscale modeling

# Epoxy Healing Efficiency

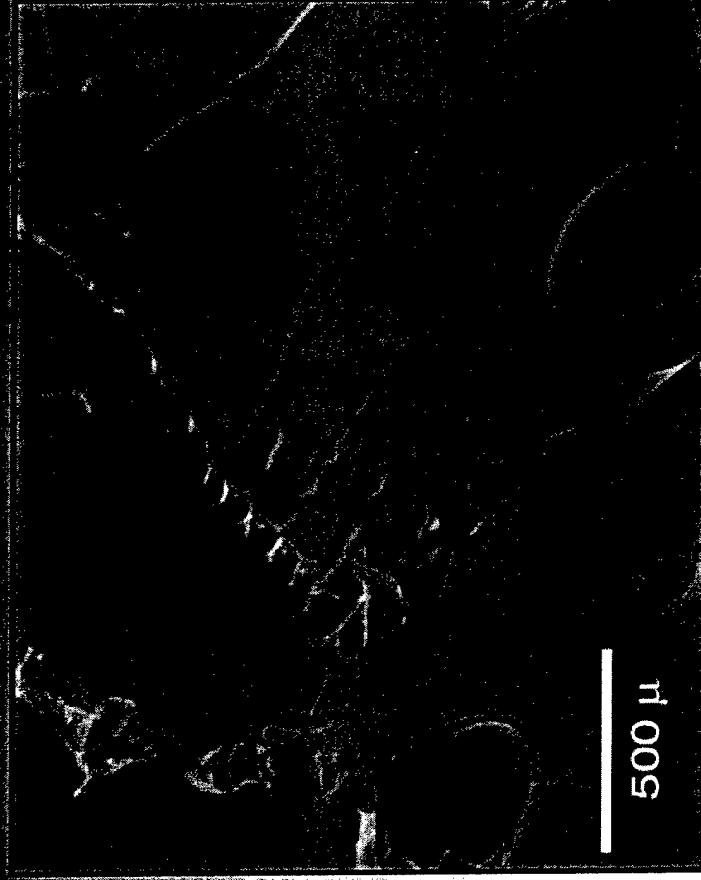
$$\eta = K_{Ic}^{healed} / K_{Ic}^{virgin}$$



neat epoxy w/  
no capsules

5 wt% microcapsules  
2.5 wt% catalyst

# Healed Fracture Surface

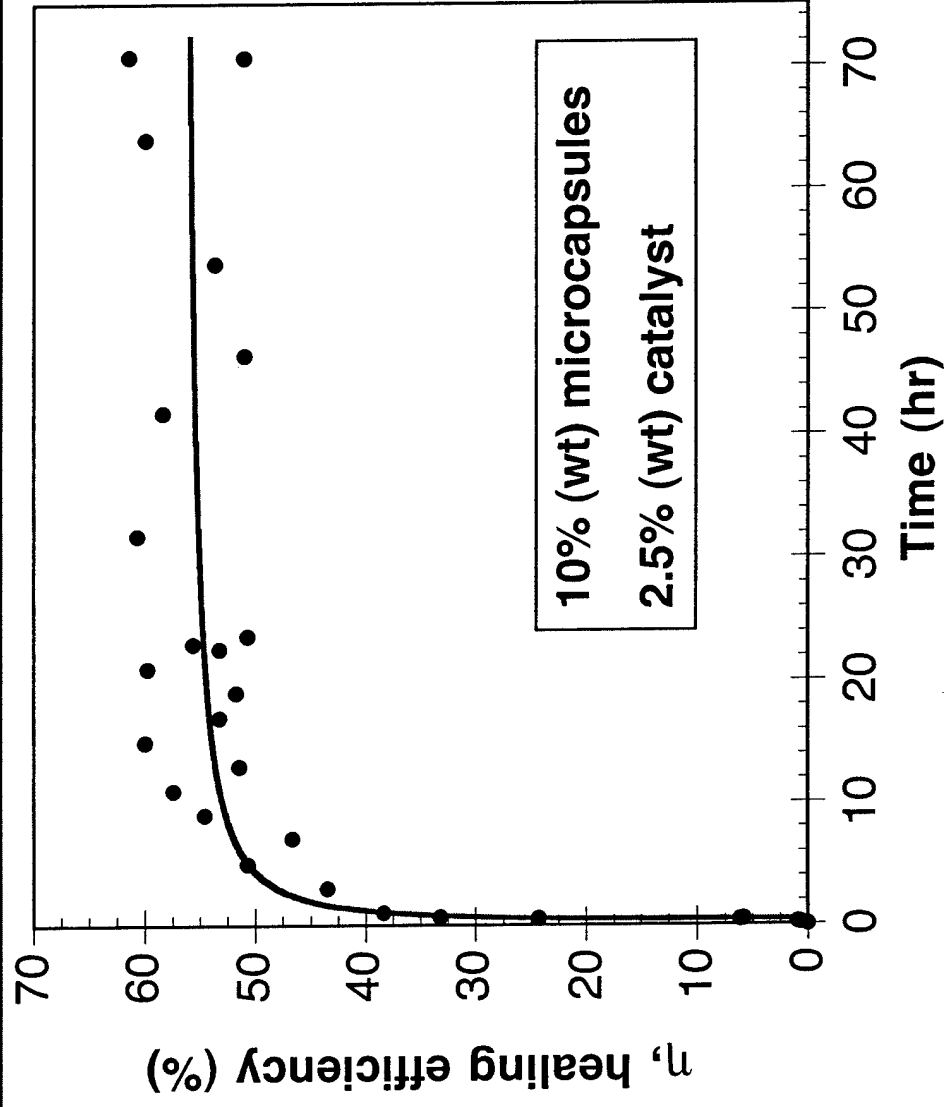


polymerized DCPD film on fracture surface

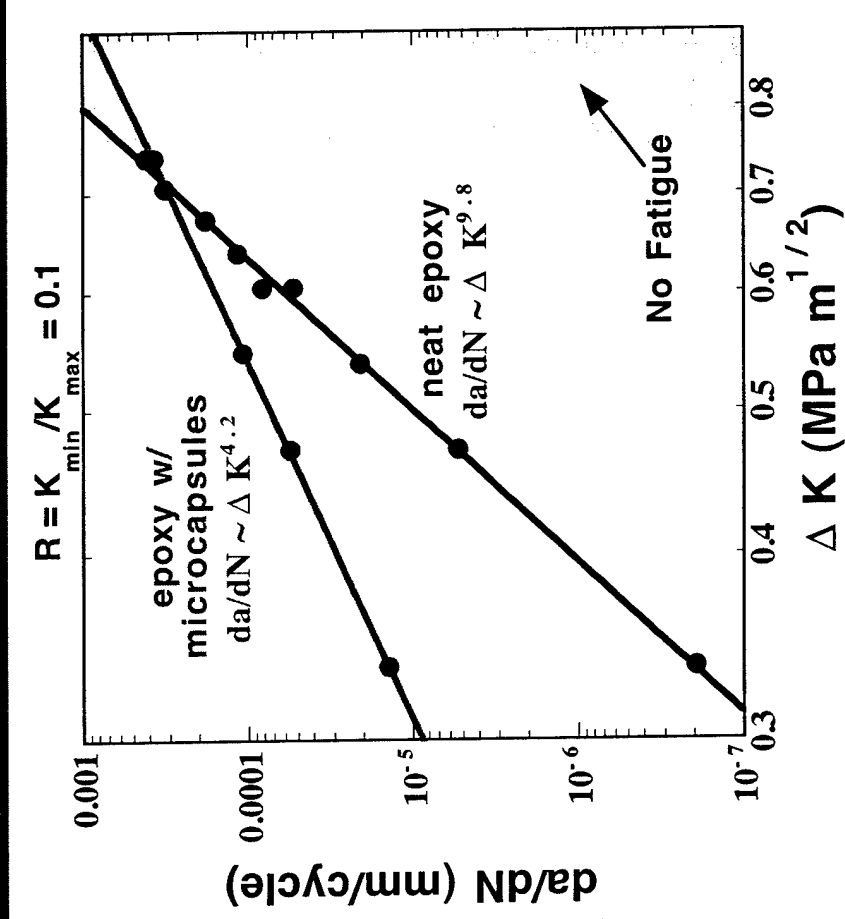
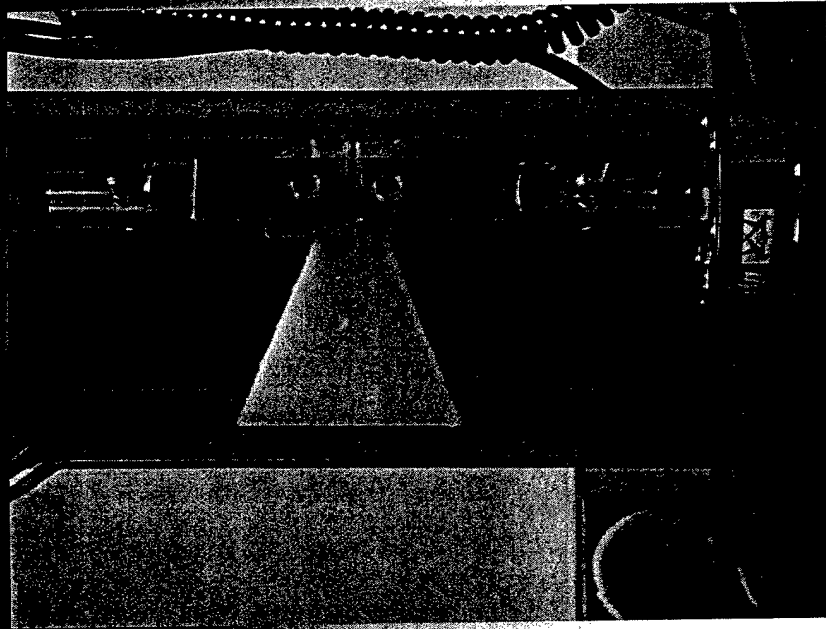
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# Healing Kinetics



# Healing Fatigue Damage



# Multiscale Modeling of Fatigue Response of Self-Healing Composite

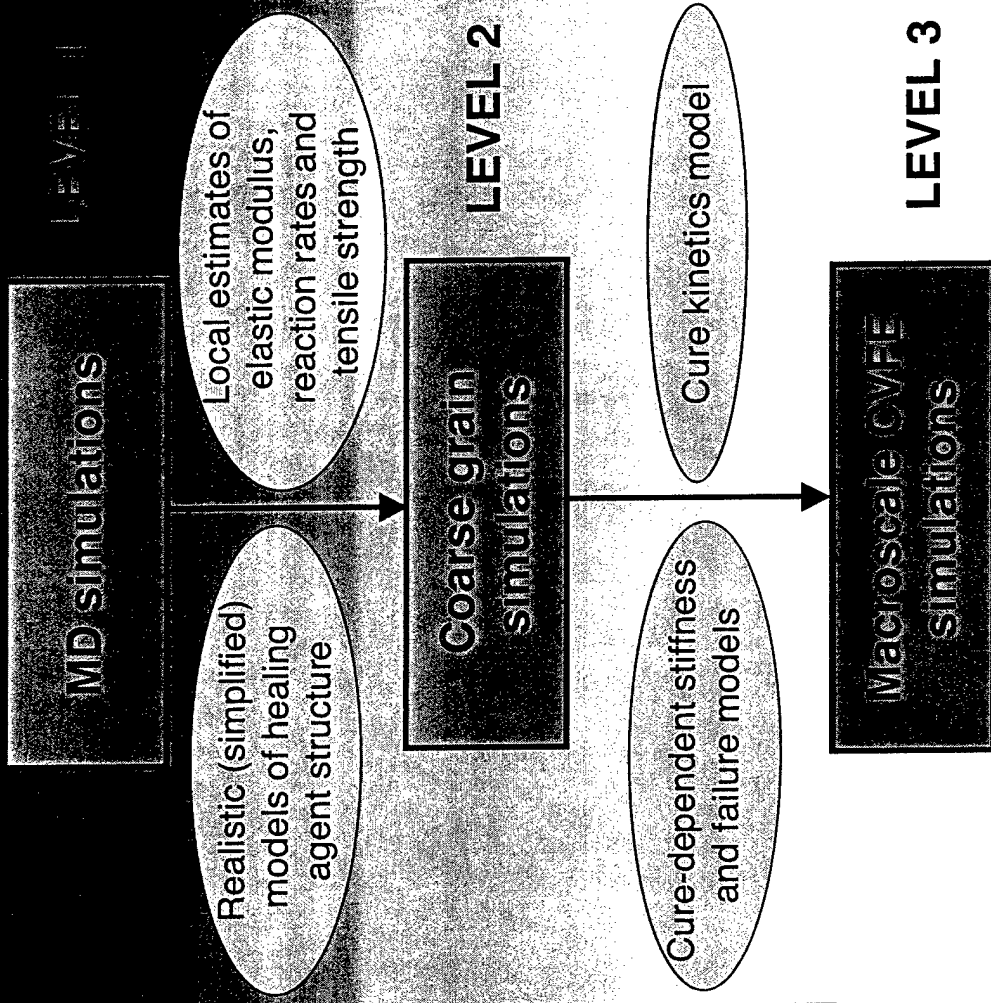
## Objective:

Model low and high-cycle fatigue response of autonomous healing in polymeric materials systems

## Approach:

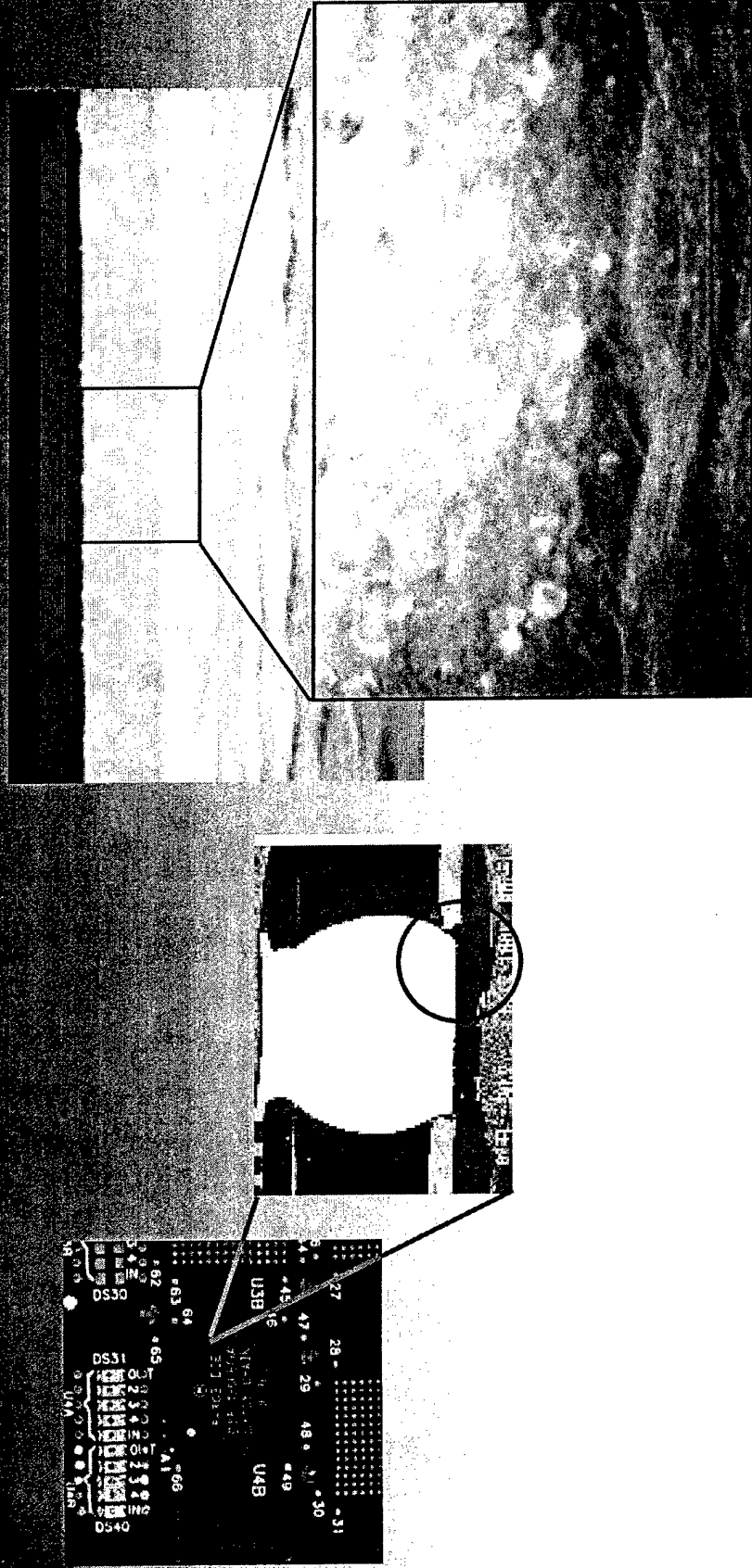
Combination of

- multilevel numerical tools
- multiscale supporting and validating experiments



# Tech Transfer: Microelectronics

Self-Healing Polymer for Improved Fatigue Life of Microelectronics  
Collaborative work with Dr. Andrew Skjor, Motorola Laboratories



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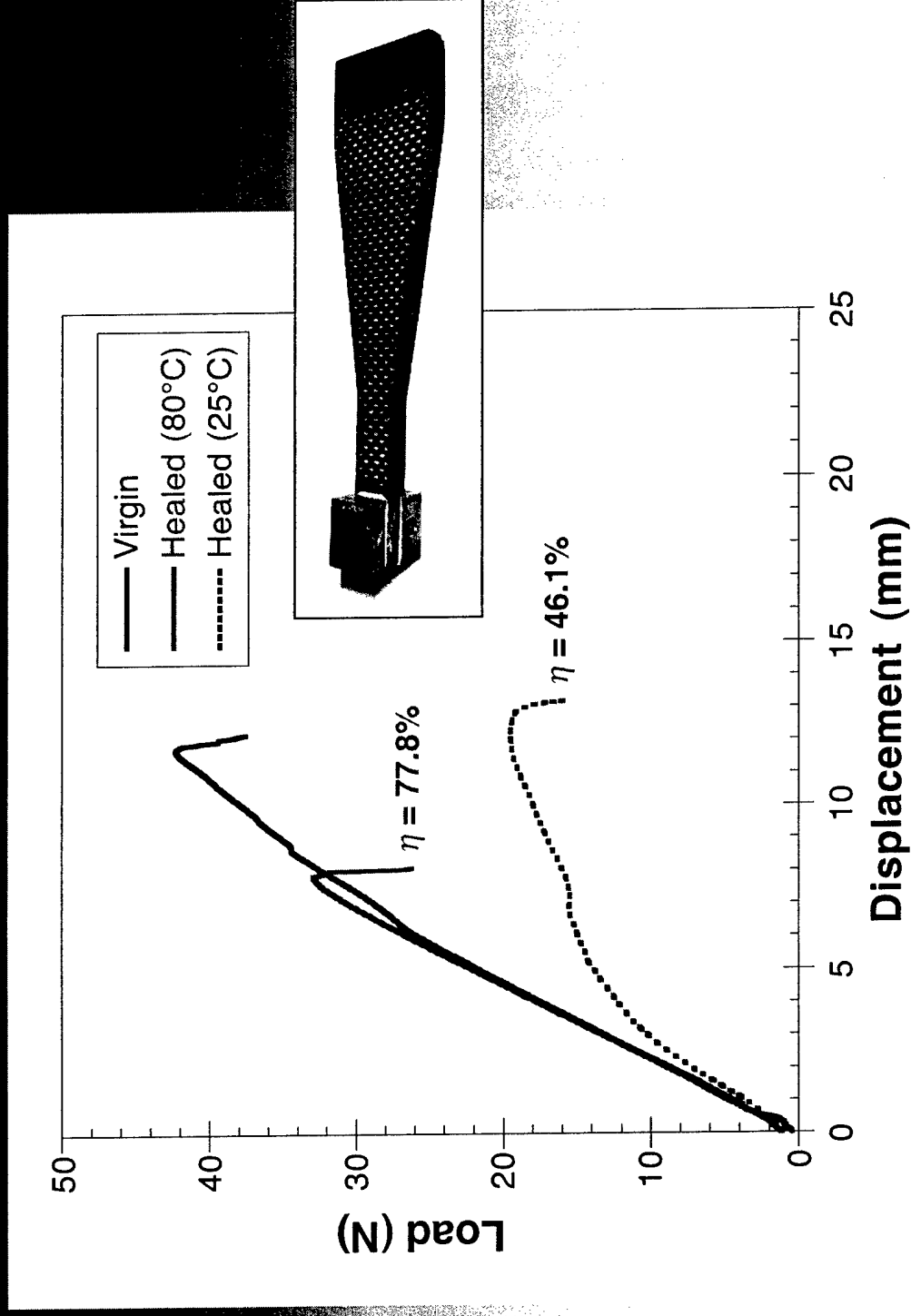
# Woven Composites

**Interlaminar fracture (delamination) is common:**

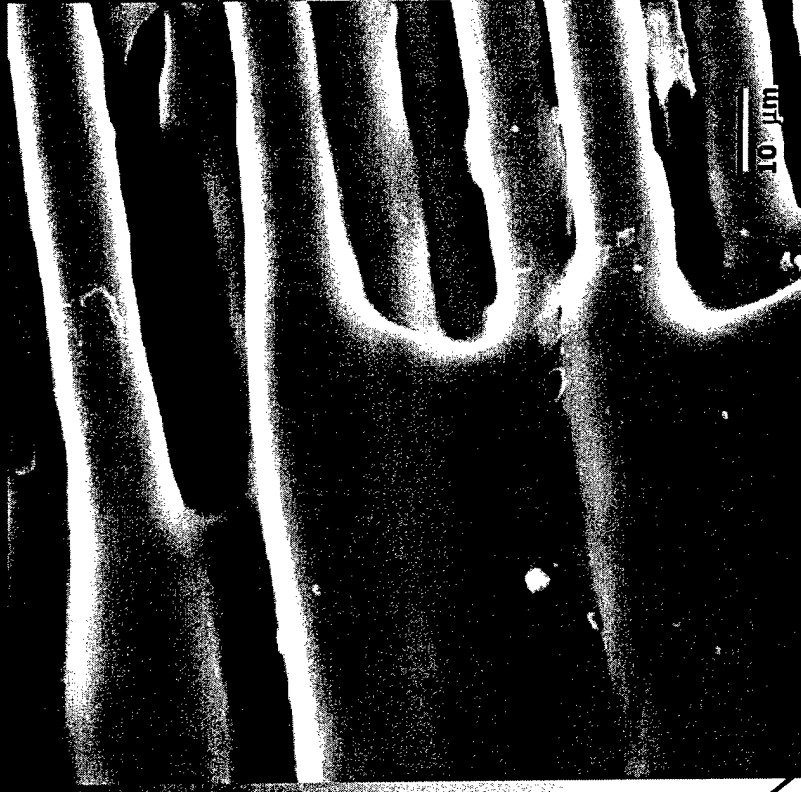
- low energy impact
  - manufacturing defect
  - initiate at stress concentrations such as holes and microcracks
- interstitial areas serve as storage sites for the microcapsules.



# Graphite/Epoxy Healing Efficiency



# Composite Fracture Surface



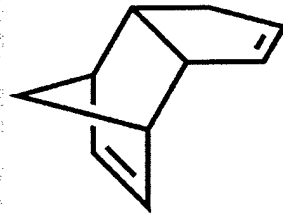
polymerized DCPD

# Tech Transfer: Cryogenic Storage Tanks

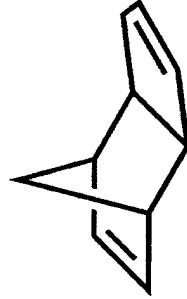
AFRL/VS STTR "Composite Materials for Cryogenic Storage Tanks and Superconductivity Applications"

- Lead by CU Aerospace, LLC (founded 1995)
- UIUC subcontract
- POC: Captain Brandon Arritt, Kirtland AFB

New Healing Agent:



endo - DCPD



exo - DCPD

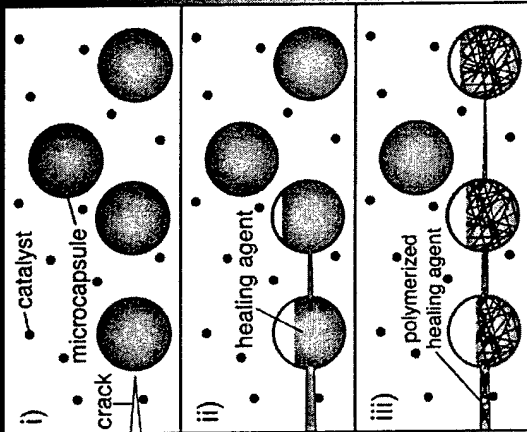


# Future Directions

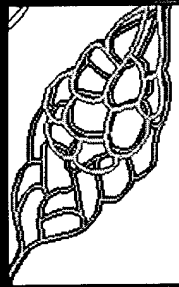
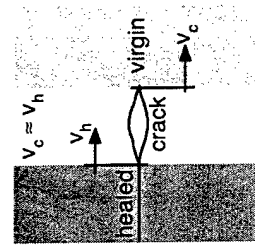


higher temp

lower temp

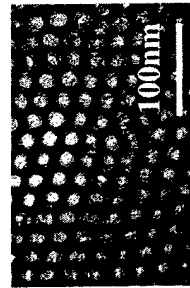


faster



continuous

smaller



# Next Generation Self-Healing

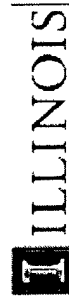
**Scott White**

**University of Illinois at Urbana-Champaign**

**1st Air Force Workshop on “Multifunctional Aerospace Materials”**

**Oct. 23-24, 2002.....Purdue University**

**Beckman Institute for Advanced Science and Technology**

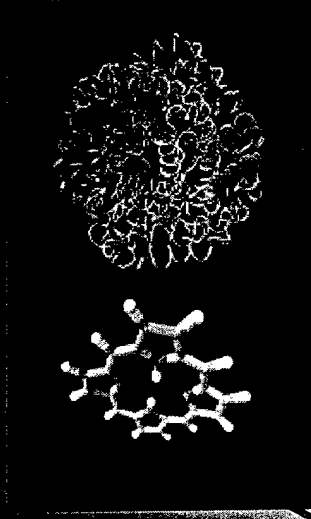
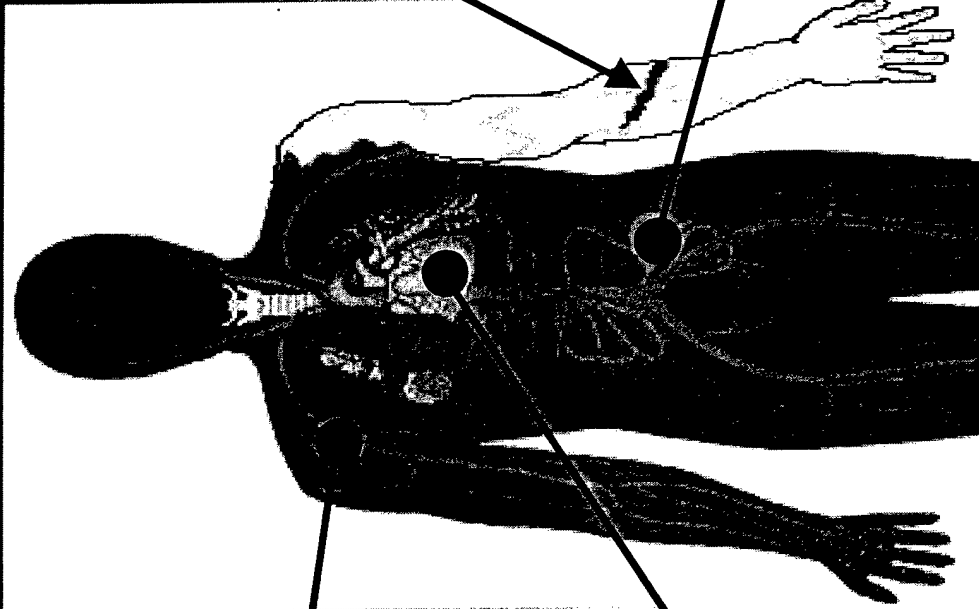
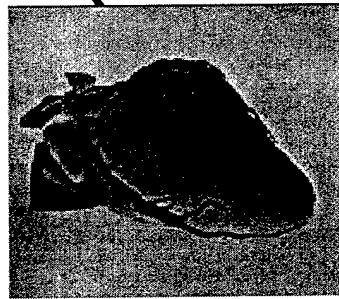


# Inspired by Biology... Creating a Synthetic Autonomic System



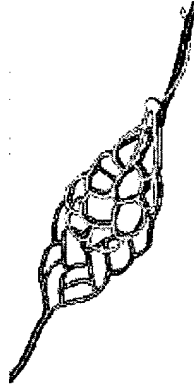
**Self-Regulating  
Function**

Active Regulation



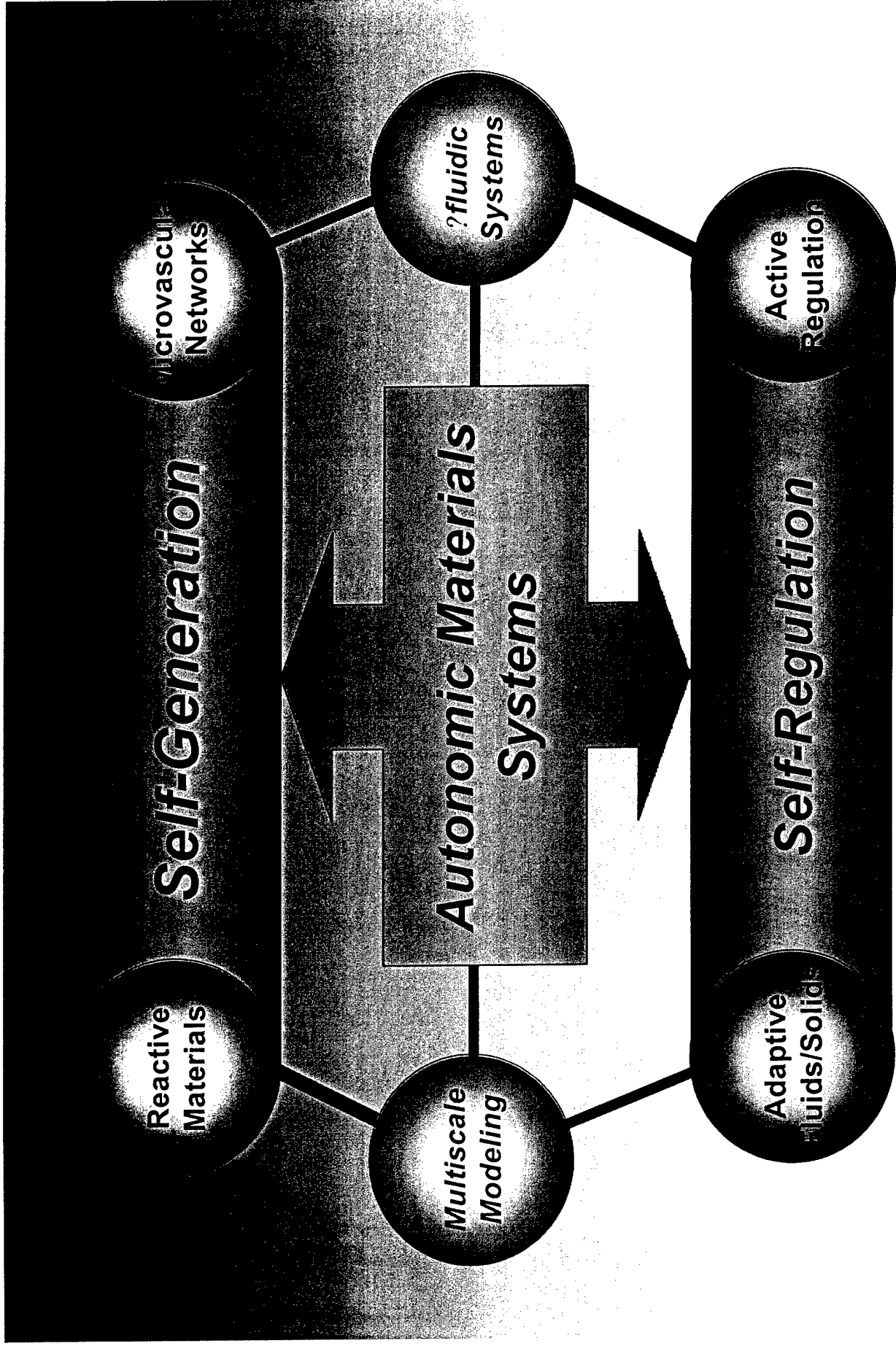
**Self-Generating  
Function**

Microvascular Networks



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# Current Limitations

- Relatively slow healing (@ reasonable temperatures & catalyst concentrations)
- Catalyst cost, stability @ high temp, exposure to O<sub>2</sub>
- No ability to replenish healing agent

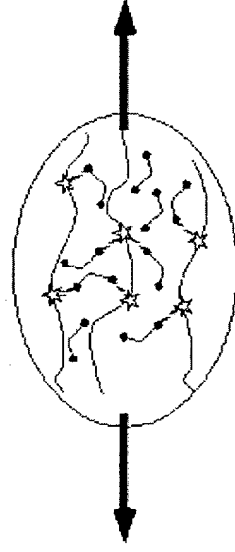
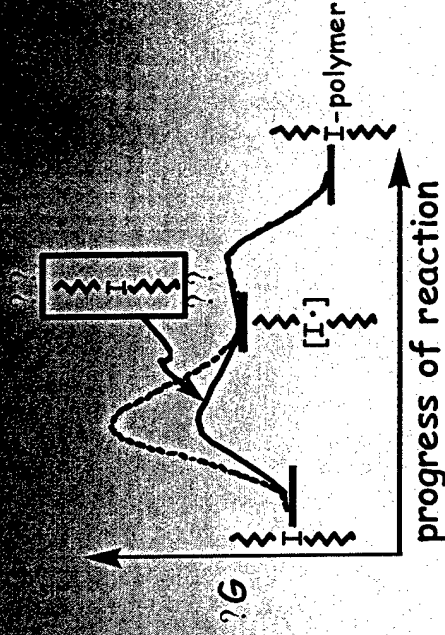
# New Healing Concepts

- **ROMP and ROP based approaches**
  - Cyclic esters, carbonates, ...
- **Mechanochemistry approaches**
- **Microvascular Networks**

# Mechanochemistry:

## Stress-Activated Schemes

- Application of a stress field lowers energy barrier to reactive state
- Radical generation is coupled directly (and tailored?) to mechanical field
- Candidate molecules have been identified that undergo *Bergman cyclization* to test concept



# Mechanochemistry:

## Fracture Triggered Polymerization

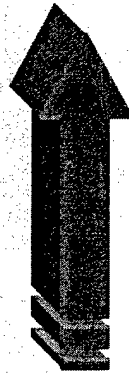
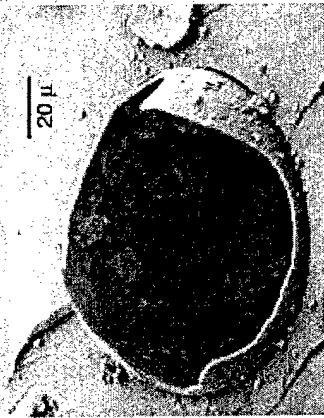
Develop “catalyst-free” systems utilizing the radicals generated on freshly fractured surfaces

### ISSUES:

- Radical turnover (amplification) by catalytic chain transfer processes
- Radical trapping (radical acceptors have been identified)
- Can we deliver monomer before secondary events (radical recombination, quenching,...) take place?

# Microvascular Networks

## Compartmentalization to Circulation

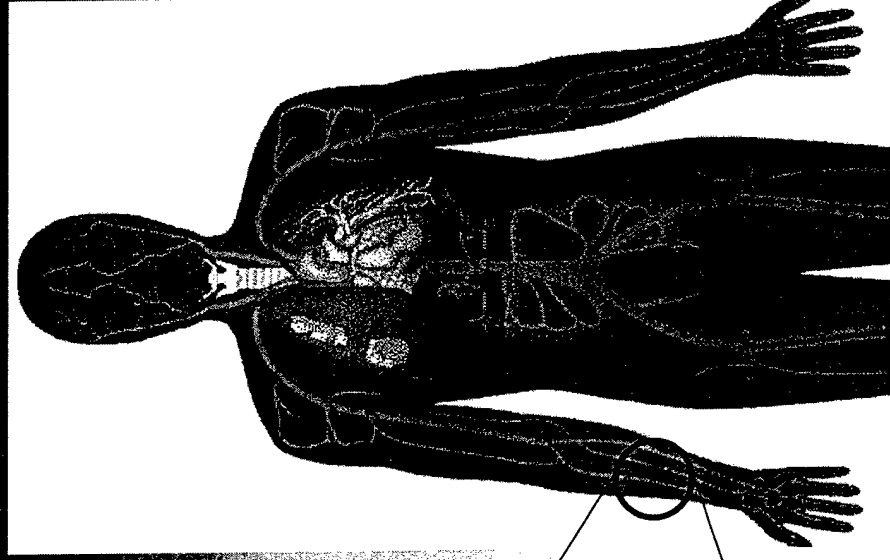
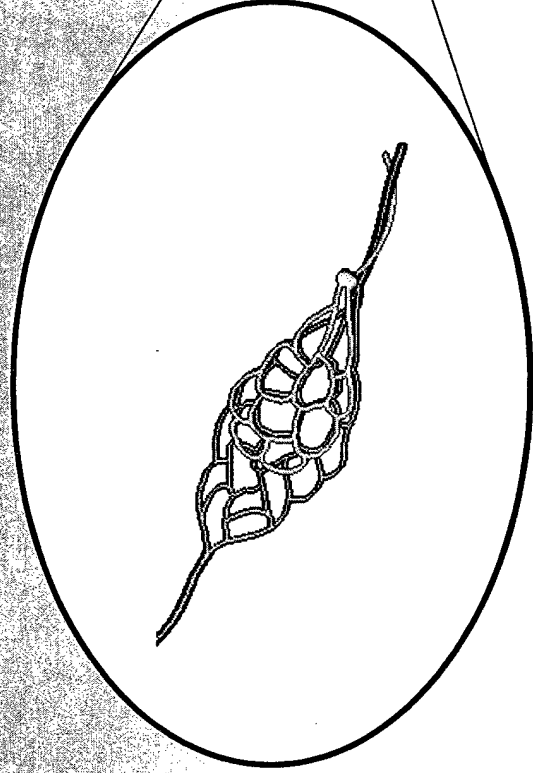


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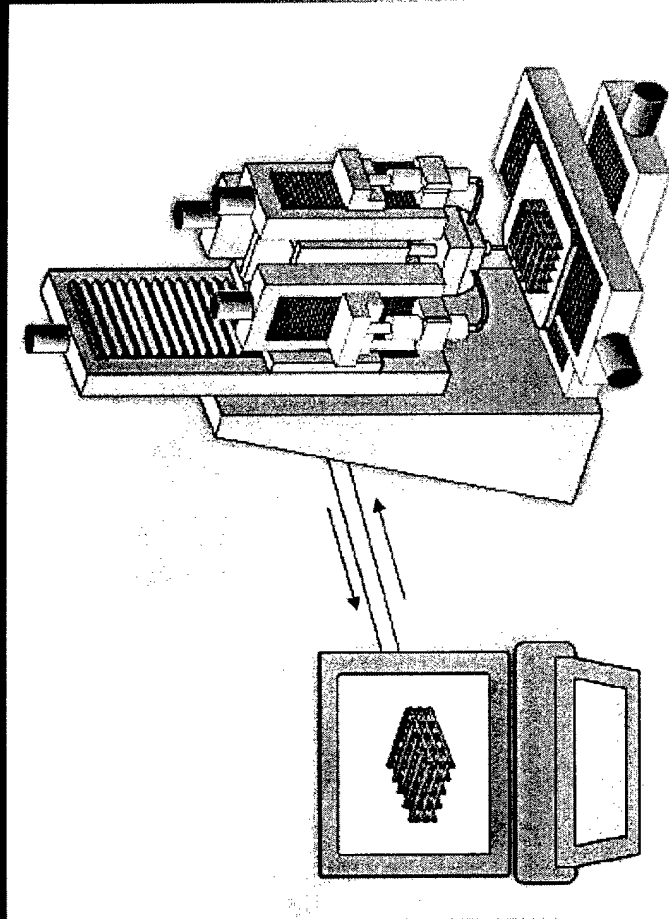
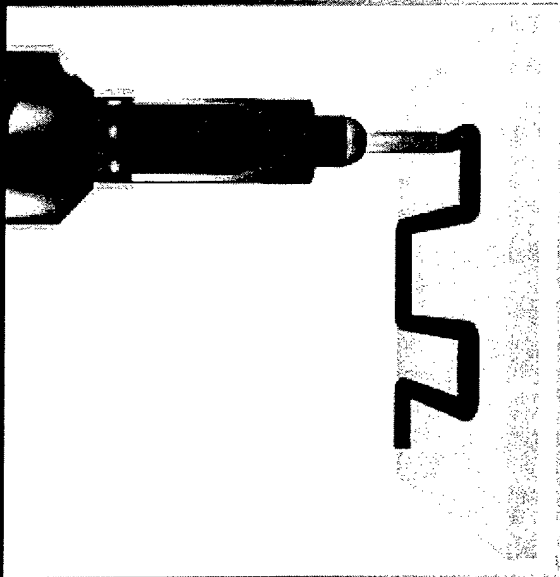
# Microvascular Networks

Hierarchical circulatory networks in biological systems

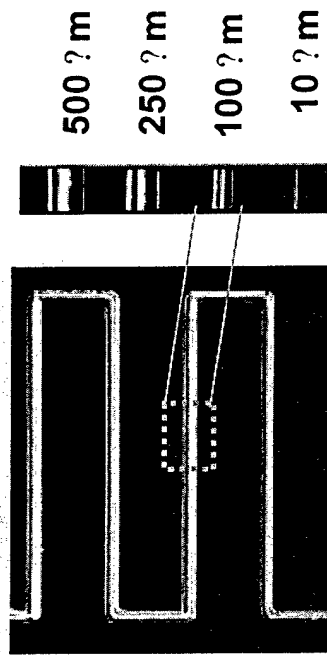
Key feature at the microscale is pervasive and interconnected system of microchannels



# Microvascular Network Fabrication



Robotically controlled deposition  
(RCD) machine



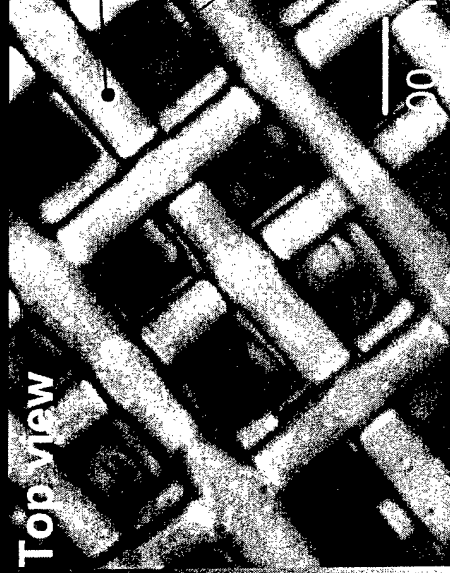
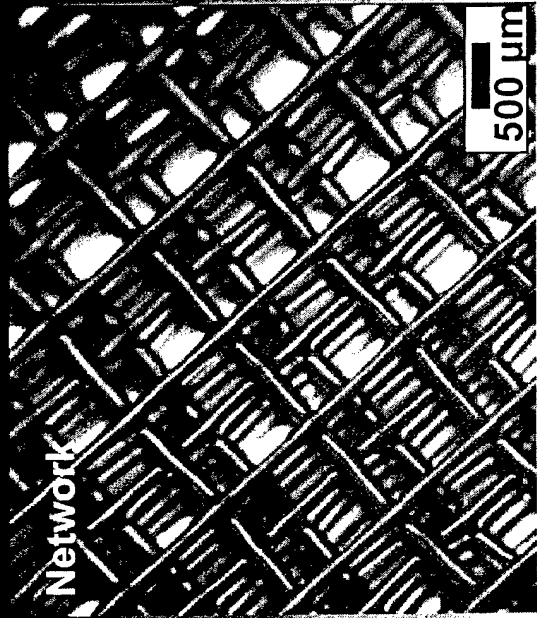
500 ? m

250 ? m

100 ? m

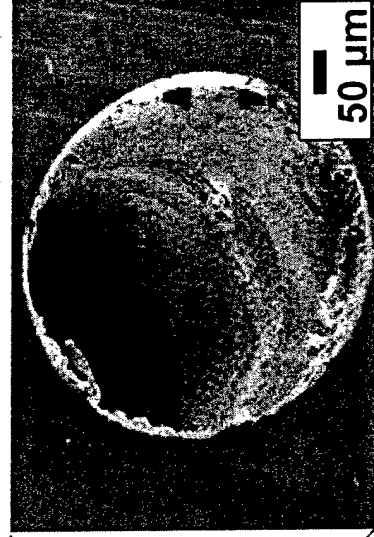
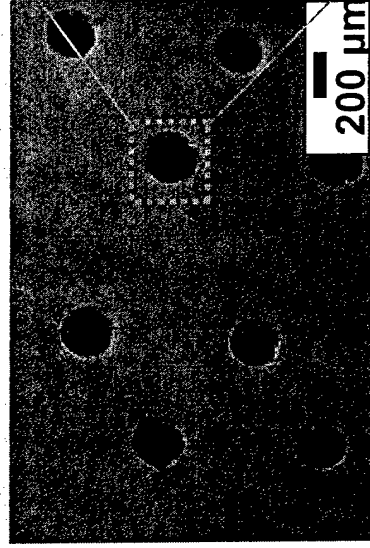
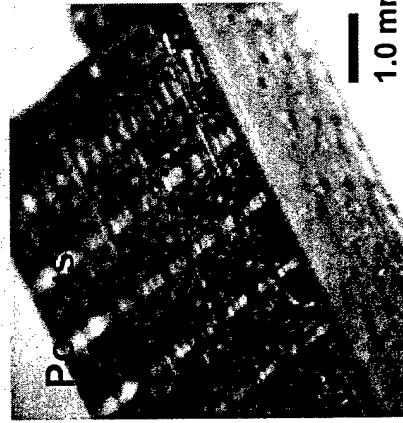
10 ? m

# 3-D Microvascular Networks



Fluid-filled  
pore channels

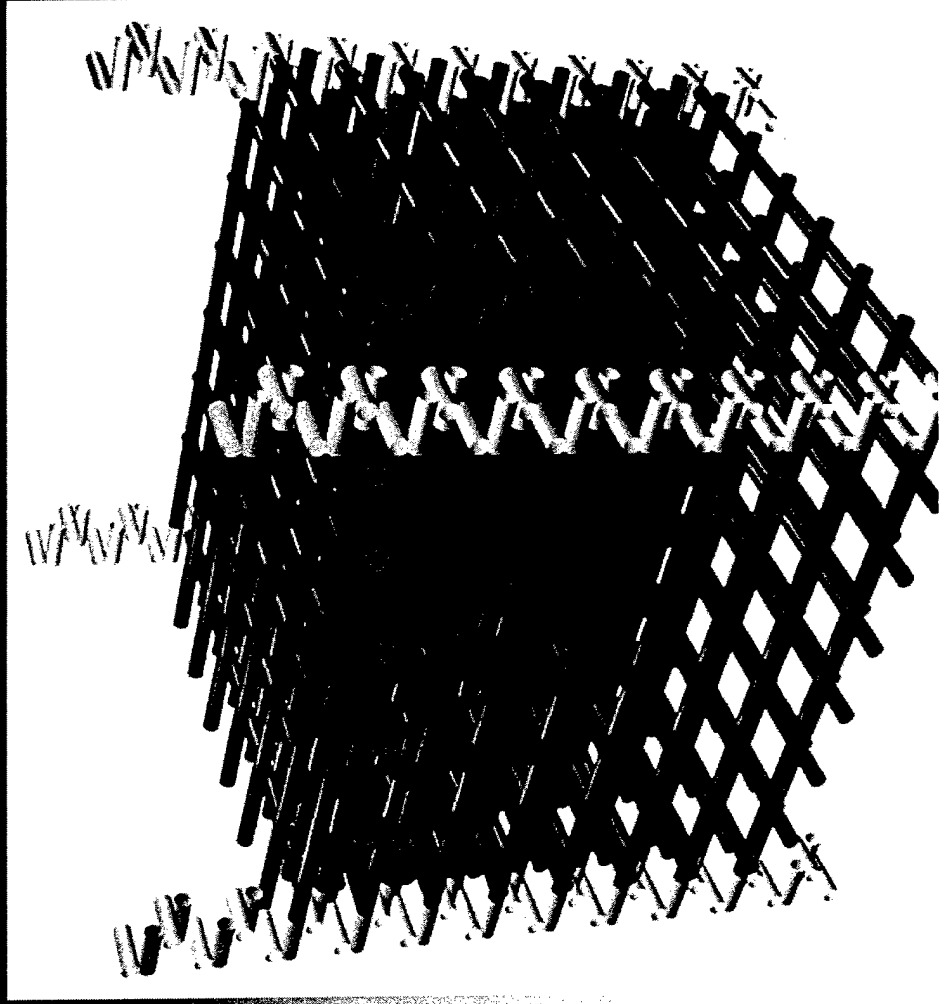
Epoxy matrix



Beckman Institute for Advanced Science and Technology

ILLINOIS

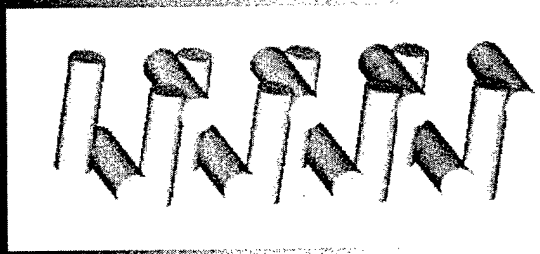
# Chaotic Advection Micromixer



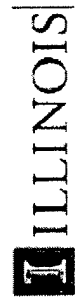
Top view



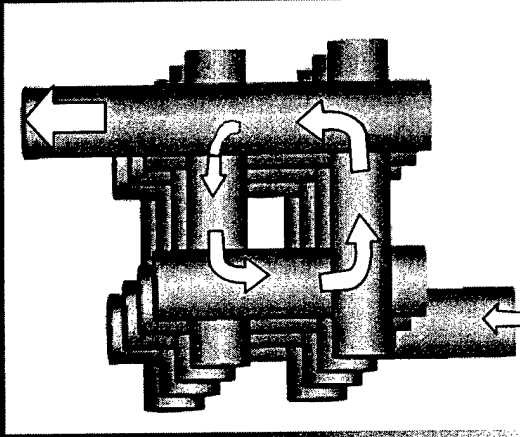
Side view



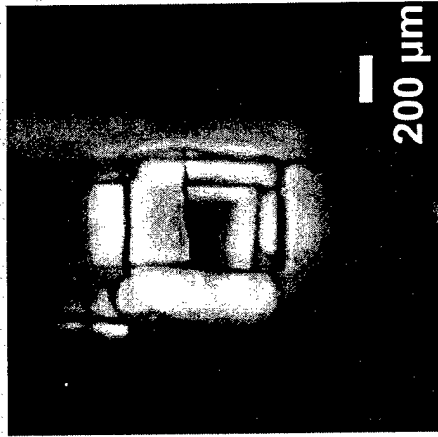
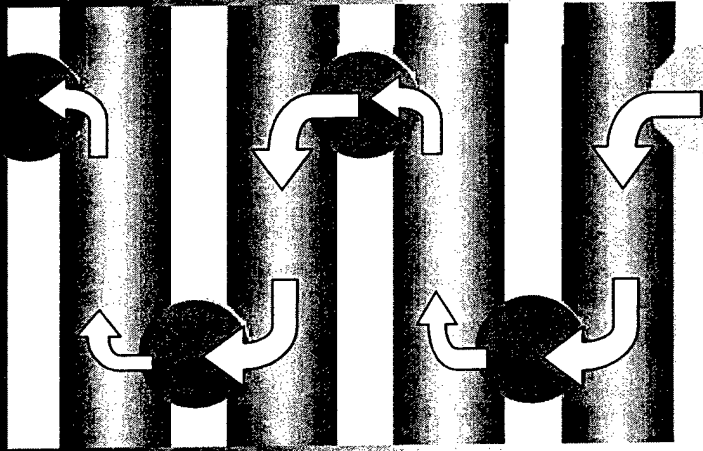
Beckman Institute for Advanced Science and Technology



# Isolated Flow Paths



Top view



Side view

# Micromixing Experiments

Re = 30.6

Straight channel (1-D)



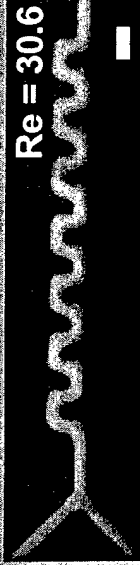
500  $\mu\text{m}^*$



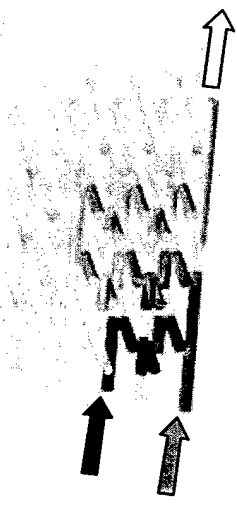
Square wave channel (2-D)



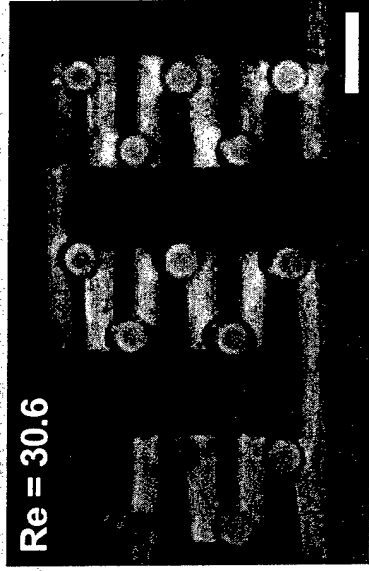
Re = 30.6



Series of mixing towers (3-D)



Re = 30.6



\*: all scale bars are 500  $\mu\text{m}$ .

# A Challenge for Mechanics...

- Multifunctionality can be (and perhaps should be) led by the mechanics community!
- This is an opportunity as a community to step to the forefront and lead the next generation of materials developments.
- We **MUST** reach out to other disciplines and facilitate collaborative research from the ground up.

→ We're talking about new materials, not bonding old ones together.

Thermally Re-mendable Cross-linked  
Polymeric Materials

*Xiangxu Chen*

*Exotic Materials Institute*

*Department of Chemistry & Biochemistry  
University of California, Los Angeles*

Polymeric Materials

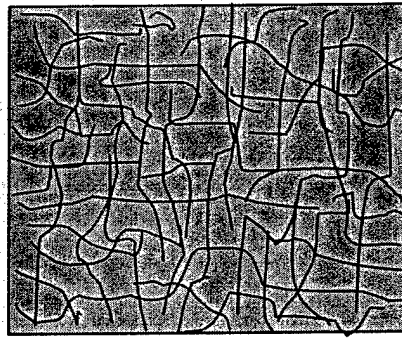
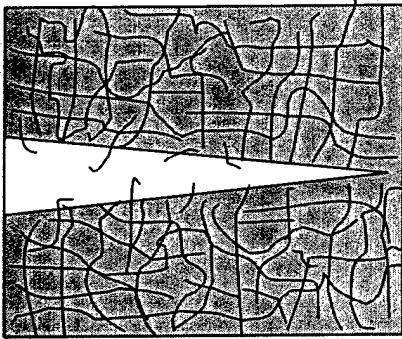


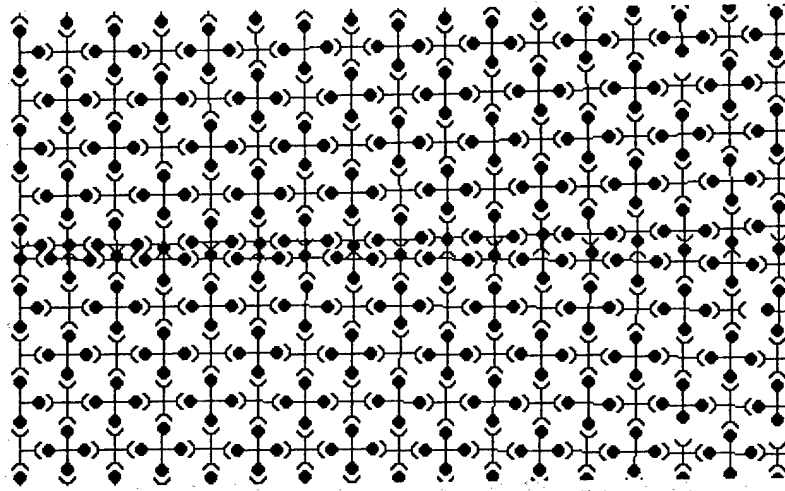
Molecules



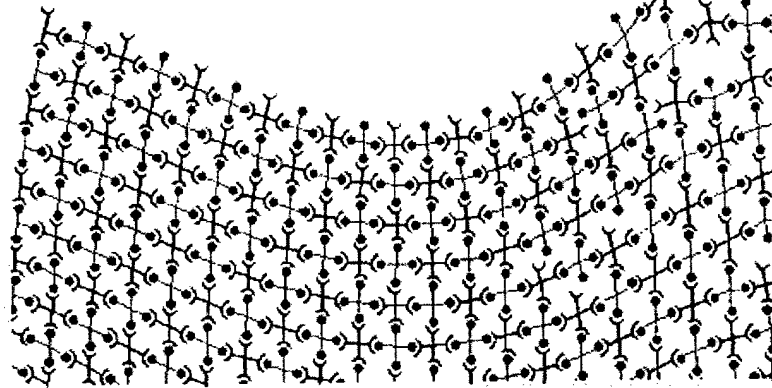
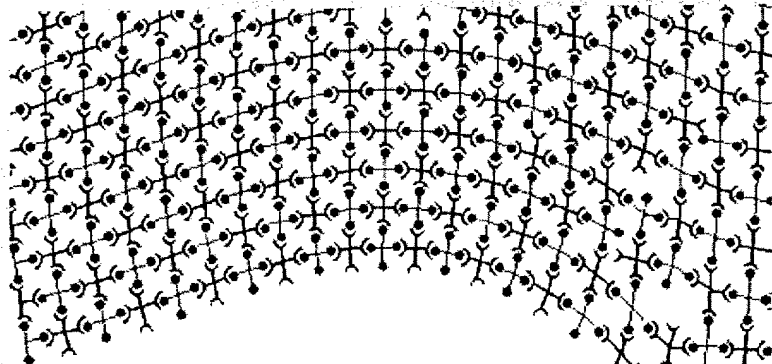
Chemical Bonds

*A material formed by re-connectable  
chemical bonds should be re-mendable.*

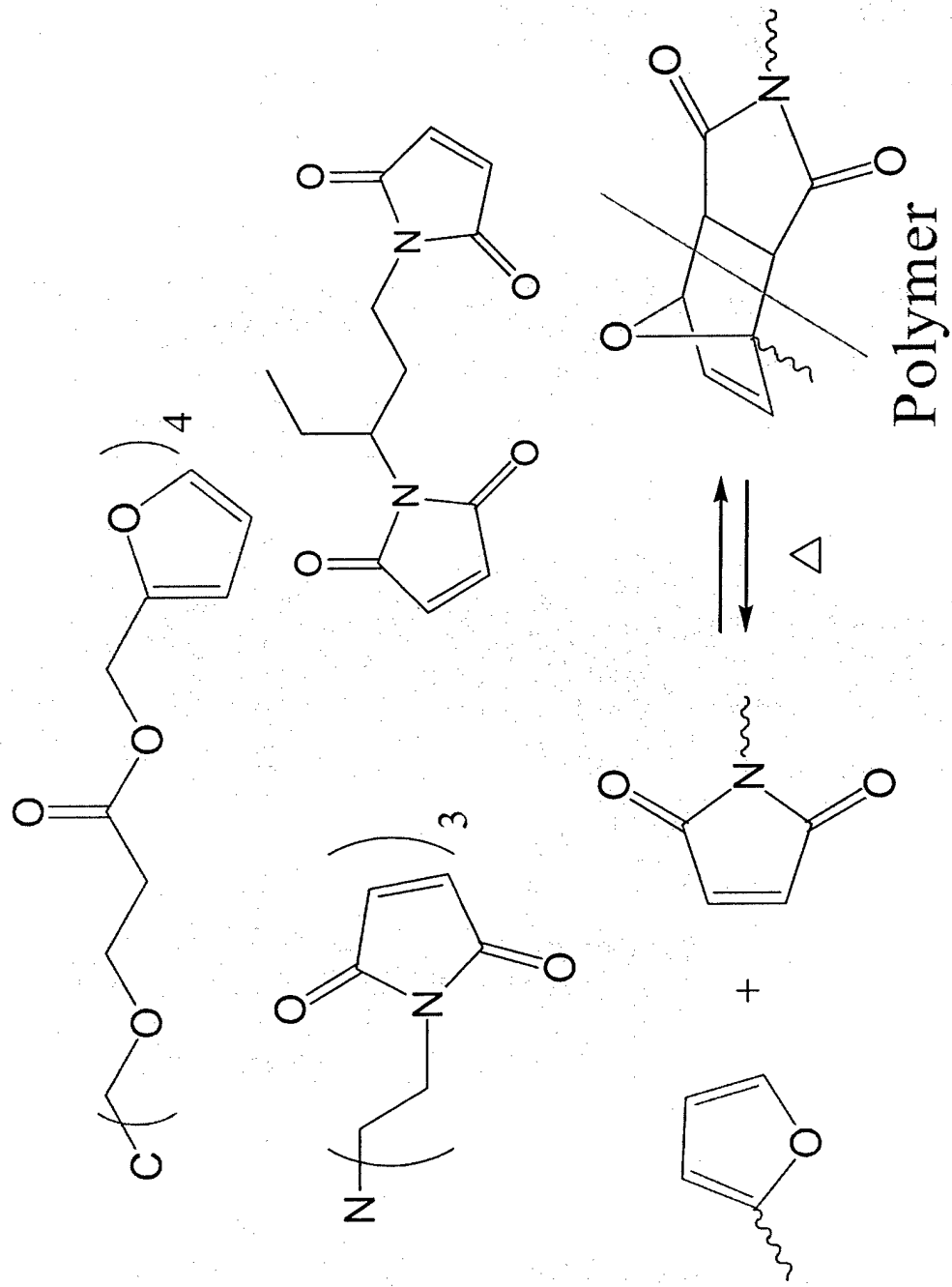


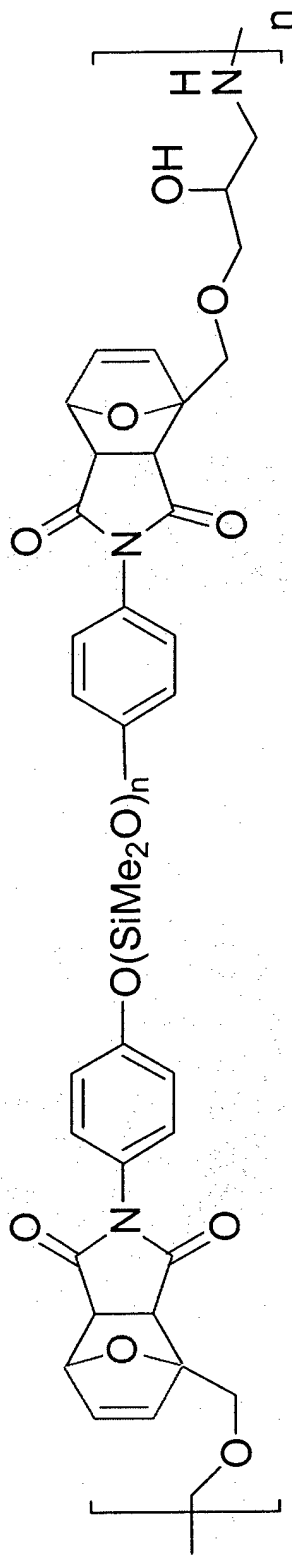
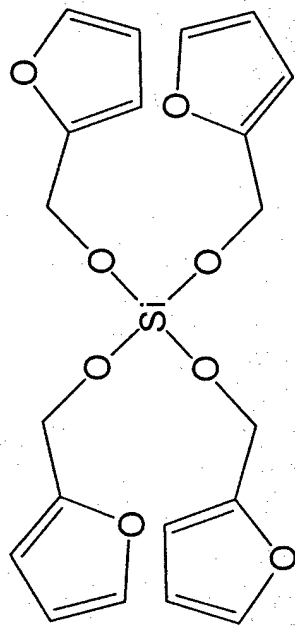


↑  
load



# Highly cross-linked re-mendable polymeric materials

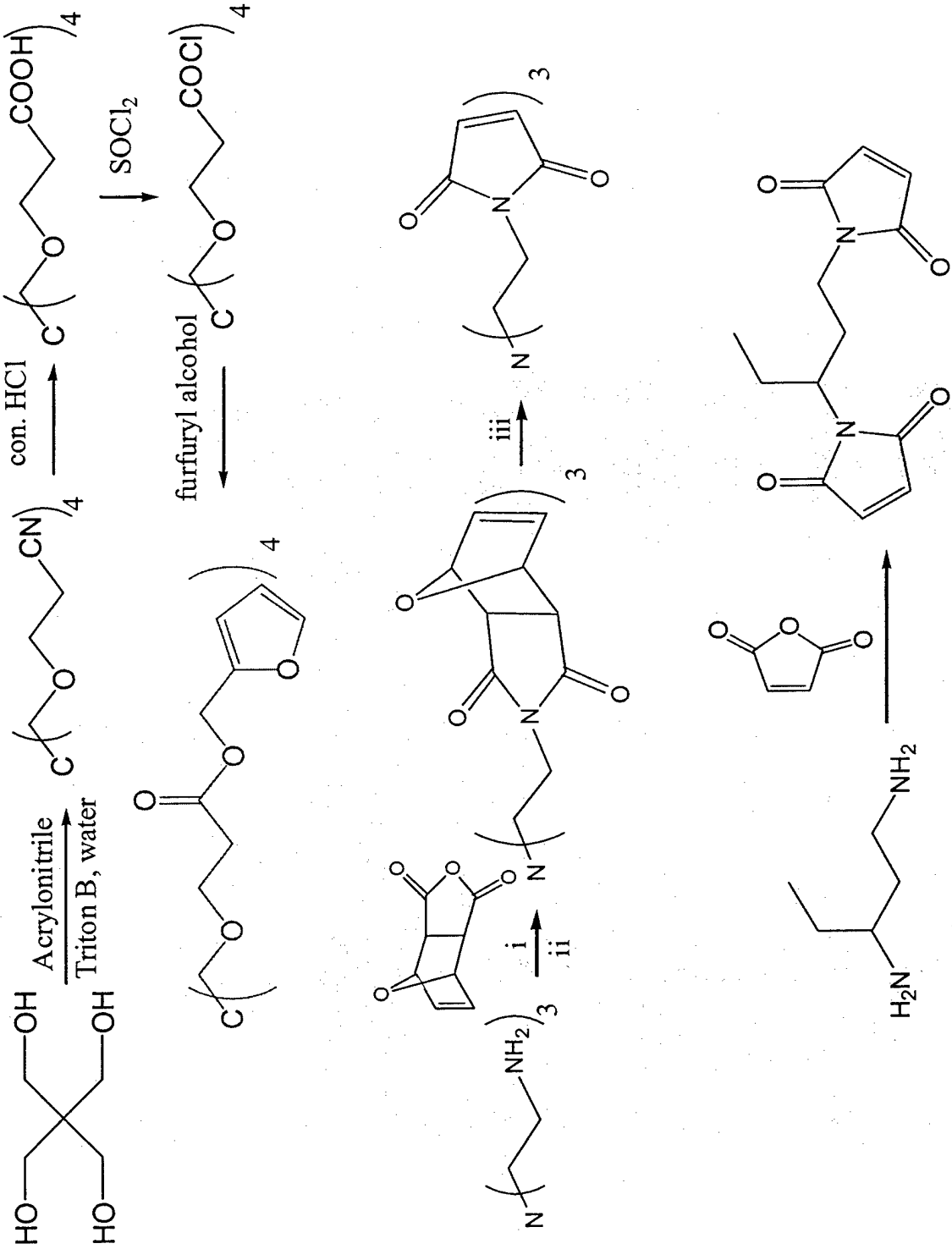




Small, J. H.; Loy, D. A.; Wheeler, D. R. McElhanon, J. R.; Saunders, R. S. *US Patent*, 6,271,335 B1 (2001).

Loy, D. A.; Wheeler, D. R.; Russick, E. M.; McElhanon, J. R.; Saunders, R. S. *US Patent*, US 6,337,384 B1 (2002).

# Synthesis of monomers

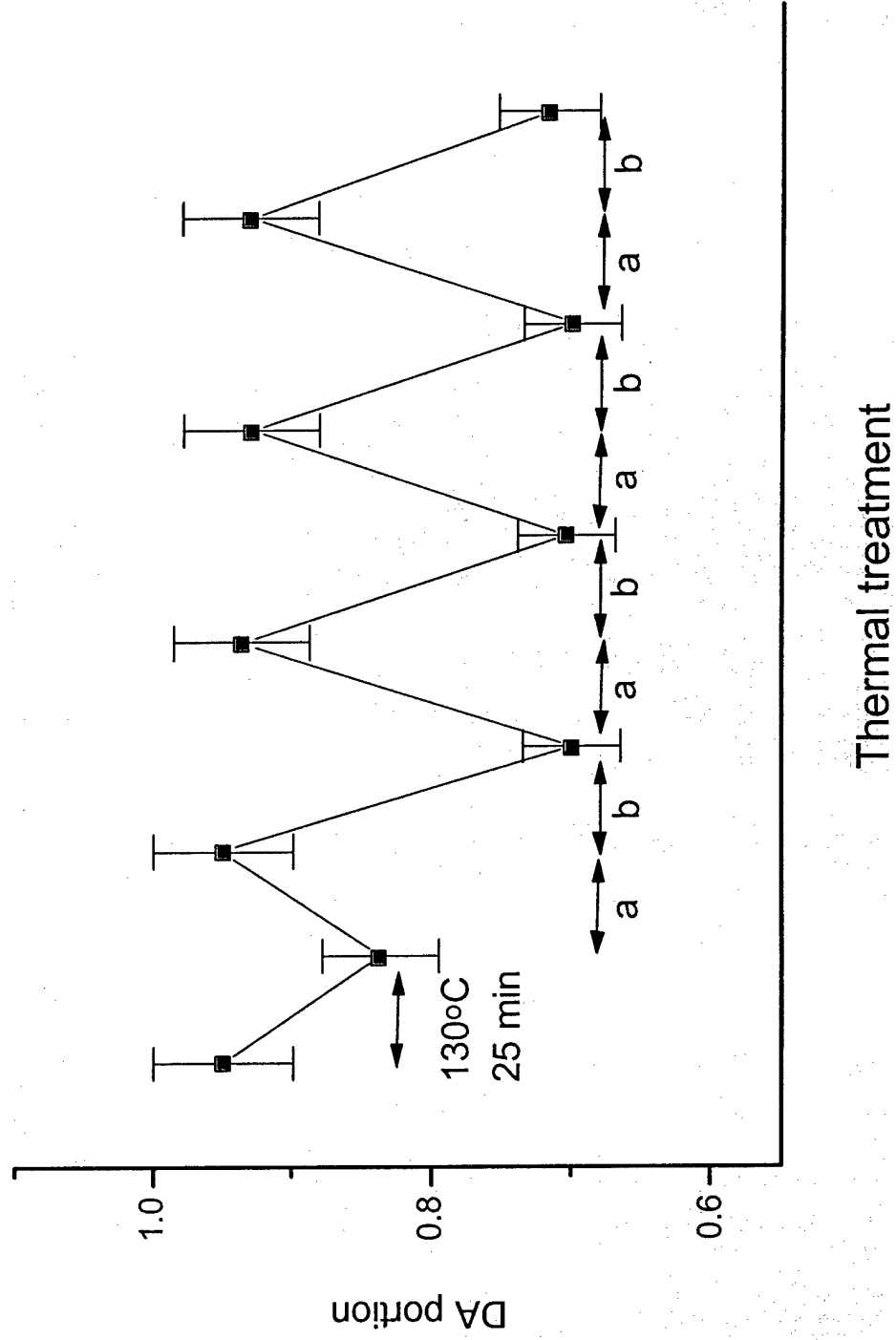


# Mechanical properties

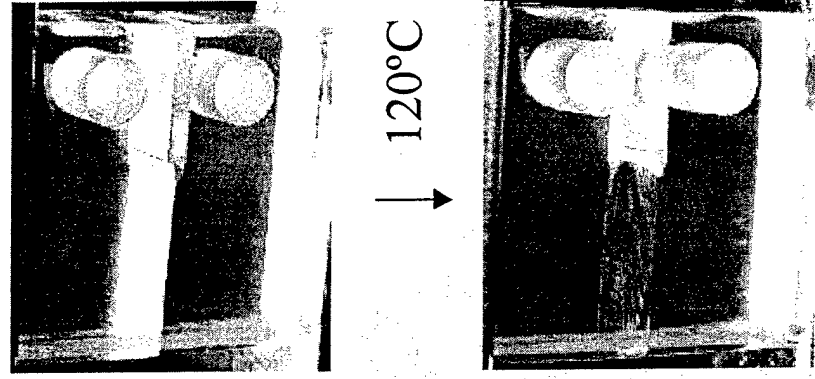
|                        | 3M4F    | 2MEP4F | Epoxy Resins | Unsat Polyesters | ASTM Test methods |
|------------------------|---------|--------|--------------|------------------|-------------------|
| Tensile                |         |        |              |                  | D638              |
| Strength (MPa)         | 68      |        | 27-88        | 4-88             |                   |
| Modulus (GPa)          | --      |        | 2.4          | 2-4.4            |                   |
| Elongation (%)         | 1.6-4.7 |        | 3-6          | <2.6             |                   |
| Ultimate Tensile (MPa) | 241     | 234    |              |                  |                   |
| Compression            |         |        |              |                  | D695              |
| Strength (MPa)         | 121     |        | 102-170      | 88-204           |                   |
| Modulus (GPa)          | 3.6     | 3.7    | 3.4          |                  |                   |
| Strain to Failure (%)  | 25      | 24     |              |                  |                   |
| Flexural               |         |        |              |                  | D790              |
| Strength (MPa)         | 143     |        | 88-143       | 58-156           |                   |
| Modulus (GPa)          | 3.5     |        |              | 3.4-4.2          |                   |
| Young's Modulus (GPa)  | 4.72    | 4.41   |              |                  |                   |
| Poisson Ratio          | 0.32    | 0.36   |              |                  |                   |
| Density                | 1.37    | 1.31   |              |                  |                   |

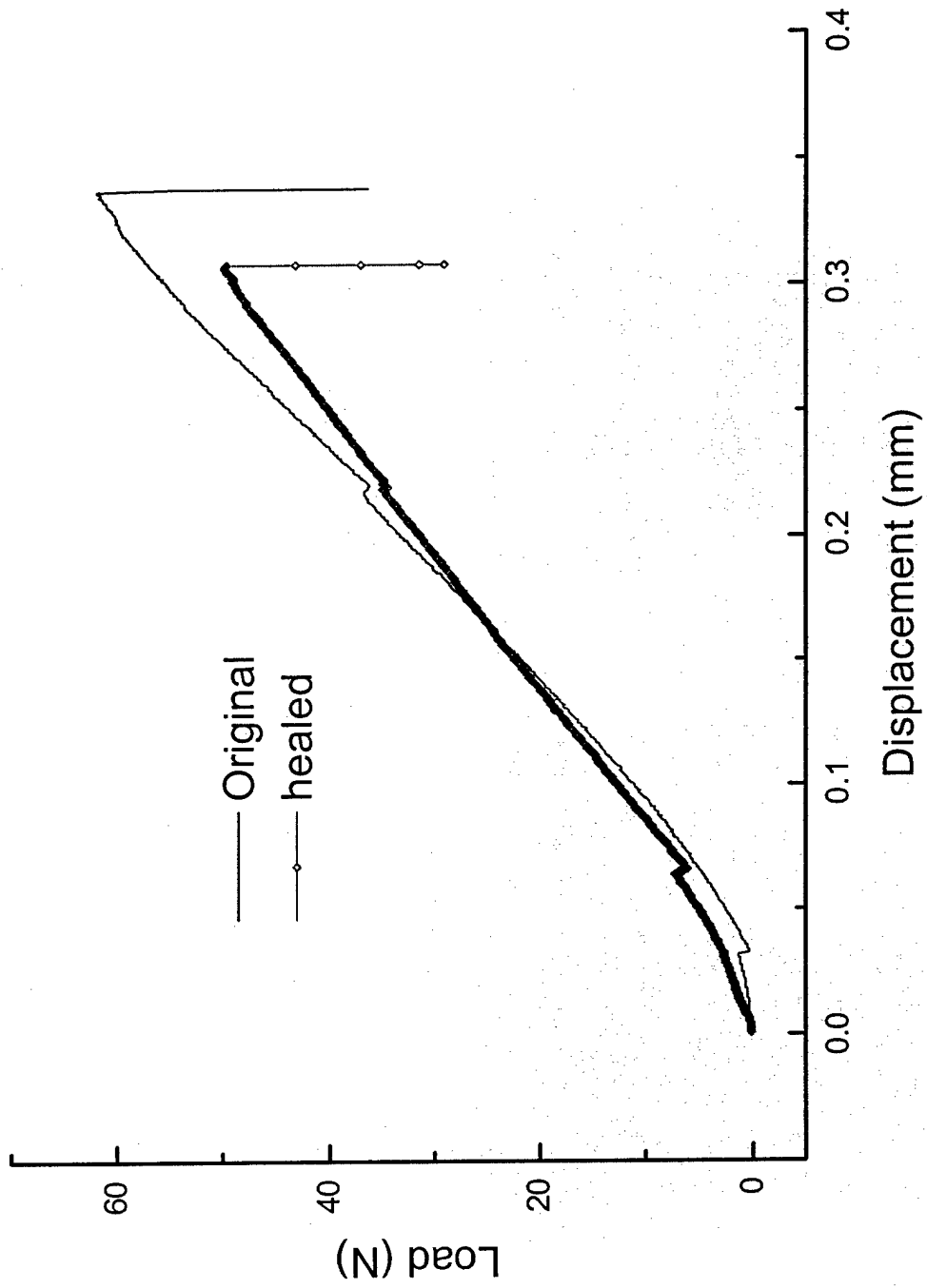
# Thermal reversibility of polymer 3M4F

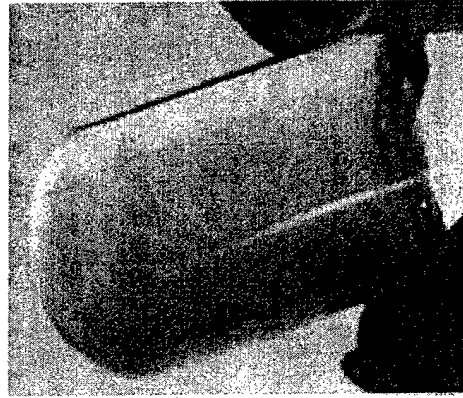
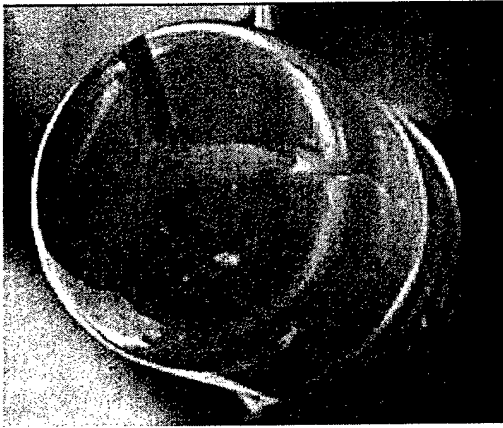
(a) 80°C, 1 h; (b) 150°C, 15 min and then quenched in 77K



# Healing (mending) efficiency of polymer 3M4F







# Healing effect



heat ↑

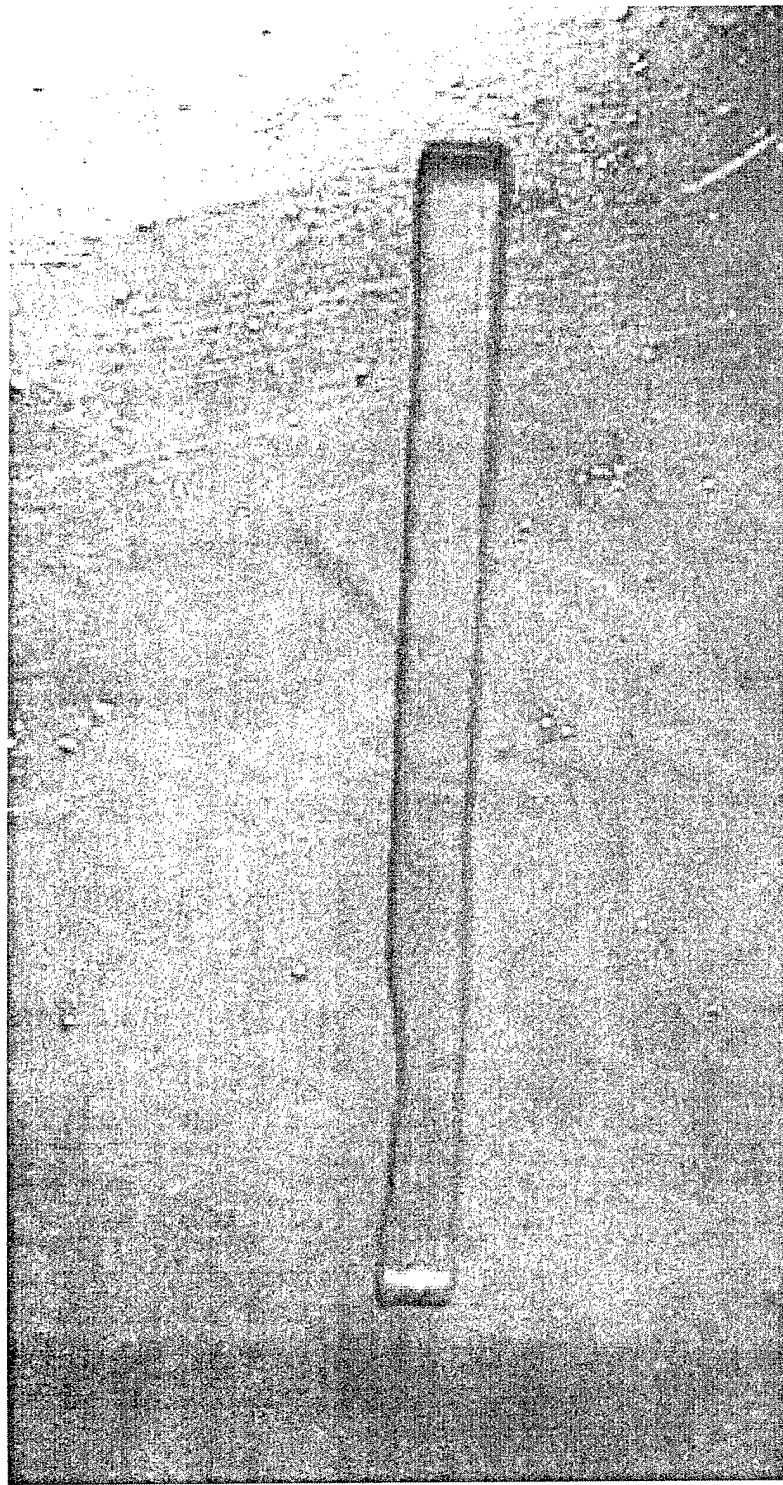


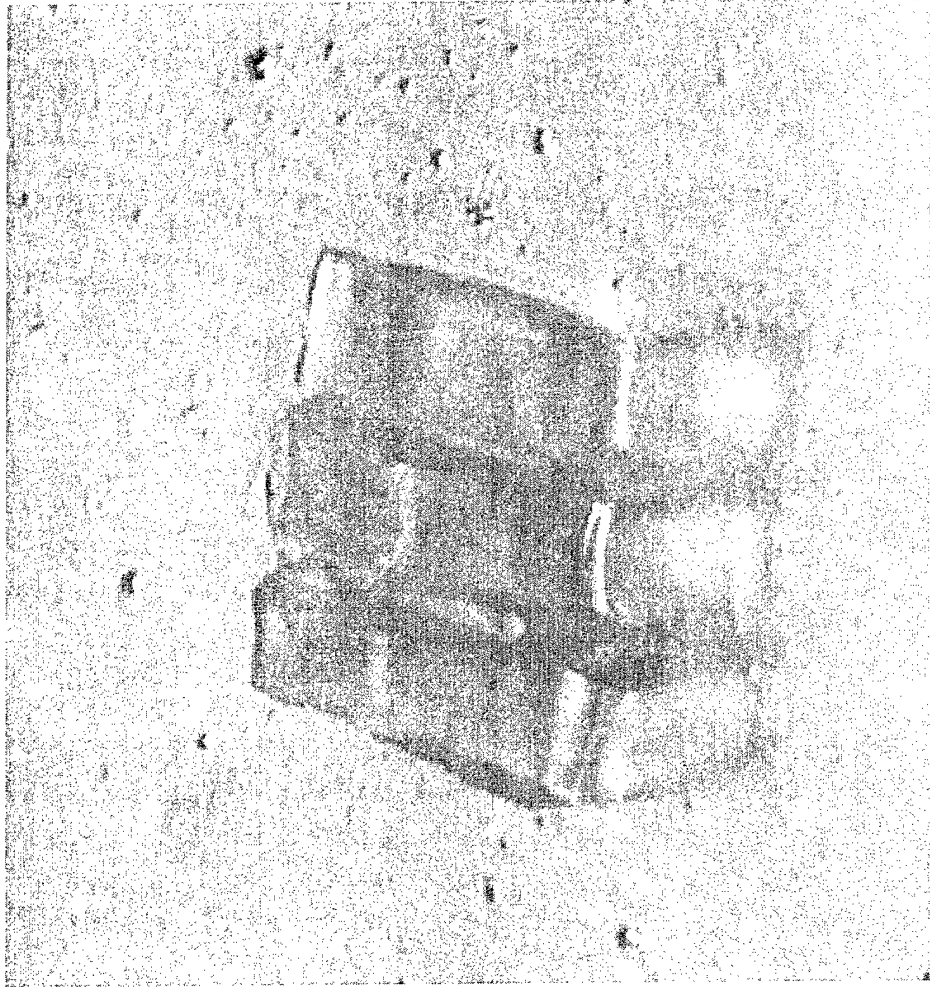
## Summary

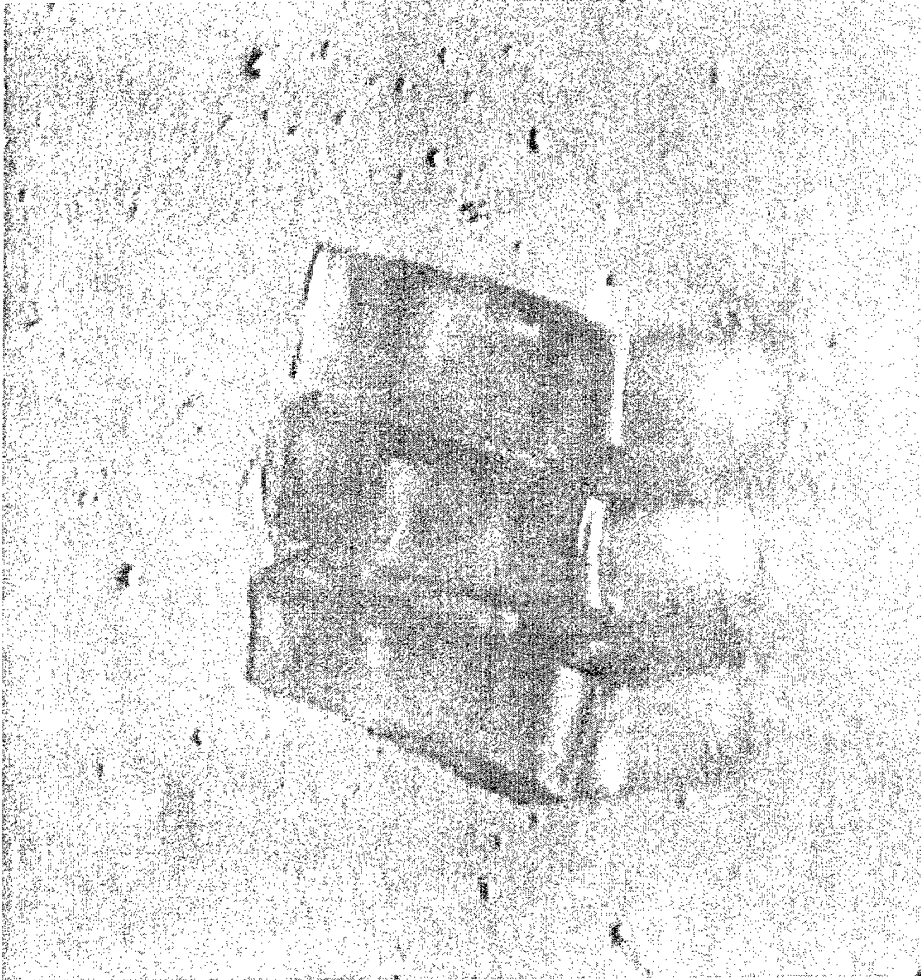
Thermally re-mendable polymers have been developed, which can be healed multiple times. The healing process does not require additional ingredients.

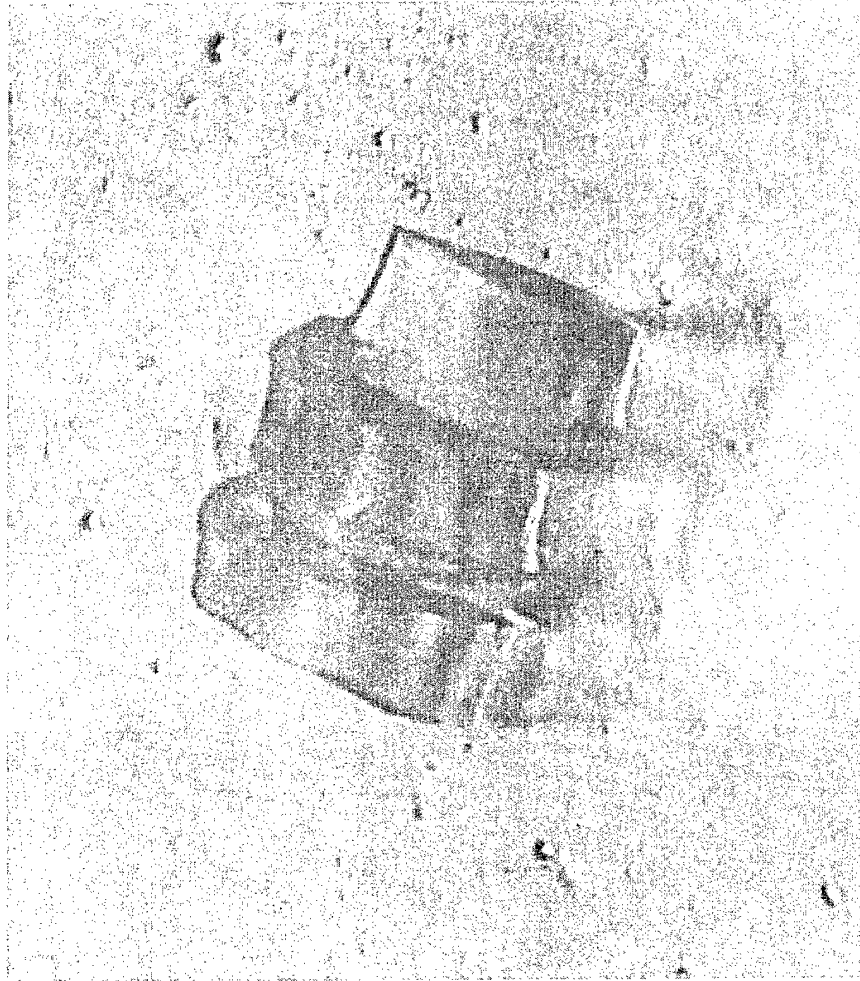
## Future designs of re-mendable polymeric materials

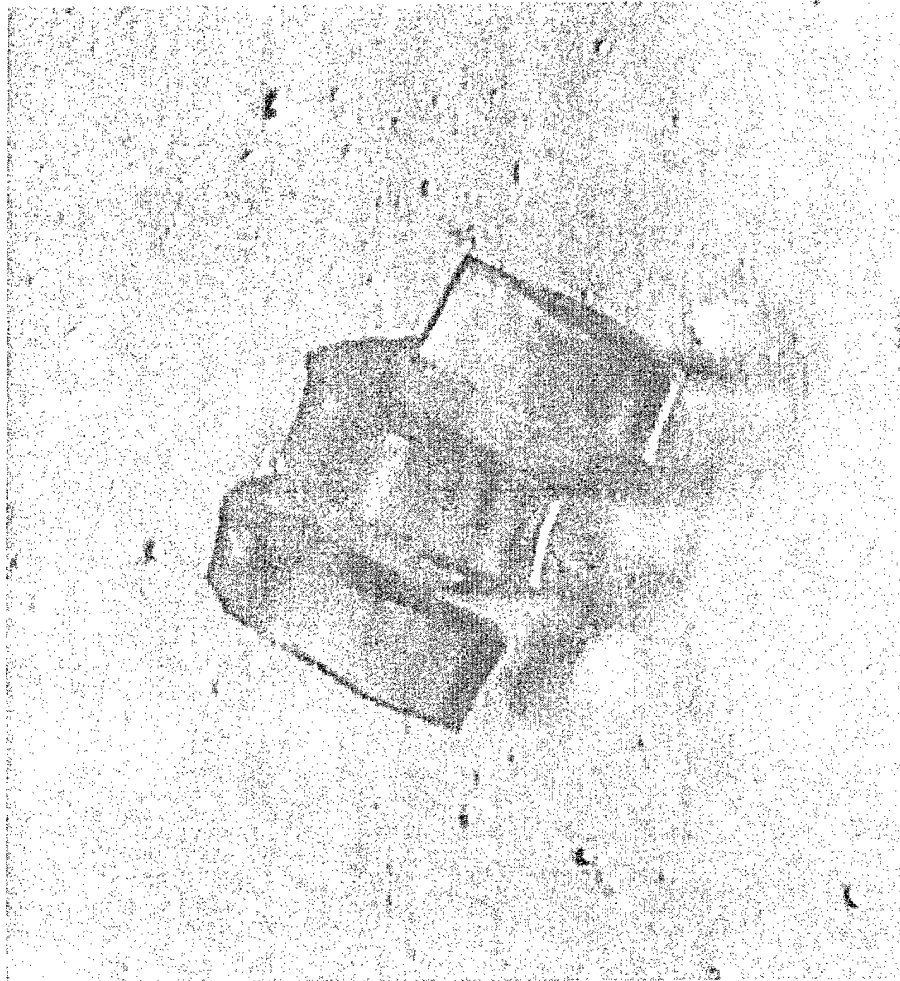
- Better mechanical properties
- Higher glass transition temperature
- Smart structures with self-response ability (shape memory)

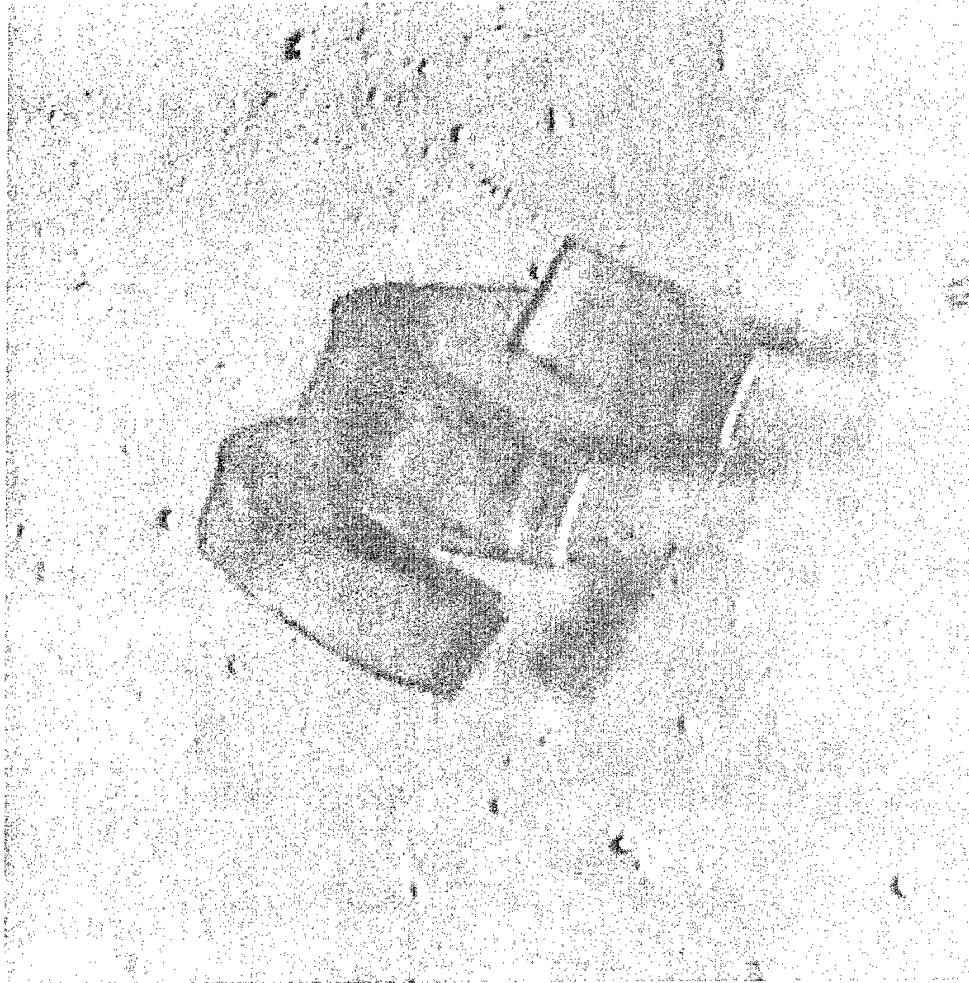


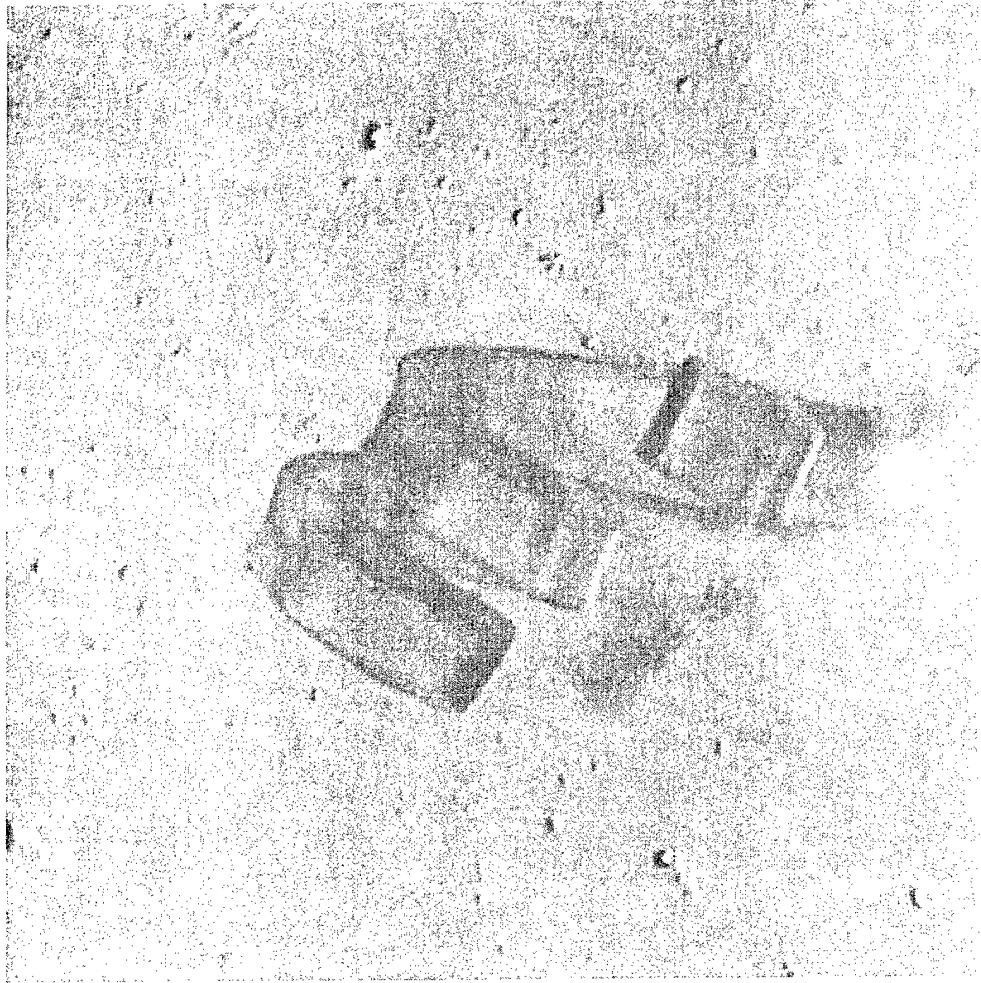


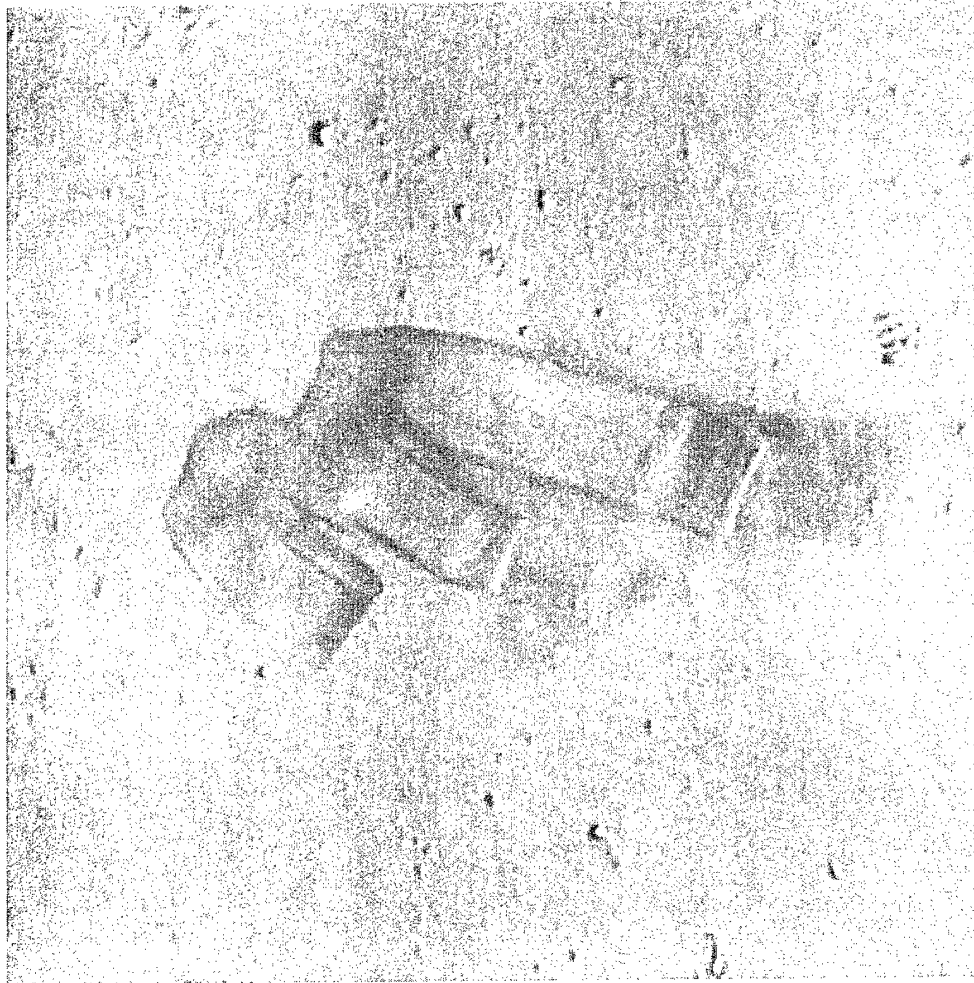


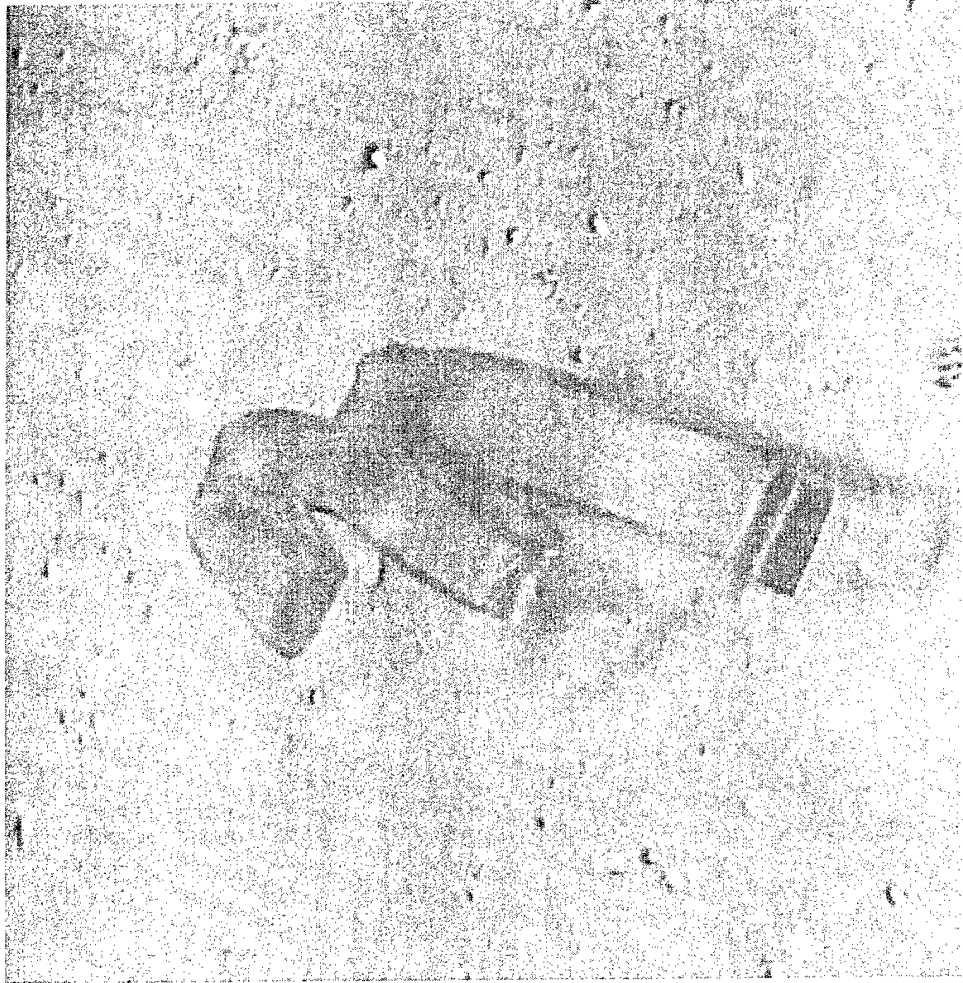


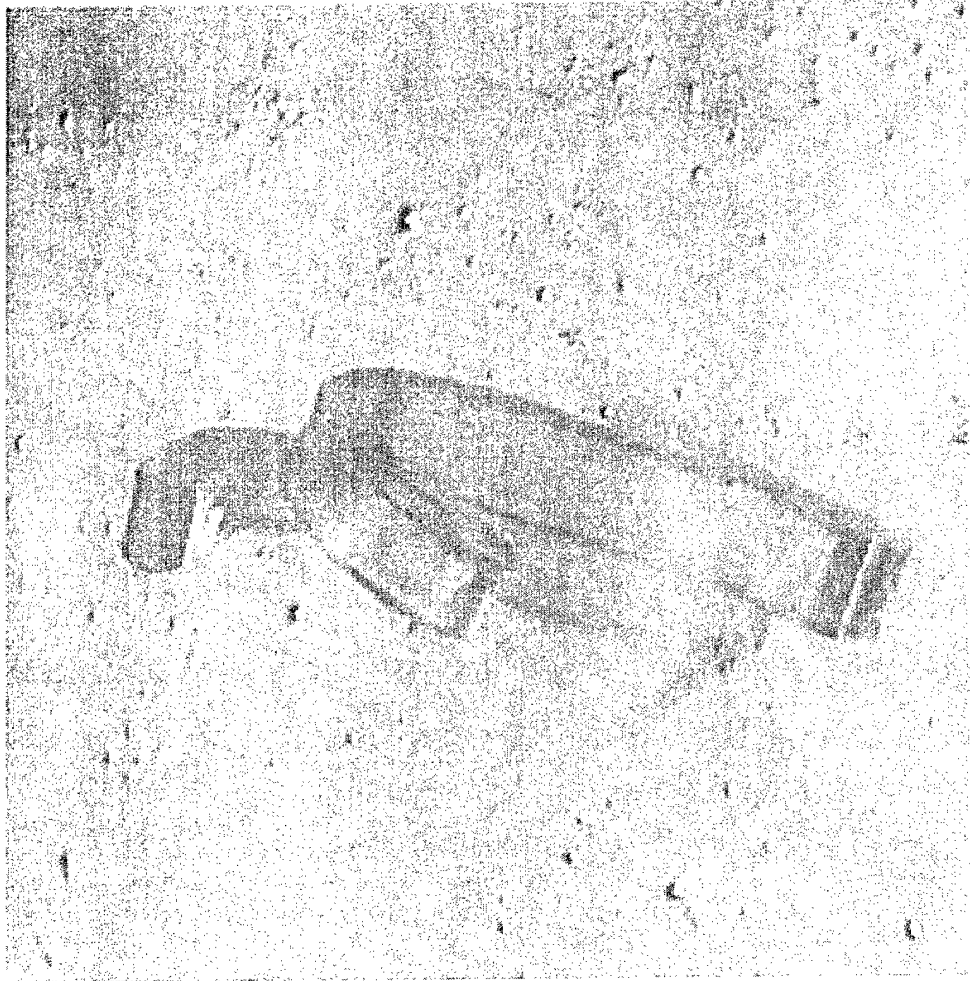


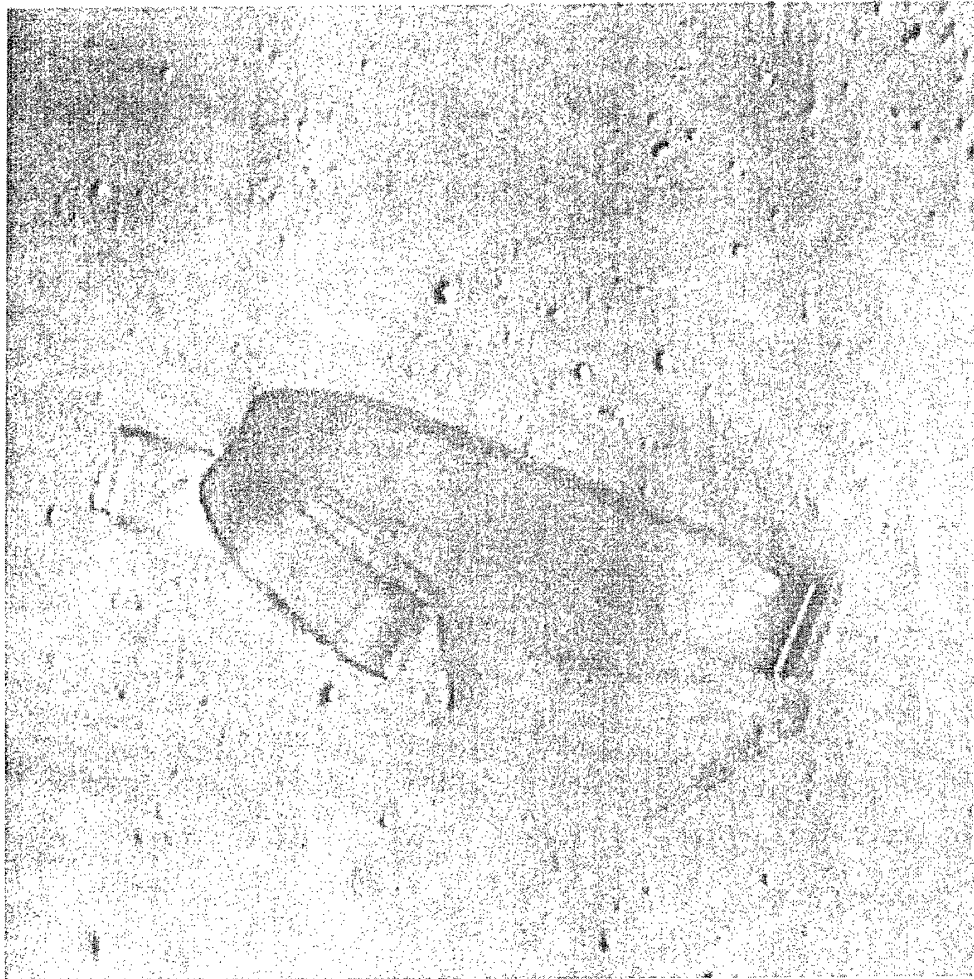


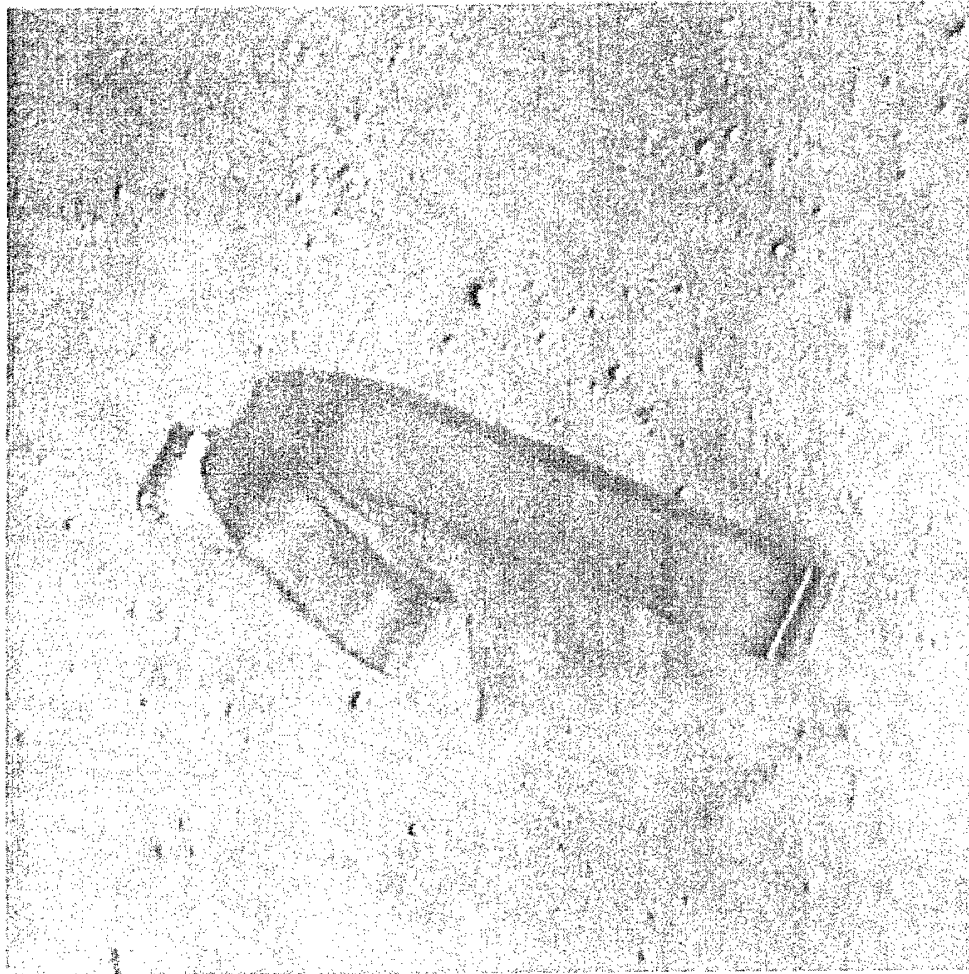


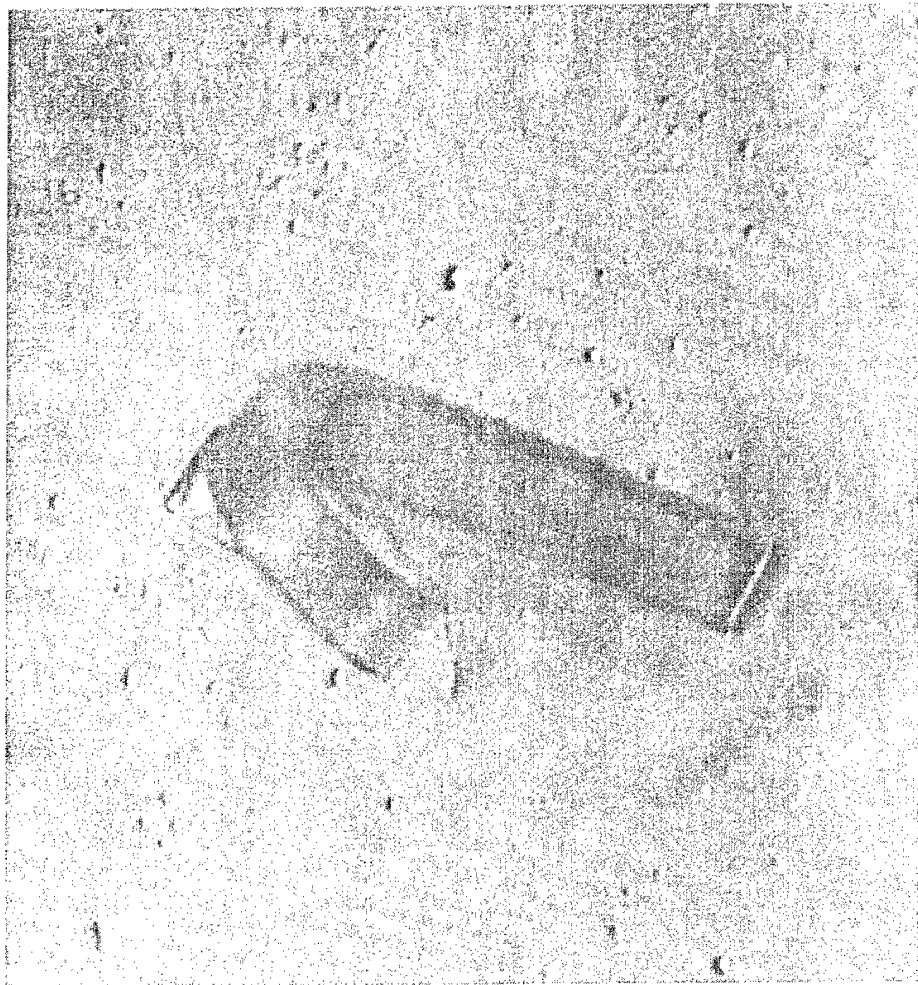


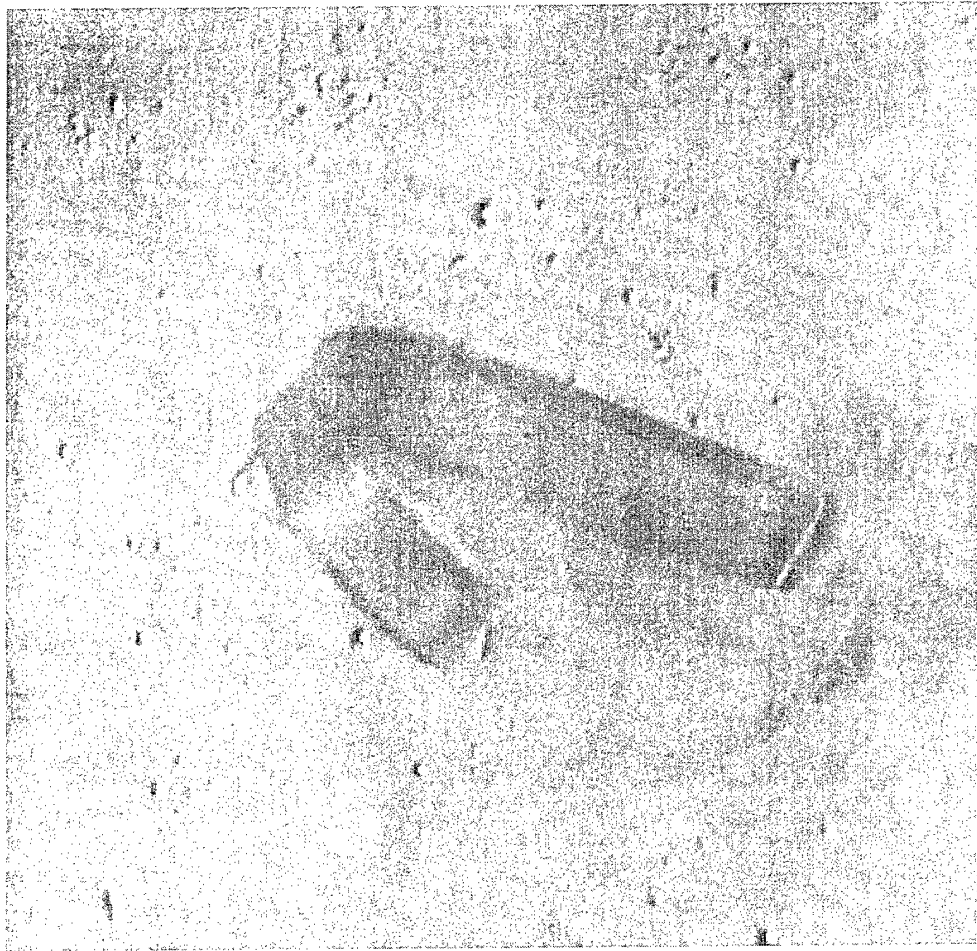




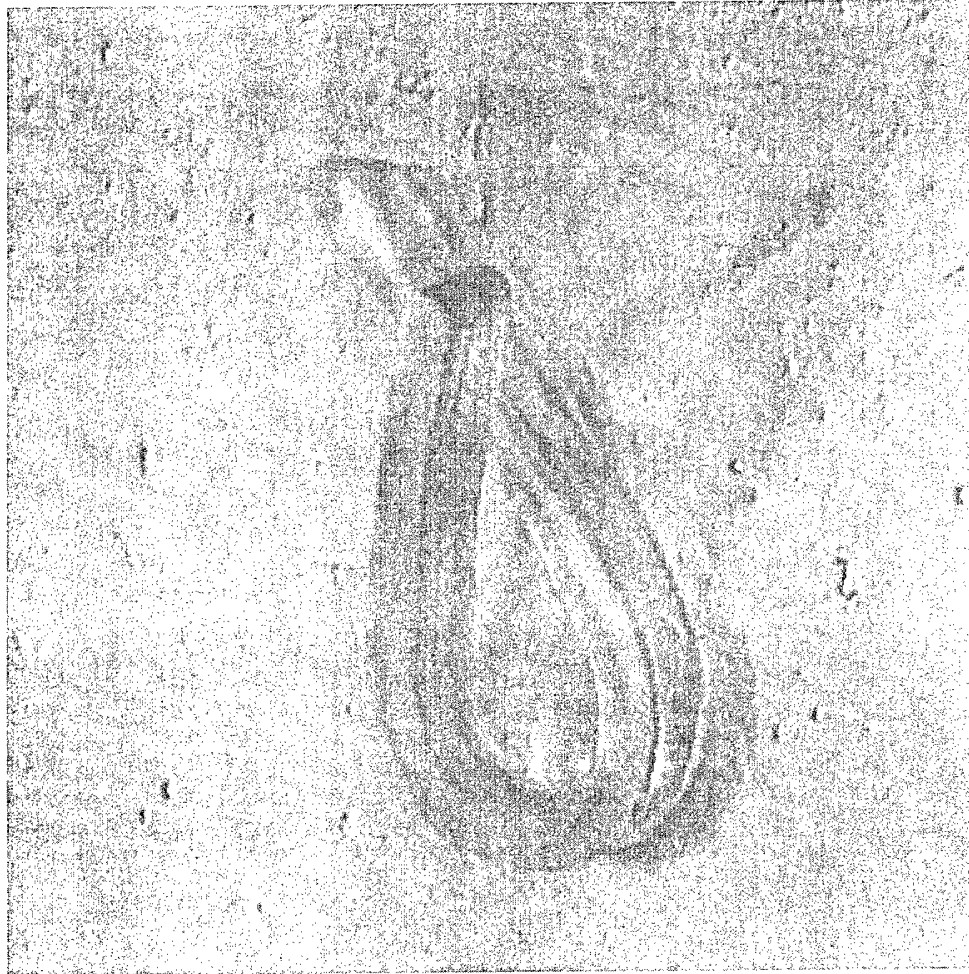


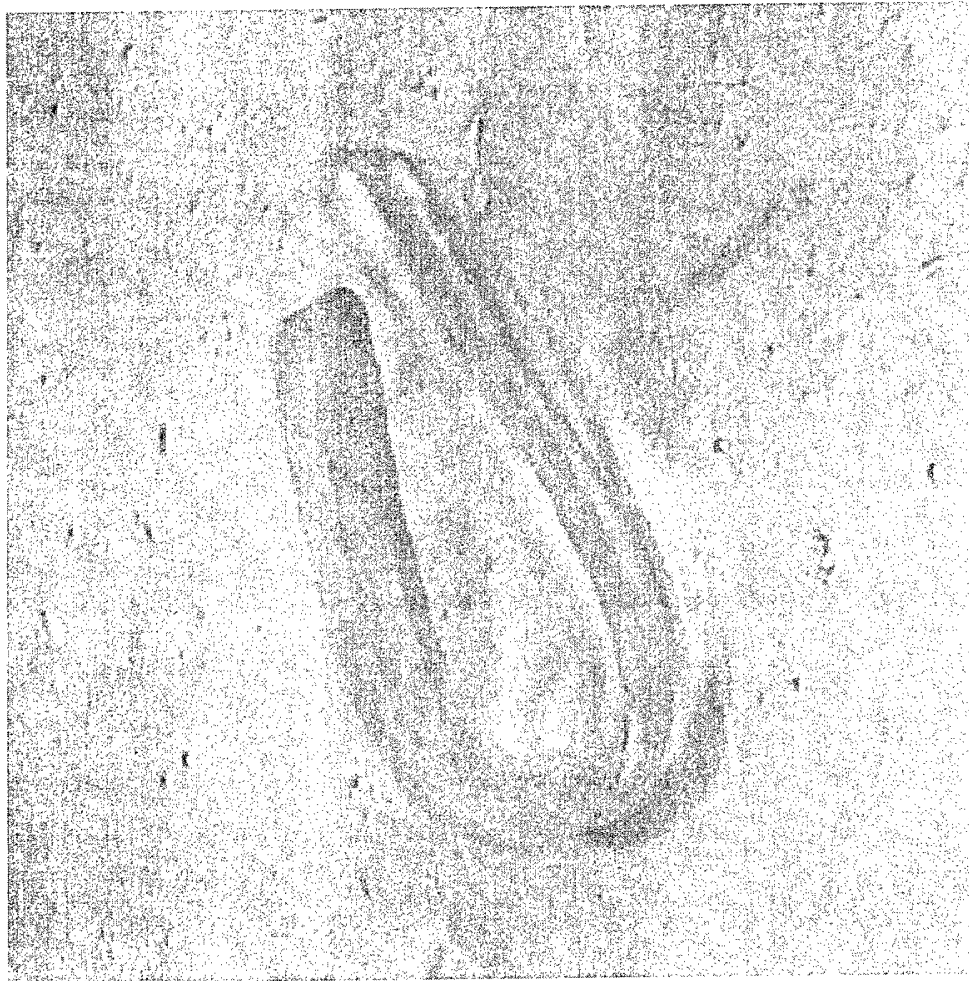


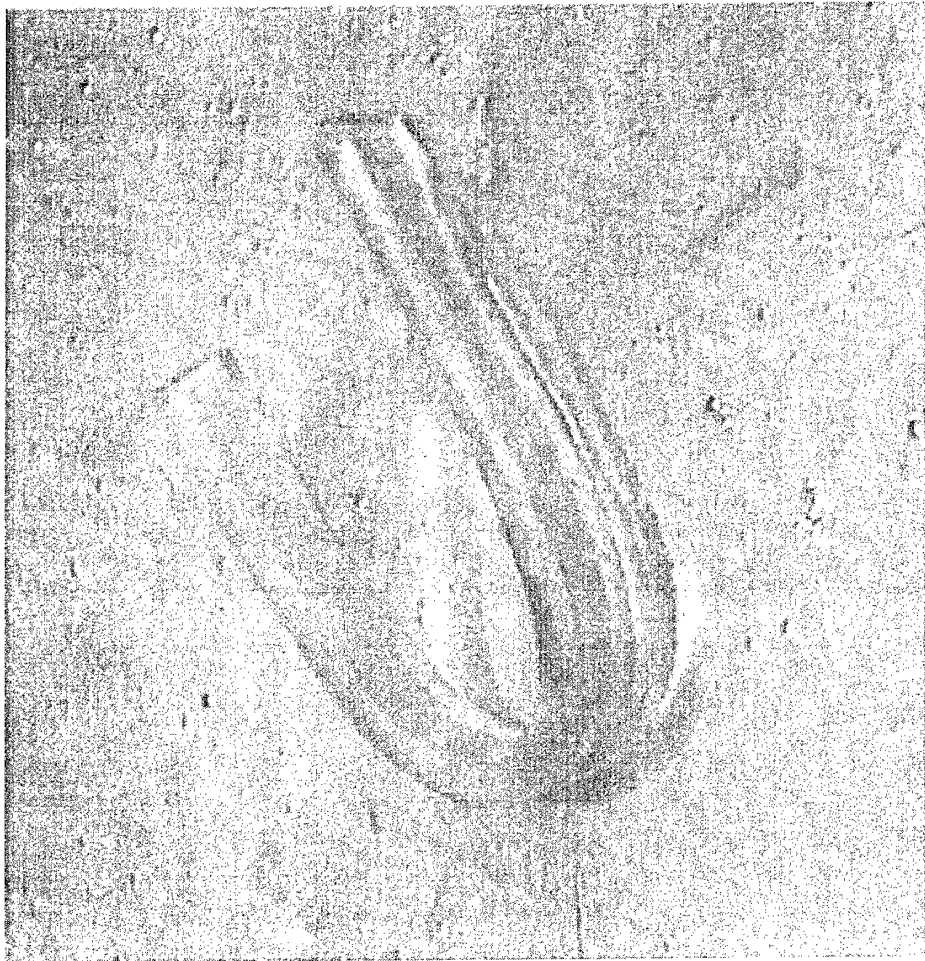


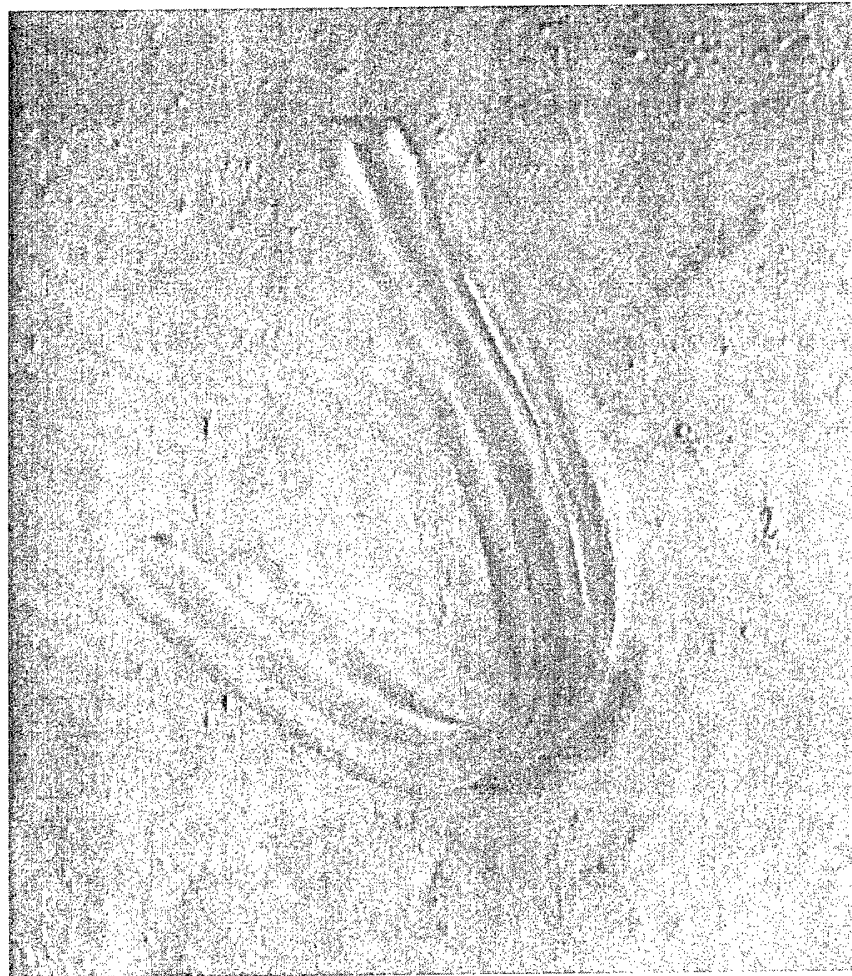


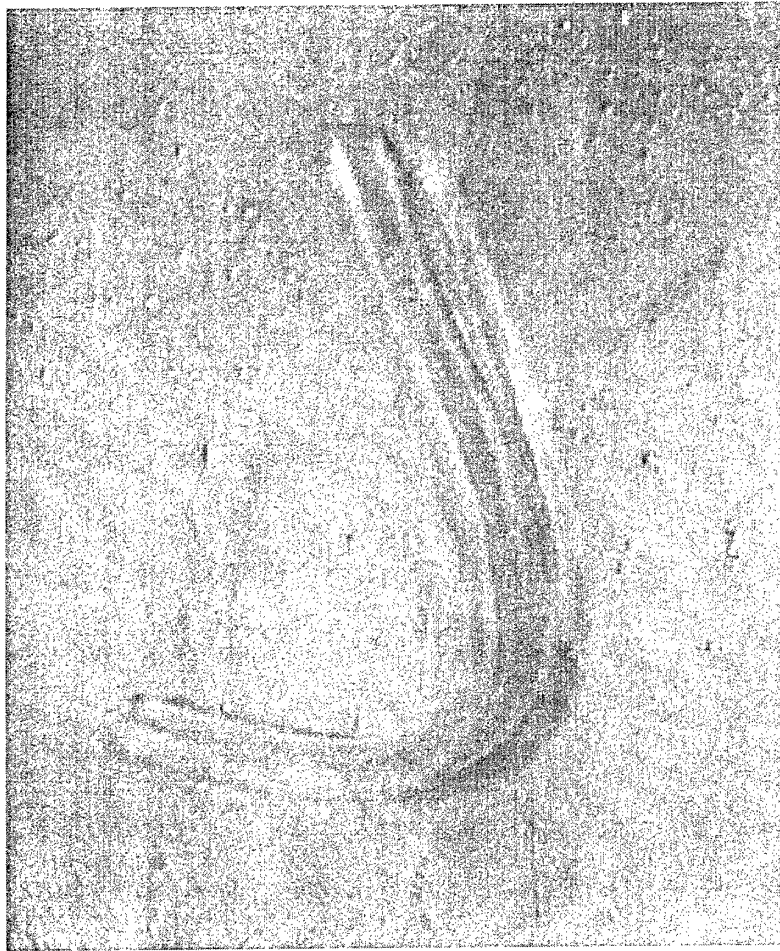










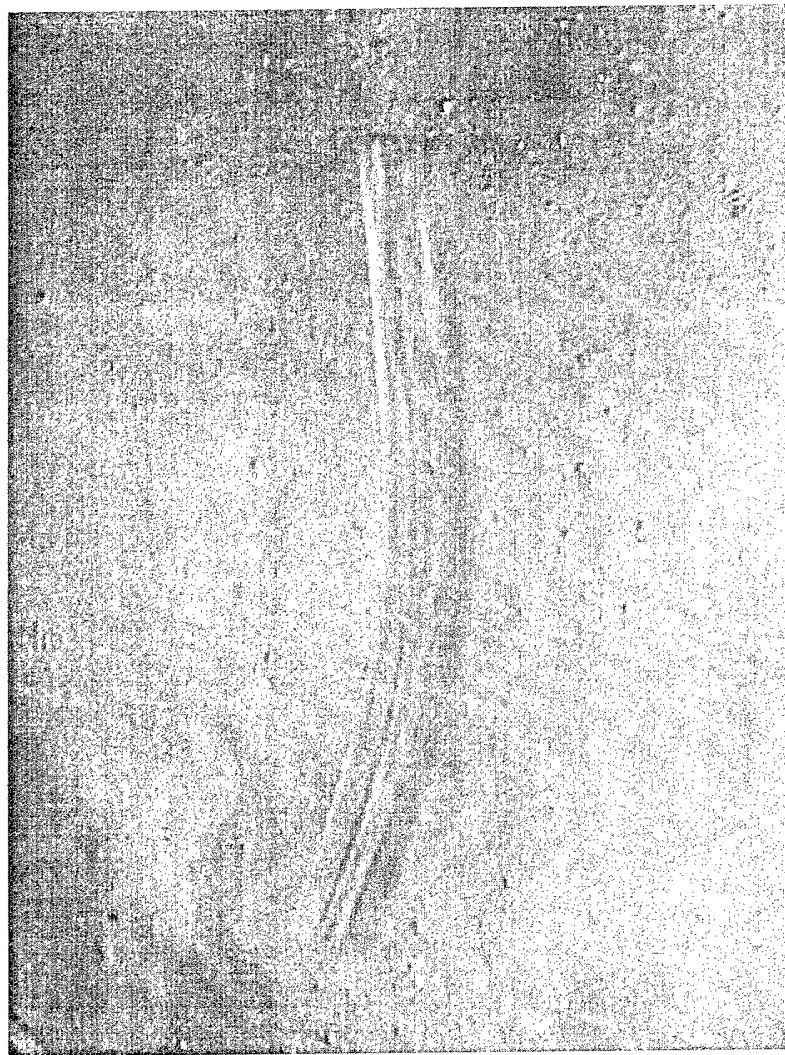


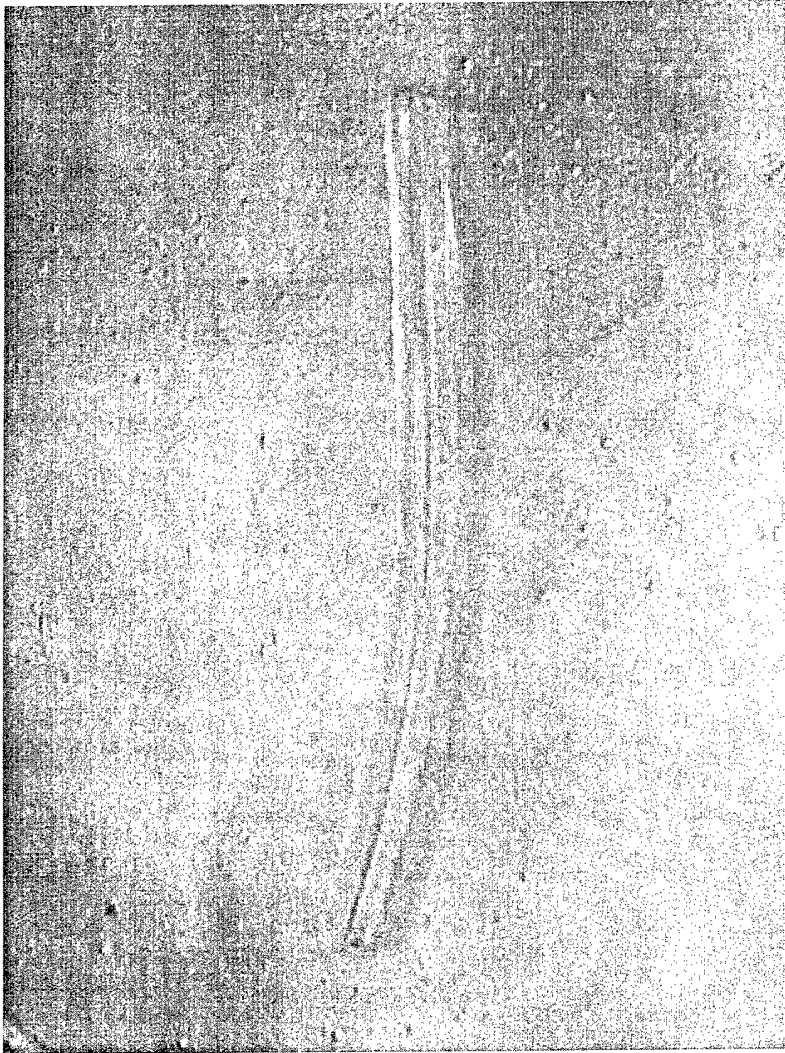


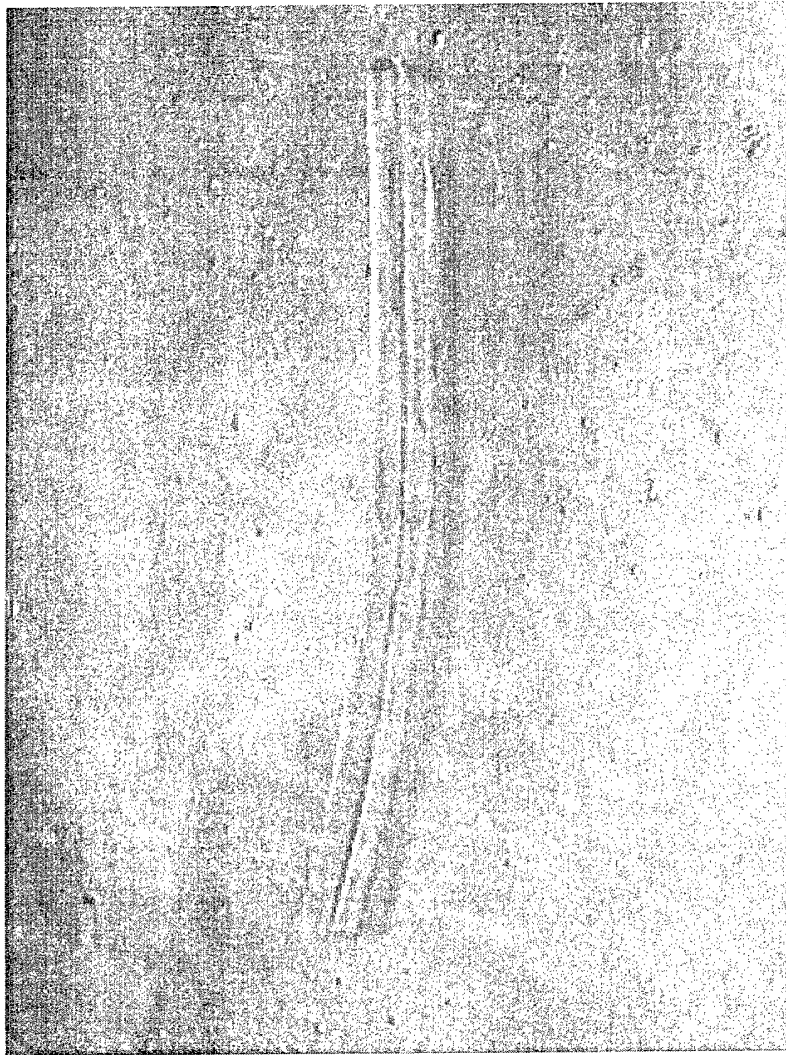


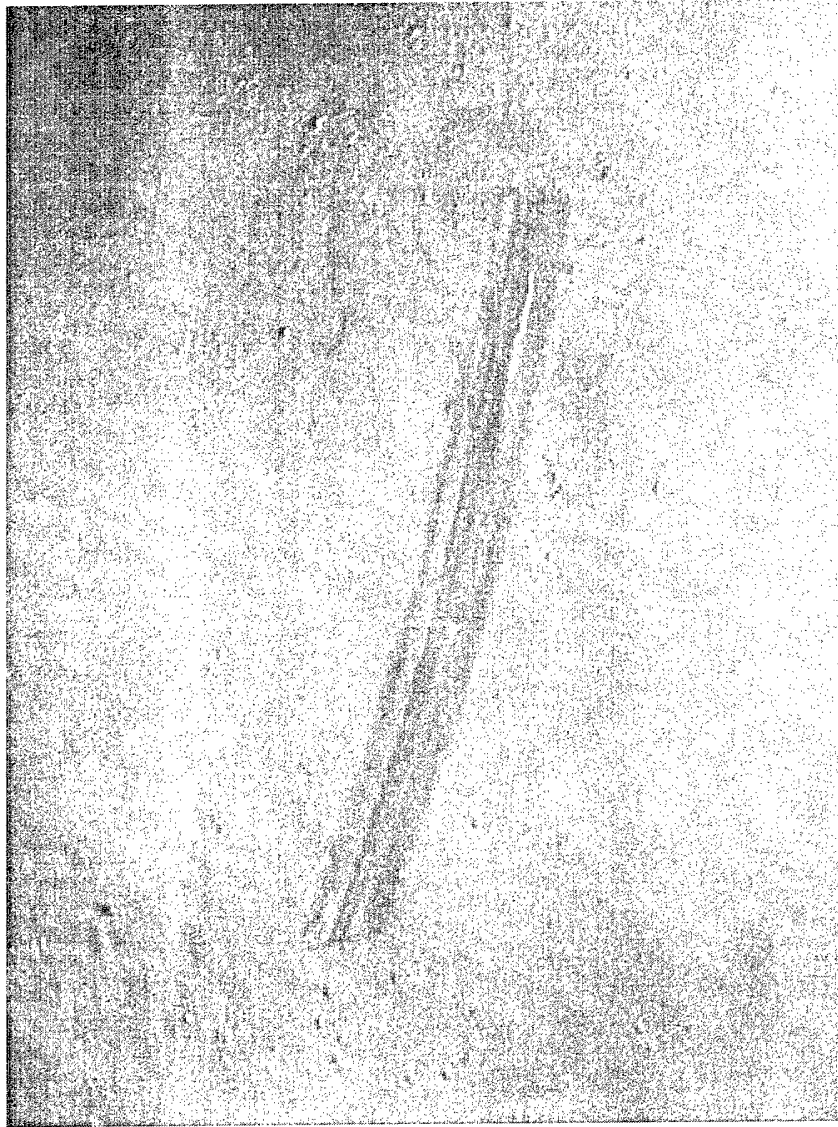


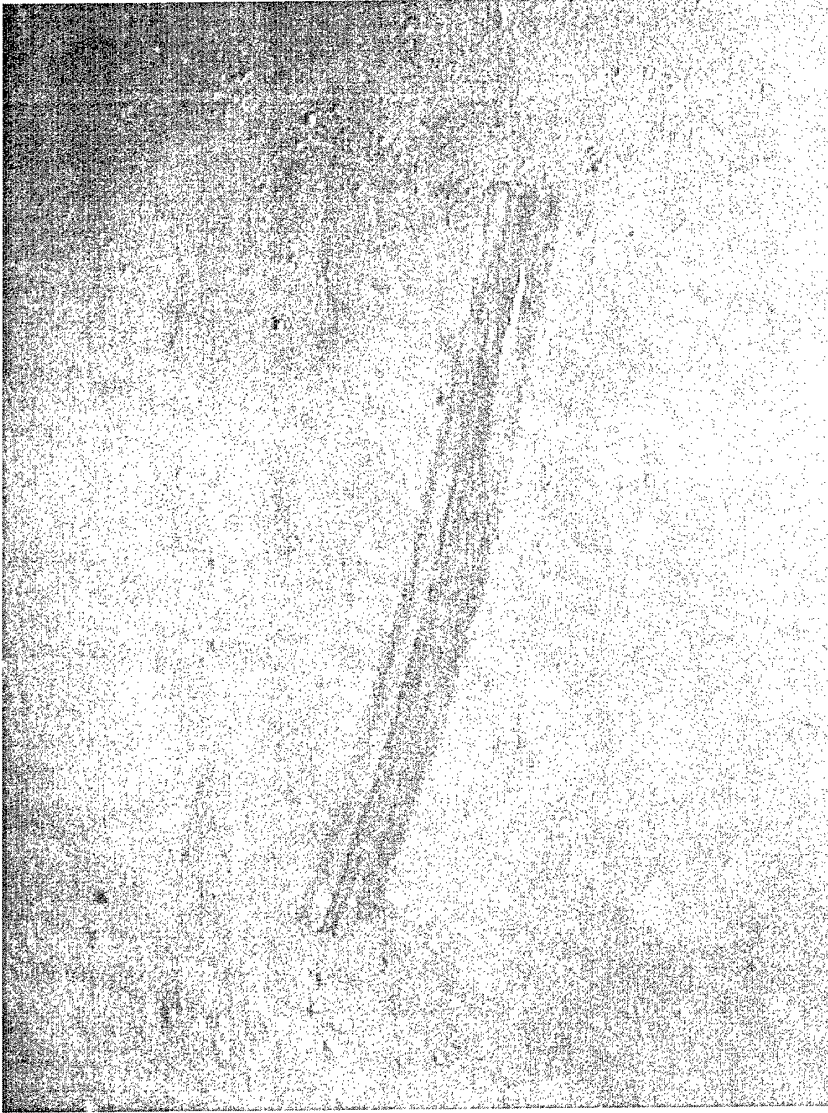






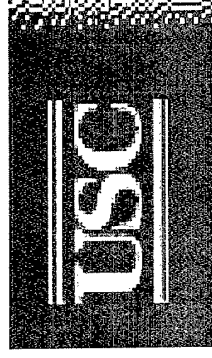






# Acknowledgments

**UCLA**



**Professor Fred Wudl**

**Prof. Steven R. Nutt**

**Prof. Ajit Mal**

**Prof. Kanji Ono**

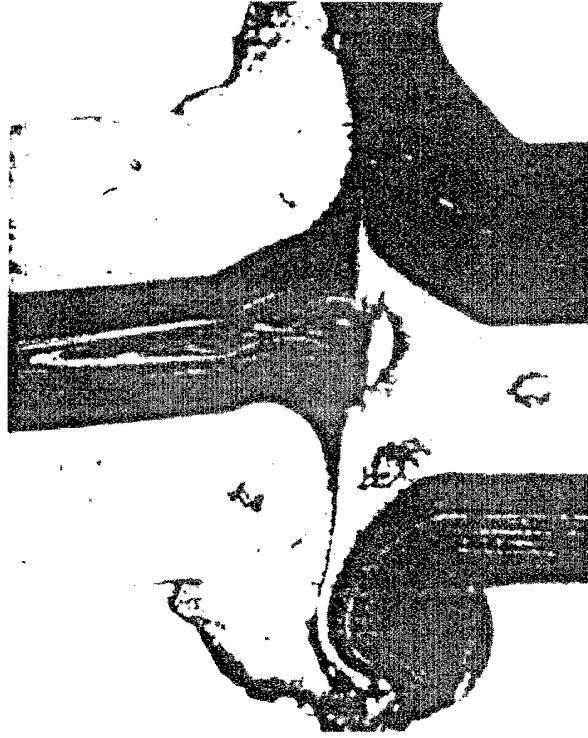
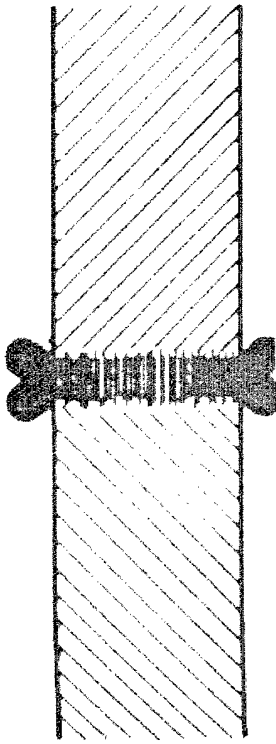
**\$\$\$ NSF \$\$\$**

Differences of healing process between our re-mendable polymers and linear polymers

Regeneration of chain entanglement is necessary for linear polymers

*Much higher operating temperatures  
(PP: 250 -300°C)*

*Manual pressure*



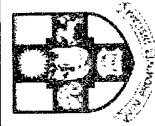
Bucknall, C. B.; Drinkwater, I. C.; Smith G. R. *Polym. Eng. Sci.* 20, 1980, 432.

# **Novel and Multi-Functional Composites**

**Michael Wisnom**

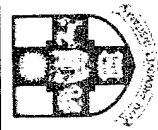
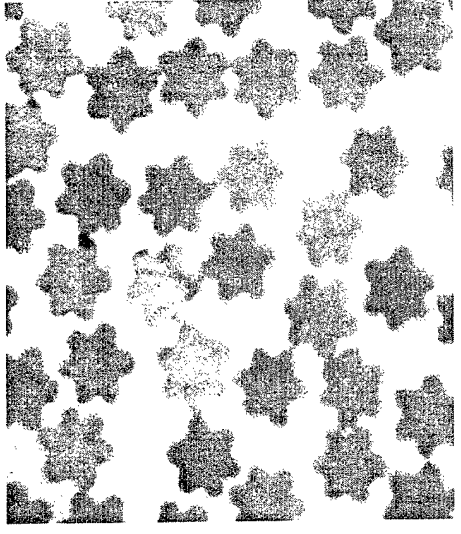
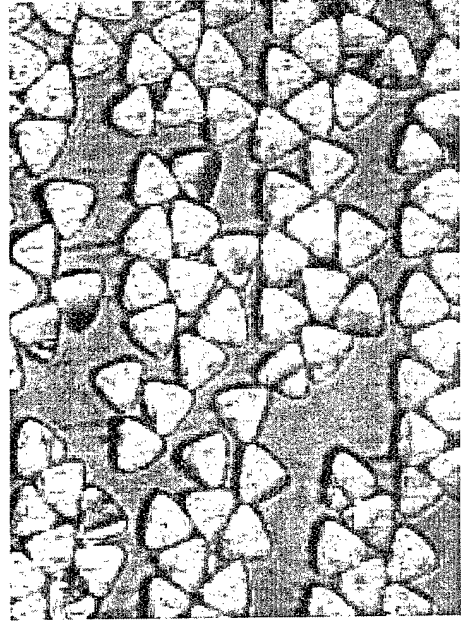
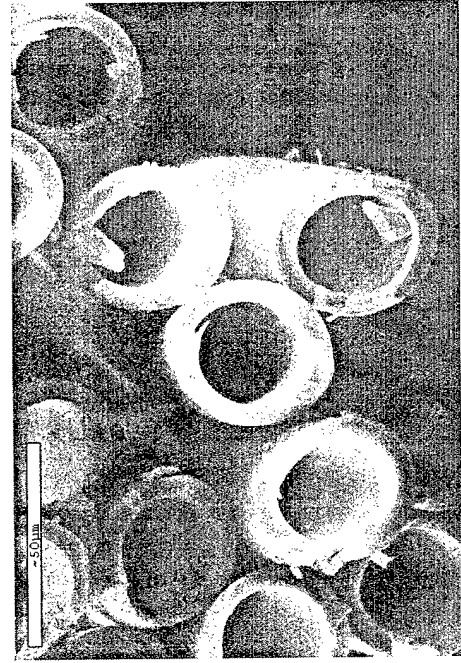
**and**

**Ian Bond**



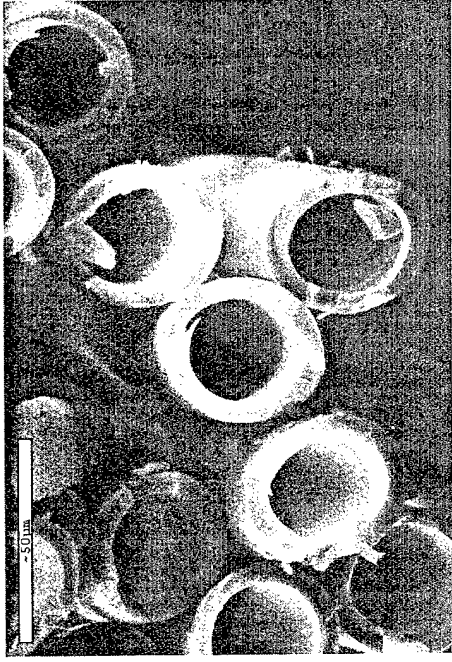
University of Bristol Department of Aerospace Engineering

# Shaped fibres made at Bristol

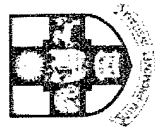


University of Bristol Department of Aerospace Engineering

# Impact detection with hollow fibre composites

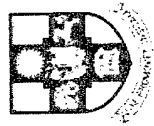
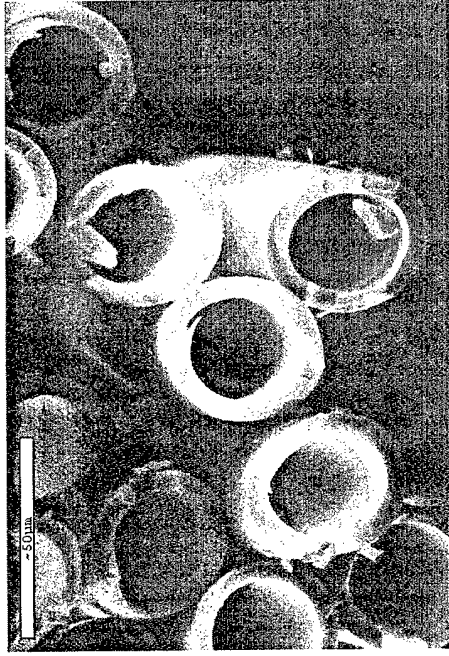


- Hollow fibre layer on surface of structure
- Fibre crushing absorbs impact energy
- Leaves visible dent
- Layer can be tuned to impact severity

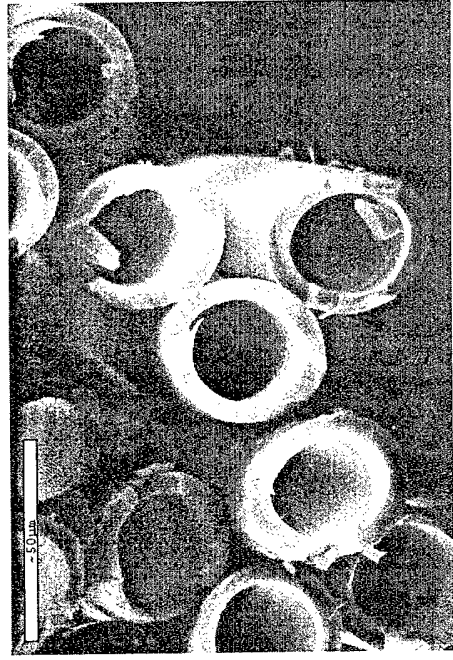


# Active fibres

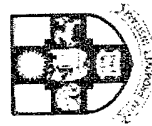
- Fibres can be filled with active component to create multi-functional composites
  - Magnetic material for electric generation
  - Stealth



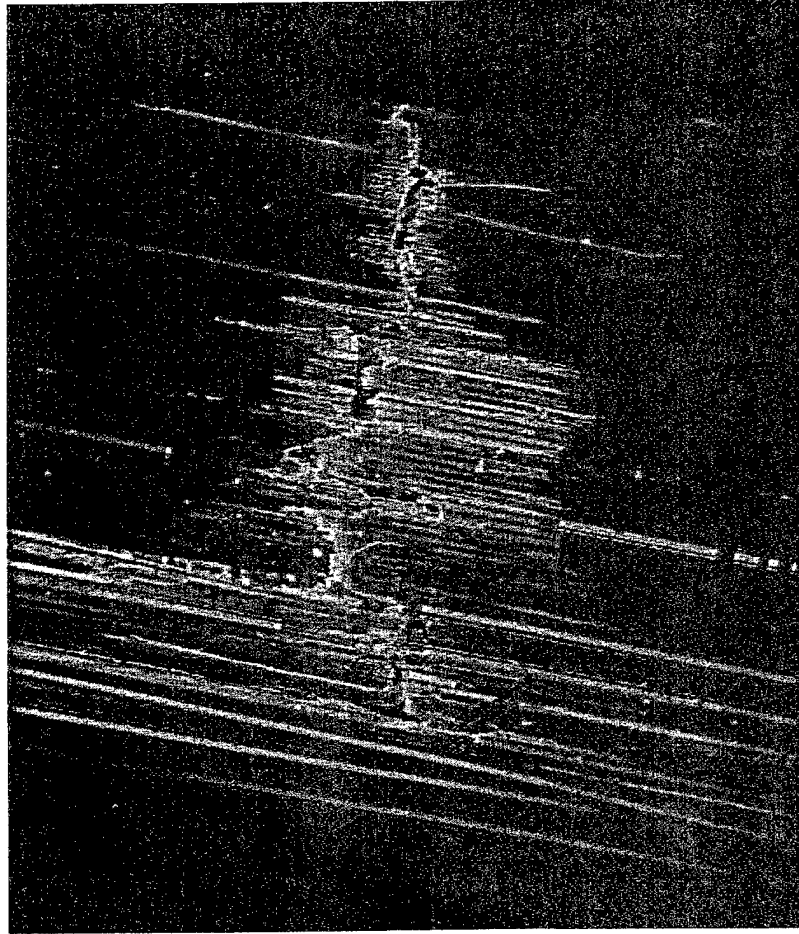
# Bleeding composites



- **Fibres can be filled with dye that bleeds out and allows damage to be detected**
- **Uncured resin in fibres can act as healing agent**

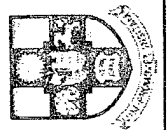


# Bleeding composites



- **Fluorescent dye mixed with uncured resin**
- **Impact damage clearly visible under UV light**

BEST AVAILABLE COPY



University of Bristol Department of Aerospace Engineering

# Self-healing and Electronic Assemblies

Andrew Skipor  
Distinguished Member of the Technical Staff

Mechanical Sciences Group  
Motorola Advanced Technology Center  
Schaumburg, IL  
847-576-0754

1<sup>st</sup> AIR FORCE WORKSHOP ON  
“MULTIFUNCTIONAL AEROSPACE MATERIALS”  
October 23-24, 2002, Purdue University,  
W. Lafayette, IN



**MOTOROLA LABS**

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# Self-Heal Materials:

Imagine a future when our products  
get damaged, they heal themselves.



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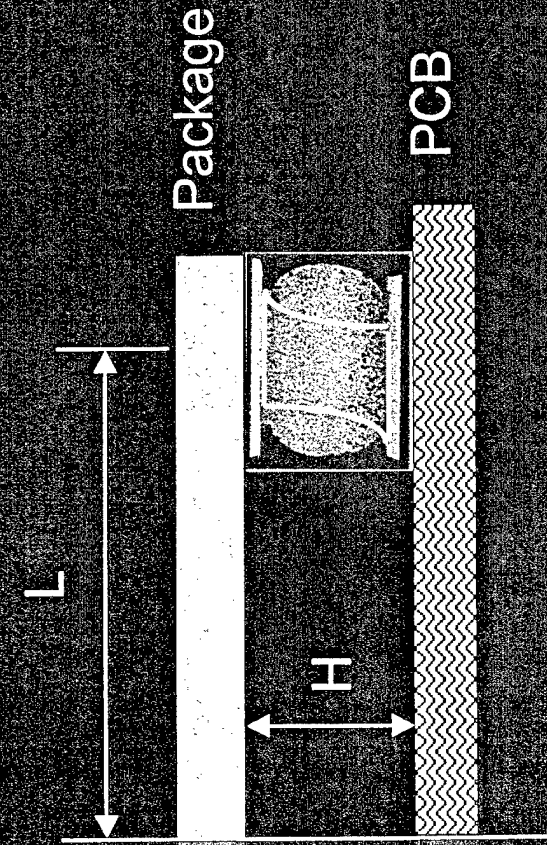
**intelligence**



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# Interconnect Stress: Background

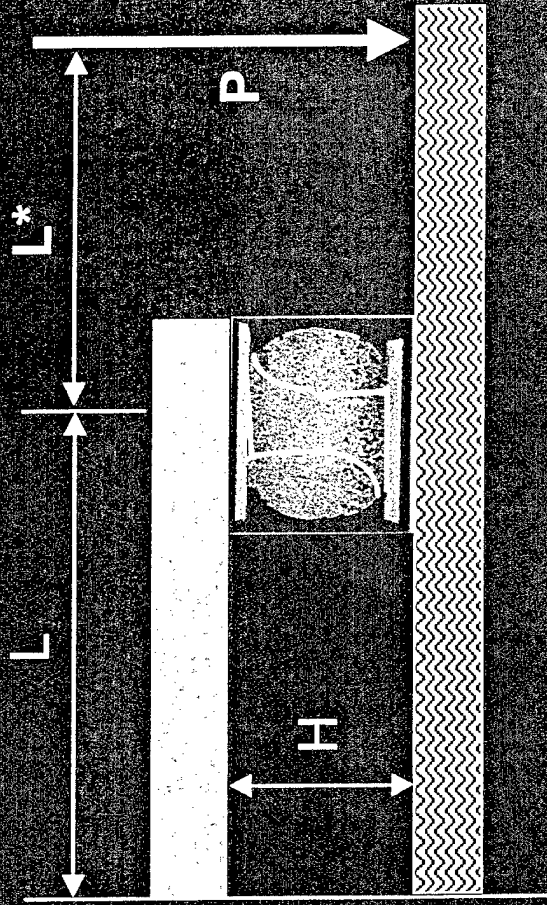
## Bending Fatigue vs. Thermal Fatigue



Solder strain drivers:

$$\sim (\alpha_1 - \alpha_2) \Delta T$$

Thermal Fatigue Reliability



Solder strain drivers:

$$\sim \Delta P \text{ (load or deflection), } L^*$$

Bending Fatigue Reliability



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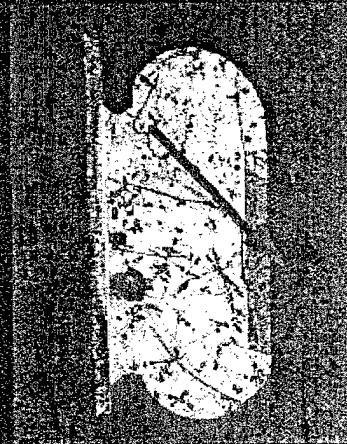
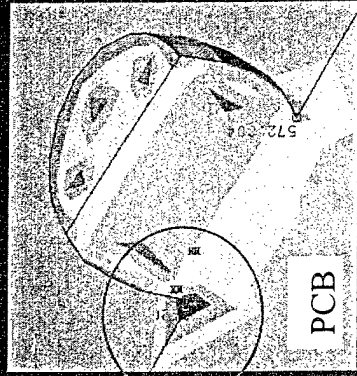
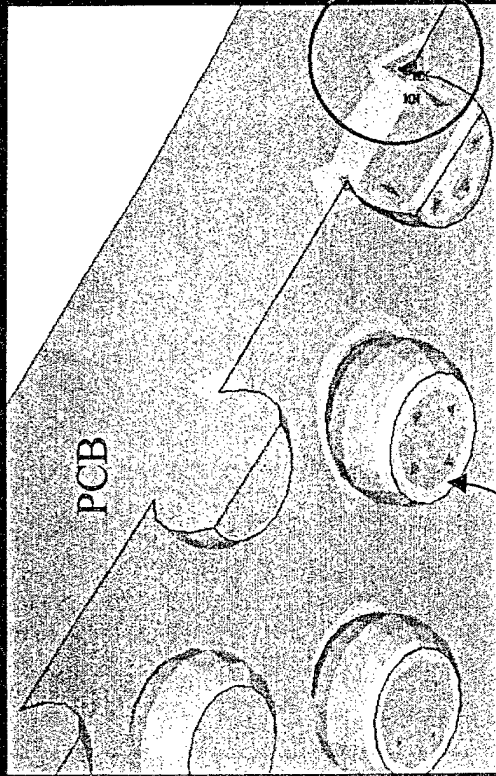
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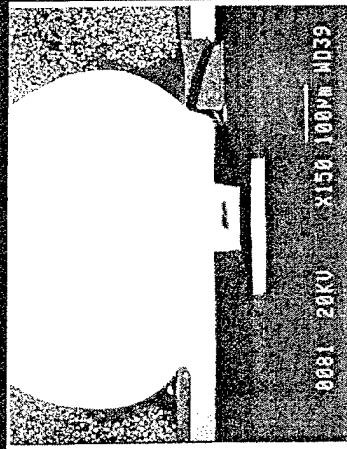
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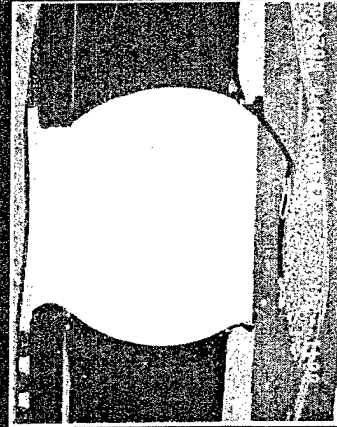
Examples of interconnect resin fracture



Mechanical bend fatigue.



Drop impact, high rate flexure.



"Squeeze" test.

Electronic Package

PCB



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Finite element model results:  
PCB strain concentration  
and distribution

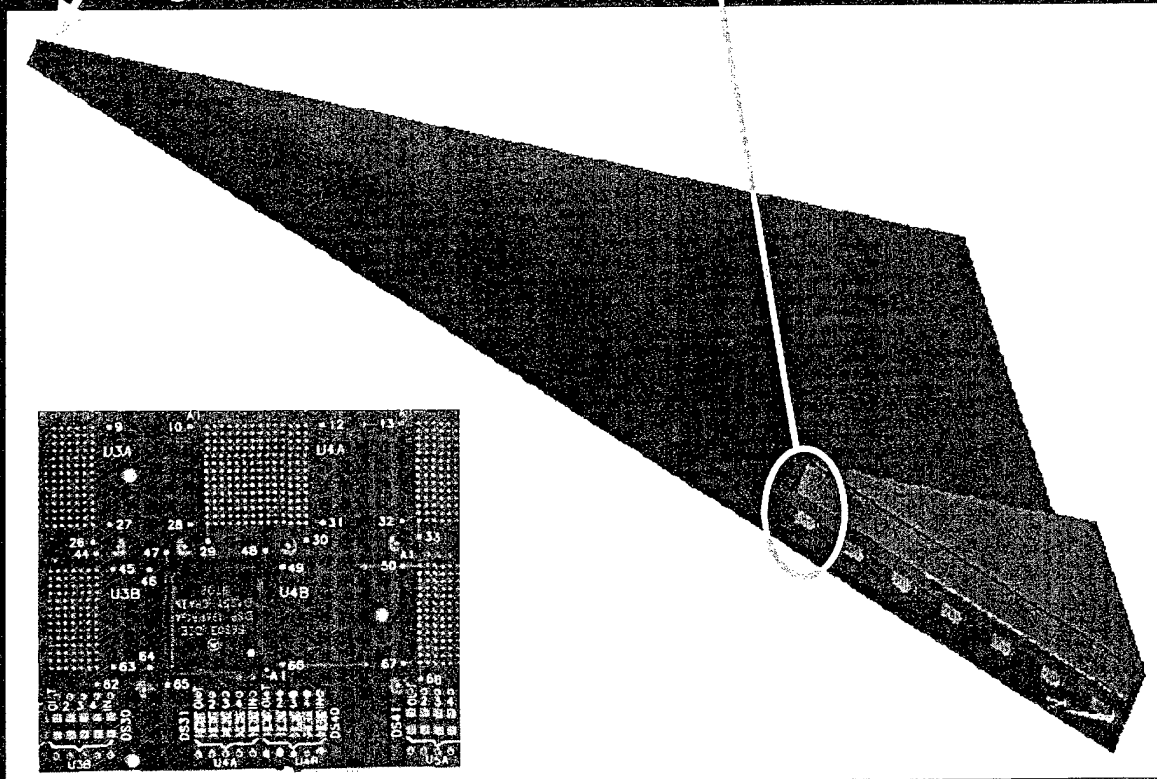
displacement

Corner  
joint #1  
location

PCB strain  
concentration,  
reduction

PCB

Package center



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# PCB Strain/Displacement Distribution

0.5mm

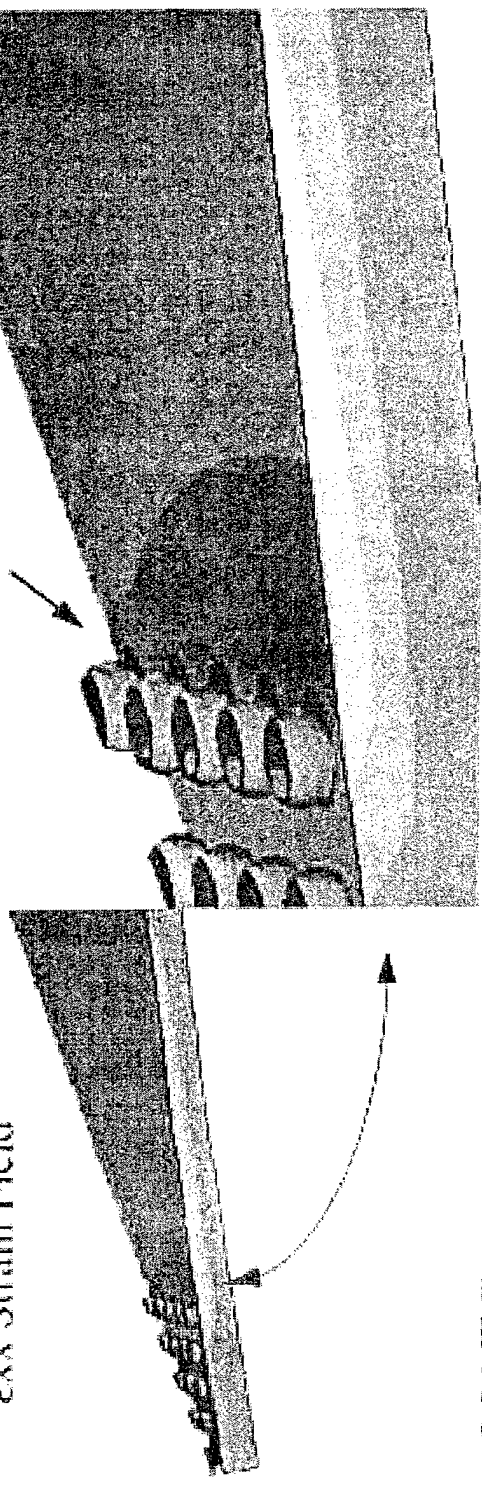
$\epsilon_{xx} = 0.002$   
 $\epsilon_{xx} = 0.00036$

## Uz Displacement Field



## $\epsilon_{xx}$ Strain Field

## Strain Concentration



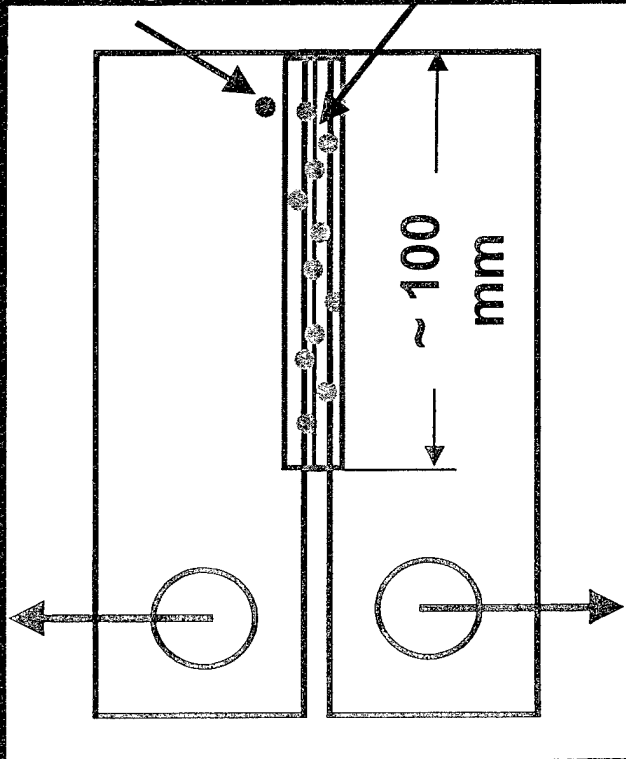
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# Near Term Challenges

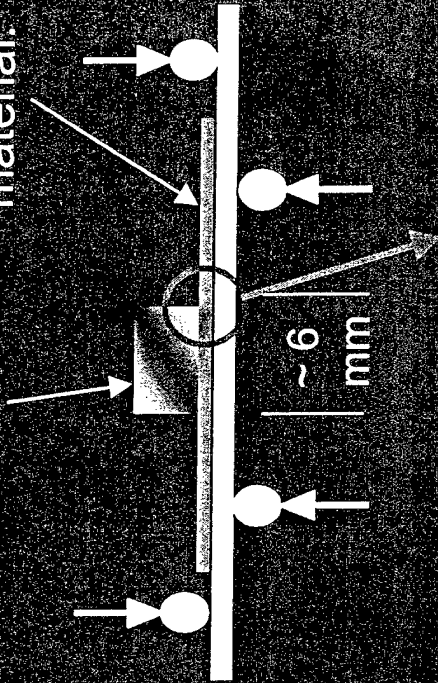
Compact Tension Specimen



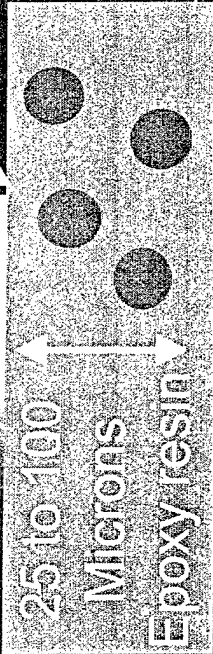
Self heal Opportunities (not to scale)

Controlled fracture path

Model microelectronic package, "stress concentration." Resin layer with self-healing material.



High stress area



Transition to PCB Laminate  
Several self-heal opportunities  
vs.  
much smaller population.



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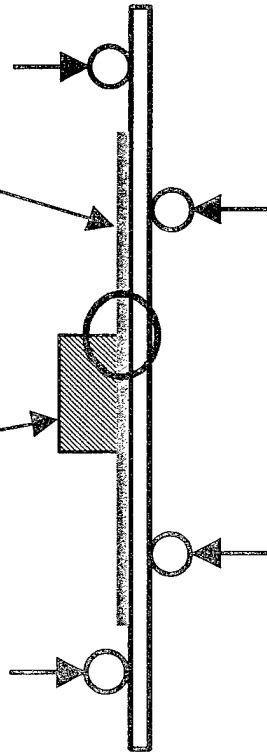
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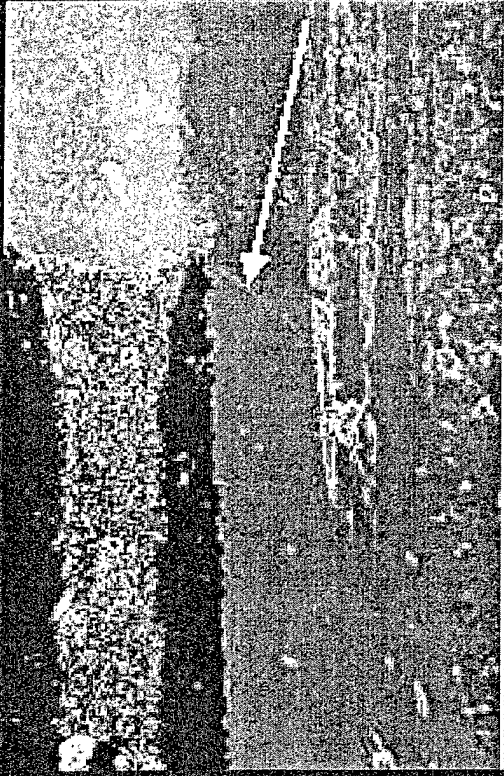


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Model microelectronic package, "stress concentration," Resin layer with self-healing Material.



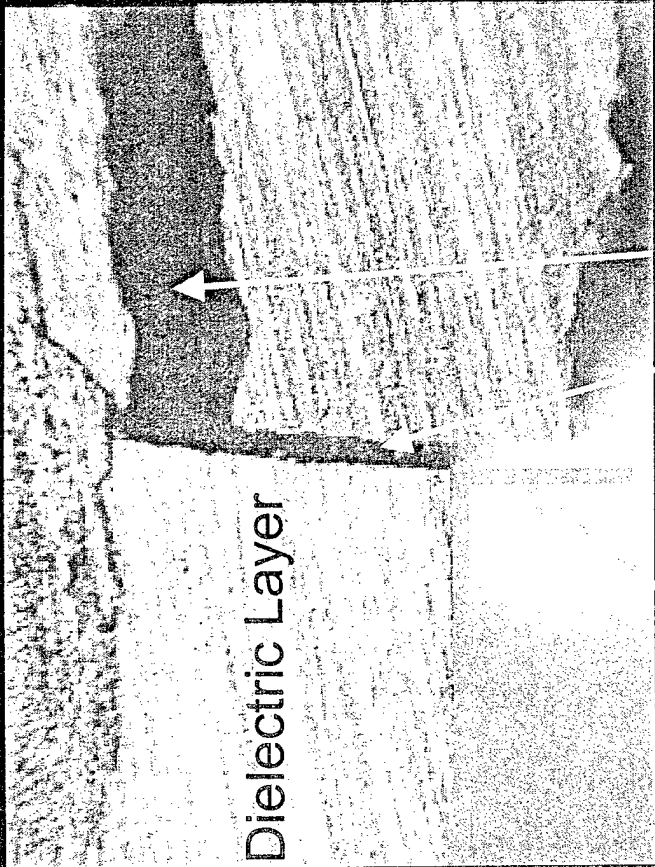
## Examples of test specimen fracture



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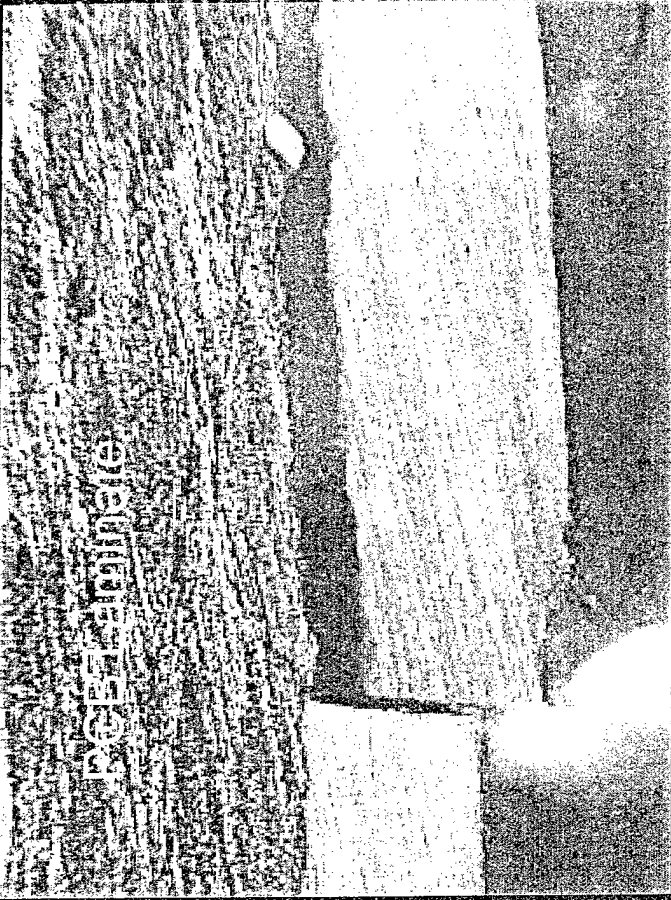
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Dielectric Layer

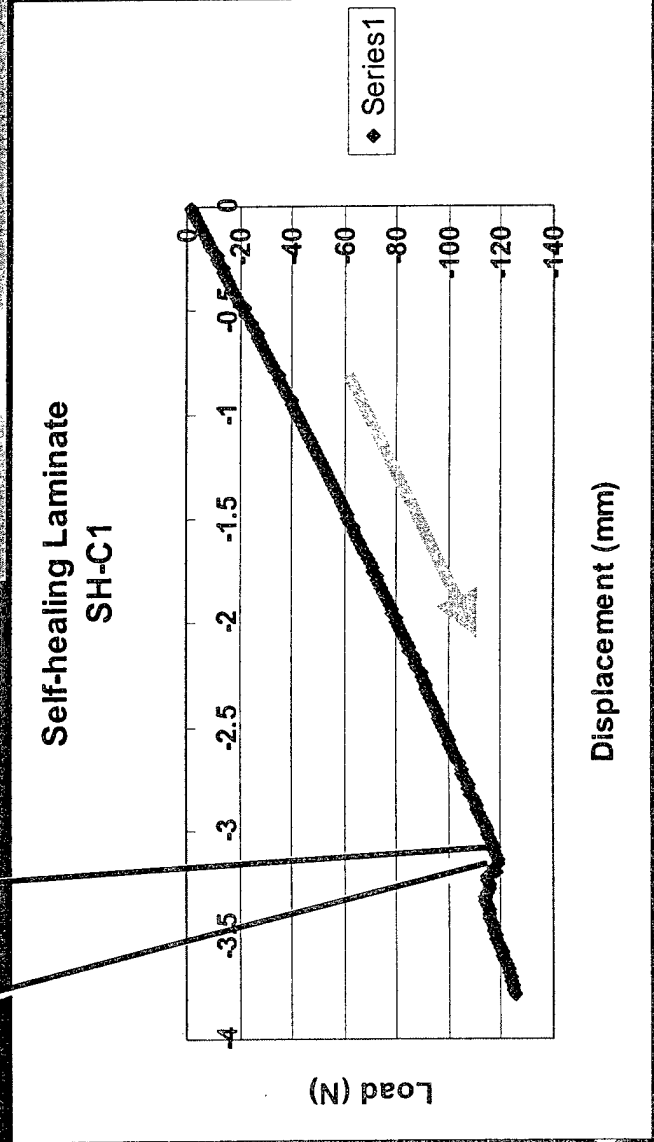
Edge of copper slug



Self-healing Laminate

Self-healing Laminate SH-C1

Load - displacement curve



## Future Considerations

- Challenge : Transition concepts to PCB Laminate
- Potential requirements:
  - Room temperature self-heal process
  - Can it work at - 40 C to 125 C ?
  - Non-invasive
  - No premature activation

## Electronic Assembly Processing

- ❖ Tolerate product operating temperatures (- 40 C to 125 C)
- ❖ Tolerate component/PCB solder assembly processing temperatures (~ 240 C for 15 seconds)

Can the PCB be recycled ?



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